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Comprehensive review of the annual haze episode in Northern Thailand

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Abstract

The mountainous part of northern Thailand is subject to an intense haze episode occurring almost every year between January and May. In the last couple of decades, this atmospheric phenomenon has been extensively covered in the media and is now a main concern for the population living in this area. In this review, we synthesized the information available from hundreds of publications on air pollution in Northern Thailand and surrounding regions. The review is tentatively comprehensive, including physical and chemical characteristics of air pollution, their emission sources and meteorological and climatological factors playing in the onset of haze. The effect on human health, the environment and development of agricultural, conservationist and technological practices is also covered. A significant part also focus on the socio-economical causes and solutions that have been brought by successive governments and organizations to solve this issue.

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1. Introduction

In the northern part of Thailand, starting at the beginning of the calendar year, a veil of smoke fill the skies from a few weeks to several months. This meteorological phenomenon, first described decades ago, is known as the burning season and many other names. It forms at the heart of the dry season, when weather conditions and extensive burning lead to the accumulation of air pollution in the atmosphere, reaching very high particulate matter levels, lowering the visibility, causing widespread health issues and inducing a significant economic impact.

In this review, we attempt to provide a full description and characterization of the phenomenon and its impact on human health and economy, but also cover the various causes (socio-cultural, administrative) that lead to the emission of pollution and a critical review on attempts to solve the issue so far. The various topics synthesized in this article are extracted from more than 250 scientific papers specifically studying pollution in Chiang Mai and Northern Thailand, published between 1986 and 2023 as well a considerable number of other publications on air pollution in Thailand, South-East Asia and elsewhere.

The aim of this review is to provide an objective and comprehensive summary of the situation in Northern Thailand. In the past few years, a handful of reviews (Pasukphun, 2018; Moran et al., 2019; Sompornratthanaphan et al., 2020; Adam et al., 2021; Phairuang et al., 2021b; 2022c; Suriyawong et al., 2022) have been published on the subject but have either a more narrow focus or an incomplete selection of publications on a specific subject. Here, we hope that this review can provide information on all general aspects related to the burning season and serve as a repository of scientific references for readers that wish to investigate the subject further. The review is separated in 12 sections covering different aspects of air pollution in Northern Thailand.

1. Introduction

2. General Description
A short section providing the main characteristics of air pollution in Northern Thailand

3. Physical characteristics of air pollution
Physical description of air pollution such as particulate matter (size, shape), concentrations through time and in different locations and monitoring and data formalism

4. Chemical characteristics of air pollution
Chemical description of air pollution including particulate matter and gaseous components

5. Atmospheric factors
Climatic and meteorological factors influencing air pollution in Northern Thailand

6. Sources of air pollution
Identification of the different sources of air pollution

7. Health impact
Health effects of air pollution in Northern Thailand

8. Environment
Various environmental consequences of air pollution and biomass burning

9. Prevention
Available methods of protection against air pollution

10. Social factors, policies and future trends
Underlying causes and consequences of burning and air pollution and the impact of government policies

Most information provided in this review is a relatively strict transcription of published data & interpretations with some summarizing of similar dataset and modification of figures to have better readability. In limited occurrences where our own basic observations and interpretations or data reprocessing has been performed, claims are marked with (*) in an effort of transparency to indicate that these pieces of information are not the product of an already published material. These pieces of information are generally regular observations (population habits, traditional media, social media) or taken from air pollution databases publicly available.

However, as explained in detail in section 11, it is important to mention here that many papers have unaddressed inconsistencies with other published articles or even within single publications. It leads to numerous unsubstantiated, conflictual or sometimes plainly false information and conclusions. This situation, covered in the last chapter on the scientific quality of Northern Thailand air pollution research, creates a strong limitation on how far and consistent this review can go as a strict non-critical assessing process would propagate these errors, false conclusions and fallacies further. To partly alleviate this issue while still providing the information available, reported interpretations that are seen as problematic for various reasons are marked with (º) while factually false and unsubstantiated claims are not included in this review.

2. <u>General description of the burning season</u>

Every year during the driest time of the year, a weather phenomenon occurs in continental South East Asia causing unhealthy ground levels of air pollution. This phenomenon is called haze episode, smokey season, burning season, PM2.5 event, etc. and is particularly extreme in Northern Thailand and the neighbouring region (Northern Laos, Central Myanmar).

Although its intensity varies from year to year and depends how the episode is defined, it systematically starts in mid-January to the end of April with variations of a couple of weeks earlier or later. Air pollution peaks in March where the horizon disappears into a yellow-orange haze that opacifies the atmosphere and reduces the visibility to a few hundred meters at the worst time. The loss of visibility hides local mountain and the skyline of cities and in some cases (2007, 2014, 2015), is extreme enough for landing airplanes to be diverted to other airports (Sattha, 2014; Bangkok Post, 2014, 2015; Chiramanee, 2016).

As the atmosphere is charged with pollution, it can reach concentrations where it affects daily life, particularly causing breathing difficulties for sensitive individuals and widespread allergy-like symptoms in the wider population. The only effective preventive measure against it is the use of masks and air purifiers inside buildings.

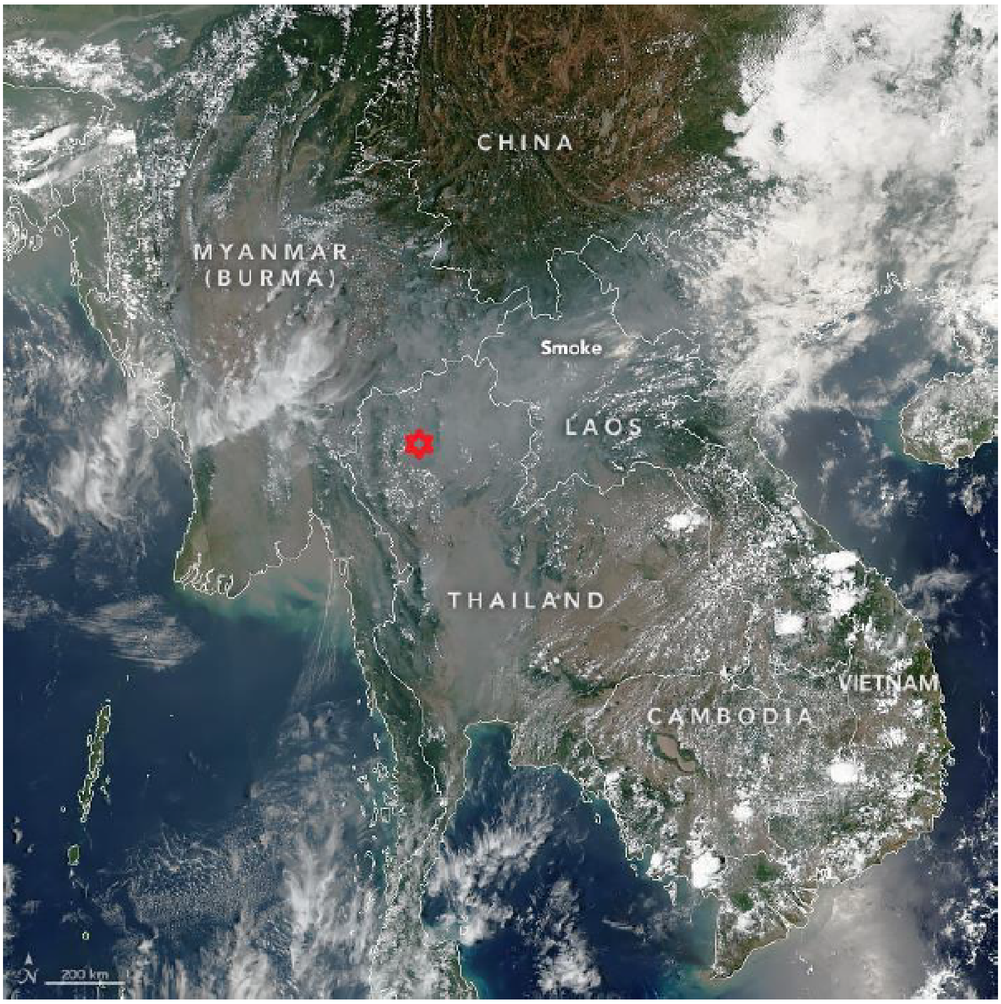

Figure 2.1. Satellite picture (visible and IR) of South East Asia on the 19th of April 2019, taken by VIIRS on Suomi National Polar Orbiting Partnership satellite. The red star is positioned over Chiang Mai (Anusananan et al., 2021).

The air pollution is widespread and not focussed on urban centres but it reaches higher concentration in valleys and basins of the mountainous north where specific meteorological conditions such as very low wind speeds and thermal inversions trap the smoke close to the surface. It is mostly produced by the incomplete combustion of biomass, producing gaseous aerosols and a large amount of smoke known as particulate matter. The particulate matter is very fine and often named PM2.5 for ‘particulate matter size below 2.5 microns’. It is mostly made of carbonaceous compounds as well as some other molecular compounds including toxic organic molecules. The sources of combustion are the forest floor covered with dead leaves, twigs and dry grasses that cover a very large proportion of Northern Thailand, Myanmar and Laos but also the burning of agricultural residues after the rice harvesting that can be a major contribution to the air pollution in some areas.

3. Physical characteristics of air pollution

Haze produced by air pollution has two components, one as gaseous aerosols and another one as solid particulate matter. Although the boundary between solids and gases seems clear cut, there is a limited phase change between the smallest particulates and some gaseous components that occur through chemical processes as smoke matures and components precipitate or evaporate in the atmosphere.

3.1. Particulate matter size distribution and time variation

Most of Northern Thailand air pollution is particulate matter. It is typically characterised using size fractions where brackets are chosen based on their physical and analytical behaviour but also to simplify monitoring, reporting and public health decisions.

Very coarse particules: Aerodynamical diameter >10 µm
Largest fraction. It is often ignored as they represent a relatively small fraction of the pollution at a reasonable distance from the source. It settles relatively quickly and it is not a significant health concern.

Coarse particules (PM10): Aerodynamical diameter <10 µm
It is historically the first fraction monitored since detection is easier.
These are a concern since particulate below 5 µm can already penetrate quite deeply in the lungs.

Fine particulates (PM2.5): Aerodynamical diameter <2.5 µm
The most common fraction reported in public announcement and monitoring devices.
It represents the majority of air pollution that has concerning health effects.

Very Fine particulates (PM1.0): Aerodynamical diameter < 1 µm
This size range is sometimes used for finer characterization of PM size distribution.

Ultrafine particulates (PM0.3): Aerodynamical diameter < 300 nm
This term is often used for technical purposes due to a transitional physical behaviour.
PM0.3 is important in filtering quality assessment.

Nanoparticulates (PM0.1): Aerodynamical diameter < 100 nm
It is the smallest non-gaseous air pollution. These are difficult to detect, collect and analyse and as a result, data on this fraction is not as abundant as larger particulates.

Gaseous components
Compounds that require a chemical or physicochemical process to be filtered.
It includes O_3, SO_2, NO_x, CO_2, CO, etc.

In most cases, particulate matter is divided into the 10-2.5-0.1 µm categories. Annual average mass distribution for Chiang Mai gives 23 wt.% PM0.1, 42 wt.% PM2.5, 20 wt.% PM10 and the remainder above 10 µm (Phairuang et al., 2019). Similar values were found by Amnuaylojaroen & Kreasuwun (2012) with roughly ¼ PM10-2.5 and ¾ PM2.5 (Fig. 3.1.).

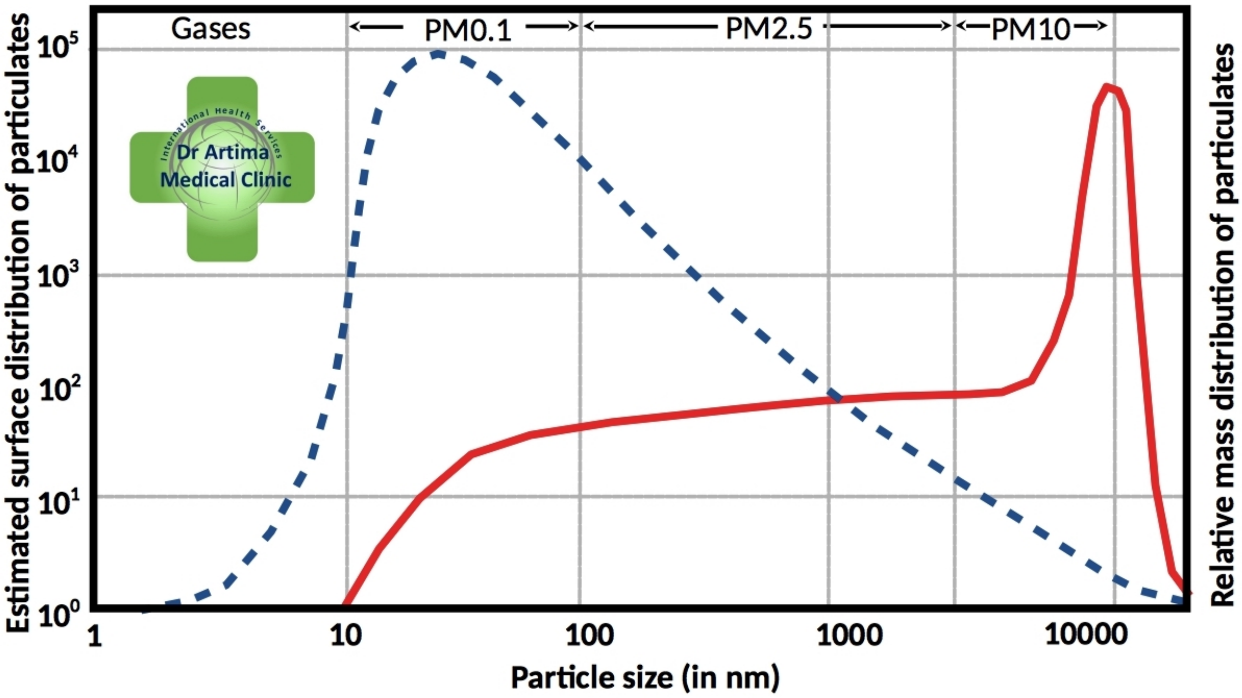

Figure 3.1. Mass distribution of particulate matter (continuous red curve) during a haze episode show the dominance of large particulates. In terms of the available surface area for particulates (dashed blue curve), the concentration peak in the ultrafine particulates. It roughly represent the number of particulates and is more relevant for health studies due to the potential for toxins adsorption (modified and recalculated from Amnuaylojaroen & Kreasuwun, 2012, Phairuang et al., 2019).

However, several variations have to be considered. PM2.5/PM10 ratio is around 0.95 during haze and the two values are highly correlated with a Spearman ρ of 0.88 (Muller et al., 2020; Othman et al., 2022) but weather conditions, particulate coarsening, the type of emission source (fuel and biomass combustion) and the proximity to a burning source do have an impact on the size distribution of particulates. The 2019 Samoeng fires and 2020 Doi Suthep-Pui fires have produced lower PM2.5/PM10 ratio in the Chiang Mai metropolitan area due to the proximity of forest fires (*, Fig. 3.2, 3.3.). In addition, major variations are present between haze and non-haze pollution. While the contribution of PM0.1 in PM2.5 is ~25% in the rainy season and non-haze periods, it drops to 10-15% during haze episodes (Sresawasd et al., 2021). PM2.5/PM10 is also lowered outside the haze season to 0.69-0.76 (Amnuaylojaroen & Kreasuwun, 2012; Othman et al., 2022).

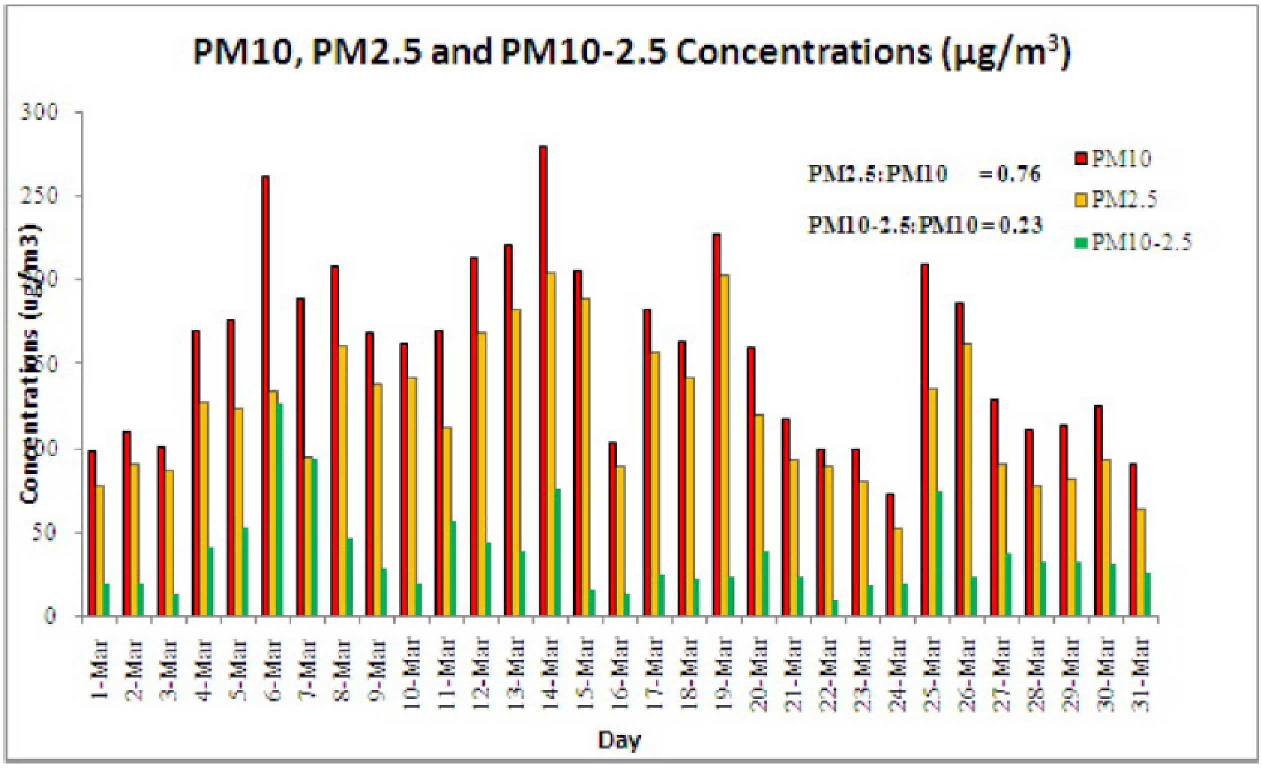

Figure 3.2. Simulated PM2.5 and PM10 concentration at the Chiang Mai Government Centre in Mae Rim for the month of March 2007. The relatively low PM2.5/PM10 ratio is correlated with a significant contribution of local wildfires in the Doi Suthep/Pui mountain range just west of the city (Amnuaylojaroen & Kreasuwun, 2012).

During haze episodes, all particulate matter fractions increase drastically, but as ratios show, in different proportions. PM10 during the wet season can go as low as 10 µg/m^3 but more often sit around 20 µg/m^3 (Pani et al., 2019). The burning season will increase it 10-fold to average concentrations of 150 µg/m^3 (Vinitketkumnuen et al., 2002) but extremely high haze days can bring these values (300-600 µg/m^3) (Matsuhita et al., 1998).

Fine particulate matter has a similar increase to PM10 between rainy season and haze episodes. While the concentration at the peak of rainy season (August-September) hoovers at similar values (10-20 µg/m^3), the burning season brings these concentrations to 150 µg/m^3 and it is not uncommon to have values far above 300 µg/m^3 some days of the dry season. The upper limit of these concentrations is a matter of definition and details. In direct proximity (a few kms) of a forest fire, considering weather and topography, it is not uncommon to reach 1 mg/m^3 for PM10 and PM2.5 or much higher near the fire front. Outside the influence of proximal fires, values of 500-800 µg/m^3 can occasionally be reached at the worst time of the day. In recent years, these are exceptions that only last a few days. However, past records of air pollution have provided 24h average values in excess of 500 µg/m^3 (18th of March 2010; Wiwatanadate & Liwsrisakun, 2011) and March 2007 had an average monthly concentration of 350 µg/m^3 (Trang & Tripathi, 2014) while the PM2.5 (but also PM10) record for the past 5 years in Chiang Mai is possibly the 30th of March 2019 with a 24h average around ~350 µg/m^3 (*, Fig. 3.3.).

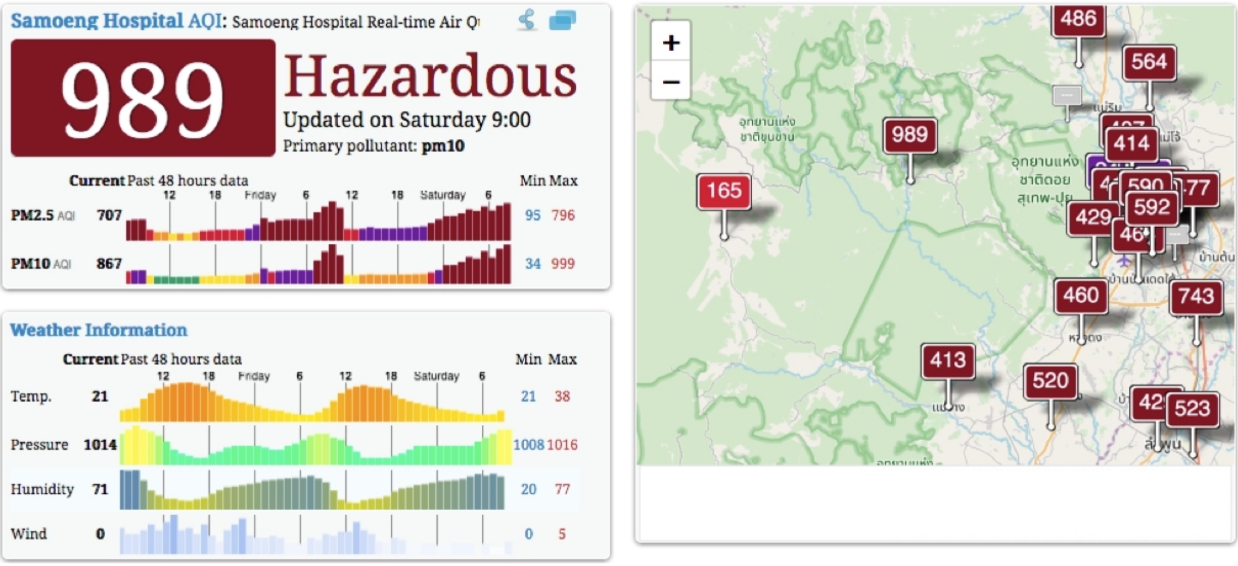

Figure 3.3. AQI (chinese scale) from AQICN for the western side of Chiang Mai and Samoeng valley in particular showing very high level of particulate matter on the 30th of March 2019 at 9:00 caused by nearby forest fires.

Ultrafine particulate matter is the most abundant fraction in fresh smoke from forest burning as emission peaks at 120 nm (Phairuang et al., 2022b) with around 20-30% nanoparticulates (<70 nm) and ultrafines 40-50% (70-430 nm) (Hata et al., 2014). Detrained smoke is slightly different as ultrafines can interact with the atmosphere, other pollutants and sunlight. Nevertheless, PM0.1 still forms 15-20 % of suspended particulate matter (Phairuang et al., 2022a) and reach values around 25 μg/m^3 during haze episode which is considerably higher than peak values for the rest of the country (Phairuang et al., 2019; 2021b) where PM proportions are lower (5.7 to 14.8%) (Chomanee et al., 2020). Outside the burning season, PM0.1 levels are around 3x lower and similar to other regions (Sresawasd et al., 2021). The lower rate of variation for PM0.1 compared to coarser fraction indicates that PM0.1 background is essentially due to urban or other sources that have a minor relationship with biomass burning (Phairuang et al., 2022c).

3.1.1. Hourly, weekly and yearly variations of air pollution

Yearly average of PM2.5 range between 30 and 60 μg/m^3 and PM10 between 30 and 90 μg/m^3 (Vinitketkumnuen et al., 2002; Chunram et al., 2007a; Wiriya et al., 2013; Ma et al., 2019) with the lower values during La Niña and highest during El Niño (Yabueng et al., 2020) but yearly concentrations are heavily influenced by the haze episode as only 13% of the year is above 50 μg/m^3 (Solanki et al., 2019) with peak months being 50% of the time above 150 μg/m^3.

All fractions considered, particulate matter levels start to increase dramatically over the whole region around mid-January, with variation of ± 2 weeks (Song et al., 2022a) but some authors makes the increase starting much earlier in December (Sukkhum et al., 2022). However, it is tacitly admitted that the haze episode itself, where visibility is constantly reduced and health symptoms are significant covers the entirety of February-March-April period with only a few rare (if any) days with acceptable pollution levels (Fig. 3.4.). Monthly averages range between 100 and 300 μg/m^3 at the peak of the burning season while it stays lower than 30 or even 20 μg/m^3 monthly values during the rainy season (Vinitketkumnuen et al., 2002).

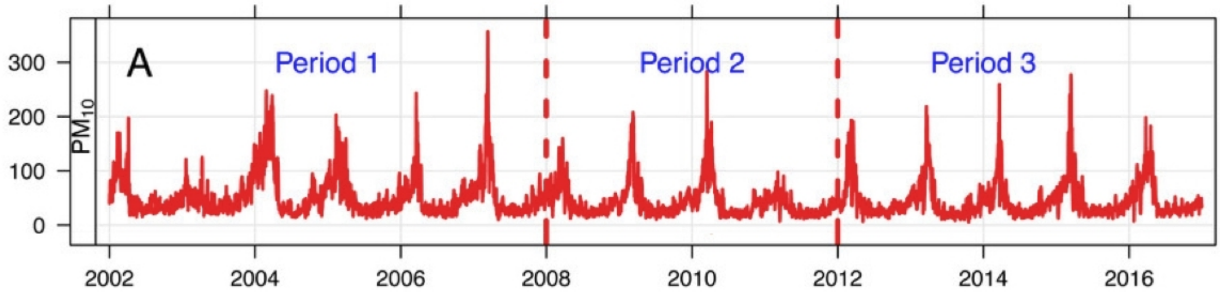

Figure 3.4. PM10 concentration between 2002 and 2016 in Chiang Mai province. The figure shows the regularity of the onset of the annual haze episode and the variations that exist between heavily polluted years (e.g. 2007, 2010) and mild burning seasons (e.g. 2003, 2011) (Vajanapoom et al., 2020).

Weekly and daily concentrations are subject to general meteorological patterns and 3-4 fold variations are not uncommon with lowest daily values around 100 µg/m^3 during haze episodes, a large number of days above 150 µg/m^3 and daily records above 300 µg/m^3 occurring during bad years (Vinitketkumnuen et al., 2002, Fig. 3.2.). A slight decrease of ~1% is described to occur on weekends in Chiang Mai, regardless of the season, and could be related to urban activities (º, Chunram et al., 2007b).

Hourly variations are more strictly controlled by atmospheric characteristics. Particulate matter has typically a bimodal distribution with peak concentrations in the early morning, and as late as 10:00 am and an occasional secondary peak in the evening (20:00-22:00) (Janta et al., 2020). These fluctuations are very stable and described in data as early as 1998 (Puangthongthub et al., 2007) but can substantially vary in different geographical areas (Fig. 3.5.).

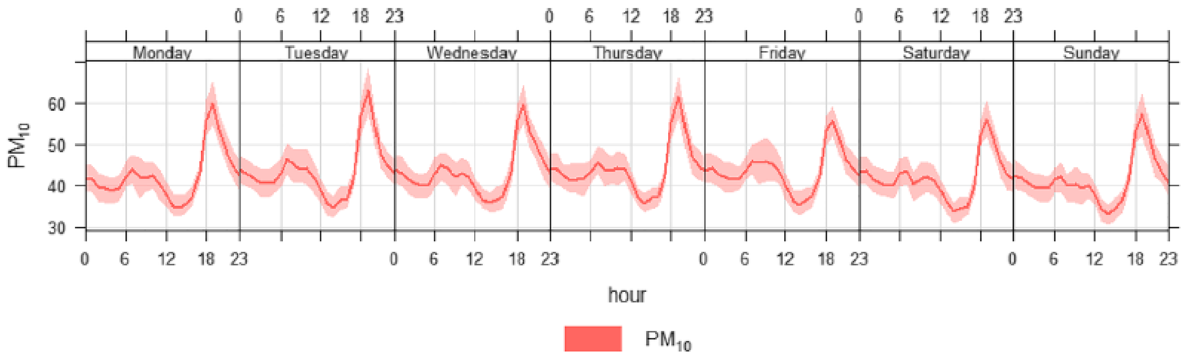

Figure 3.5. PM10 concentration over a week during the haze season of 2021 in Lamphun. The figure shows the lowest pollution levels in the afternoon and the increase of particulate matter overnight. In other zones, night time is characterised by a continuous increase reaching its maximum in the early morning (Kliengchuay et al., 2021) (Fig. 3.2, 5.8)

There are many studies on the type of particulate matter produced during wildfires. The particulate size distribution and the chemical composition of haze will change with the type of fire and the intensity of the burning stage (ignition, flaming, smoldering,…) (Hosseini et al., 2010), the fuel conditions (live, dead, wet, dry,…), its distribution (dense/light, flat/sloped,…) and fuel type (grasses, leaves, branches,…) as well as atmospheric conditions such as humidity, wind, access to O_2, CO_2 and CO during the combustion process.

Fuel characteristics and some atmospheric conditions dictate the characteristics of smoke sources. However, wind and humidity in combination with the oxidising effect of the atmosphere, play a role in transforming fresh smoke (from local sources) into detrained smoke after considerable vertical and horizontal transport and a secondary growth by in-cloud coagulation, increasing particle size by 20% (Guyon et al., 2005). In most river basins of Northern Thailand, the haze characteristics show an origin in low intensity surface fires of dried grasses, dried leaves and some shrubs (Chernkhunthod & Hioki, 2020) with medium to long-distance transport providing chemical and physical characteristics of detrained smoke. The fine assessment of smoke composition (physical & chemical characteristics) requires some knowledge of the contribution of local combustion sources to explain some characteristics of haze variations through short period of time and different localities.

3.1.2. Long term trends

Particulate matter concentration during the haze episode have wide inter-annual variations that mostly depend on the climate and more particularly the state of ENSO. However, through these wide inter-annual variations, some attempts have been made to decipher a general trend in air pollution in Northern Thailand over long period of time.

According to some studies, PM2.5 and PM10 have been slightly decreasing over the past couple of decades (Vajanapoom & Kooncumchu, 2019; Thongrod et al., 2022). Quantification gives an average of -0.83 $\mu g/m^3$ per year (Sukkhum et al., 2022). On the other hand, some other research have suggested that particulate matter is increasing (Pongpiachan et al., 2013; Mitmark & Jinsart, 2017) with an average value of +0.3 $\mu g/m^3$ per year (Ma et al., 2019). These trends, positive or negative, are more than 2 orders of magnitude below the measured inter-annual variation and can be considered as almost negligible. It is worth mentioning here that the common claim from various organization, media sources and academic papers that the haze event is getting worse is not supported by scientific data (Fig. 3.6.).

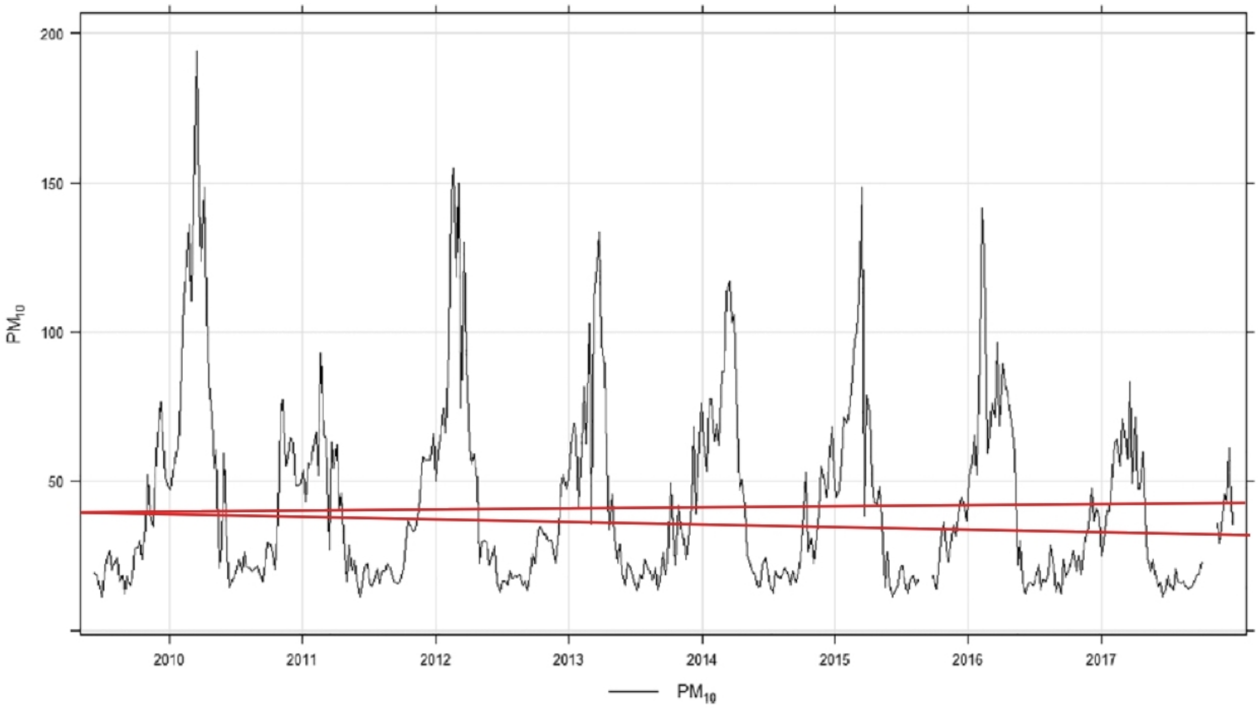

Figure 3.6. Daily values of PM10 in Lamphun between 2009 and 2018 (modified from Kliengchuay et al., 2021). Red lines show the strongest increasing and decreasing trends published at yearly average values of PM10 (Ma et al., 2019; Sukkhum et al., 2022).

3.2. Monitoring

Monitoring of air pollution has increased considerably in the past decades due to several factors. The satellite coverage, precision and resolution of the imagery that can be obtained provide daily information on the regional situation. The quality of ground-based detectors has made the analysis of finer particulate matter such as PM2.5 the norm to estimate particulate matter air pollution. The development of these ground-based detectors into relatively maintenance-free, reliable and cheap instruments has allowed the installation of these devices in many places (public and private), giving a quite precise characterisation of the air pollution in an area, with a spatial resolution lower than a kilometer in urban area and hourly time resolution.

3.2.1. Satellite monitoring

Before the launch of satellites fully dedicated to the remote study of air pollution and wild fires, the burning season was observable, but not fully quantifiable by infrared observations, standard weather observation of cloud & aerosol covers and atmospheric transparency. The extent of fires could be assessed a posteriori through remote land surveys of satellites such as Landsat.

The first detectors suitable for air pollution and fires were Advanced Very-High-Resolution Radiometers (AVHRR) in use since 1978 with TIROS-N followed by a dozen of NOAA satellites and a handful of MetOP satellites of the EUMETSAT system. They have a maximum resolution of 1.1 km/pixel and used infrared channels to detect thermal emission of the Earth. A program called Fire Identification, Mapping and Modeling Algorithm (FIMMA) was used to identify sources such as wildfires. Active fires in Northern Thailand were detected with AVHRR in April 1994 through this system (Christopher et al., 1998; Pochanart et al., 2001). The latest satellite NOAA-19, launched in 2009, is still equipped with AVHRR and is part of the satellite constellation monitoring the Earth for wildfires and many other observations.

In the late 90s, a series of sun-synchronous near-polar orbit satellites were designed and launched to provide data on water and carbon distribution in the atmosphere, the detection of wildfire in real-time and the properties of the atmosphere, particularly in terms of radiative characteristics influenced by aerosols.

The most successful instrument of that decade was the Moderate Resolution Imaging Spectroradiometer (MODIS) and equivalent instruments installed on a number of satellites and providing a large amount of information on some types of events occurring on the surface and in the atmosphere (Fig. 3.7.). MODIS was installed in EOS satellites Terra and Aqua in 1999 and 2002. These two satellites have a near-polar orbit of 700 km, which allow them to pass twice a day above a specific area anywhere on Earth. Terra passes over Thailand at 10:30 LST from the North to South and the opposite direction at 22:30 LST while Aqua passes at 13:30 LST South to North and the opposite direction at 1:30 LST (Sukitpaneenit & Kim Oanh, 2014; Uttajug et al., 2021). The acquisition of data is done through a swath 2330 km wide, analysing the ground and the atmosphere through 36 spectral band from 400 nm to 14.4 μm with a spatial resolution varying from 250 to 1 km (Phayungwiwattahankoon et al., 2014; Pongpiachan et al., 2021).

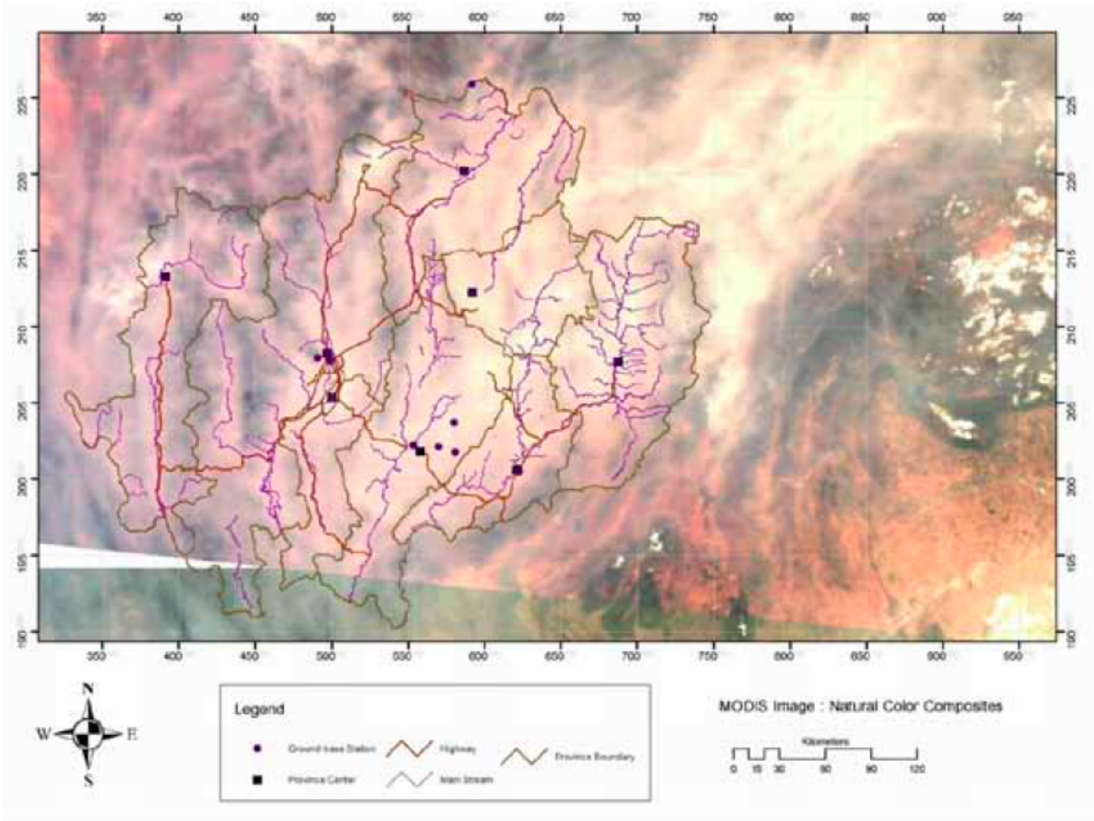

Figure 3.7. MODIS image of northern Thailand in visible light and infrared on the 8th April 2010. Some administrative, hydrographic, demographic and road information is overlaid to the satellite image (Phayungwiwattanakoon et al., 2014).

Eventually, in 2011, a new instrument was installed on NOAA Suomi NPP satellite called Visible Infrared Imaging Radiometer Suite (VIIRS) and subsequently on NOAA-20 and the recently launched NOAA-21 satellite. It is built on the experience accumulated from the aging MODIS and AVHRR systems to provide more accurate and sensitive measurements of land and the atmosphere with a higher spatial resolution. These three satellites have broadly the same orbital constrains and not fundamentally different from the MODIS satellites. Fire detection in particular is done in the mid-infrared range, where it is overlaid with land use data from other satellites and combined with an estimation of smoke plume height and various tropospheric parameters for atmospheric modeling (Punsompong et al., 2021). VIIRS has a higher resolution of 375 m/pixel with better detection of smaller fires, better identification of flaming front and improved night time detection. With 3 satellites available, passing at 00:40 and 1:30 LST, 6 images are collected per day for a chosen low-latitude region (Choommanivong et al., 2019; Hongthong et al., 2022).

VIIRS data collected at 4 µm is processed into hotspot data by the Land, Atmosphere Near Real-Time Capability for EOS (LANCE). The MCD14ML tool (NASA, 2020; Lalitaporn & Mekaumnauychai, 2020) is then made available on the Fire Information for Resources Management System (FIRMS) to be consulted publicly. The processing takes into account reflective surfaces, cloud cover, spectral characteristics, etc. and only high confidence hotspots are displayed as fires (Sritong-aon et al., 2021) but the full dataset will provide geographical coordinates, date & time, temperature brightness, fire power and fire detection confidence level as well as some basic information associated with each hotspot (Sirimongkonlertkun, 2018a) (Fig. 3.8.).

Forest fires are picked up by MODIS and VIIRS but cloud cover or thick canopy can limit the detection. Based on ground survey and high-resolution satellite imagery, these spectroradiometers can pick 95 to 96% of forest fires (Tanpipat et al., 2009; Phairuang et al., 2016; 2021) in a 1 km^2 resolution with a recorded minimum of 84% (Zhu et al., 2017). In some cases, the improvement in fire detection from satellite remote sensing can be 500% of ground estimations (Junpen et al., 2013a).

Agricultural fires are more significantly underestimated by near-polar orbit satellites due to the spatial and temporal resolution (Lakso et al., 2017). The average farmer in northern Thailand owns 7.9 ha of land per household, often split in small section of 100 m with a burning time of 2-3 hours (Kanabkaew & Oanh, 2011; Kim Oanh & Leelasakultum, 2011; Junpen et al., 2018). Field burning can completely occur in the observation gap between two satellites (Junpen et al., 2013a; 2018; Stavrakou et al., 2016). Active fires with a narrow front are also hardly detectable with MODIS since 1 pixel = 25 ha but also VIIRS (1 pixel = ~15 ha). Some estimations put the detection of cropland fires as low as 13% (Zhu et al., 2017). In such case, ground surveys might still achieve better results for the foreseeable future (Phairuang, 2021).

MCD64A1 (and predecessors) algorithmic tools used on both MODIS & VIIRS, with pre-, syn- and post-burn satellite imagery show that a significant amount of small fires (<100 ha) can be undetected, either due to their size (i.e. croplands) or due to the low spectral reflectance of ash/charcoal and scorched leaves hidden under the canopy of forests when compared with high resolution (30 to 2 m) satellite imagery in the same spectral range (Zhu et al., 2017). The number of fires can also be underestimated when several fires occur per pixel (Suriyawong et al., 2023) or overestimated when random ground truthing is done (Boonman et al., 2014). Aside from undetected fires, strong emission at 4 and 11 µm wavelength can also be linked to artificial hotspots such as infrared reflectance from metal roofs (Kamthonkiat et al., 2021).

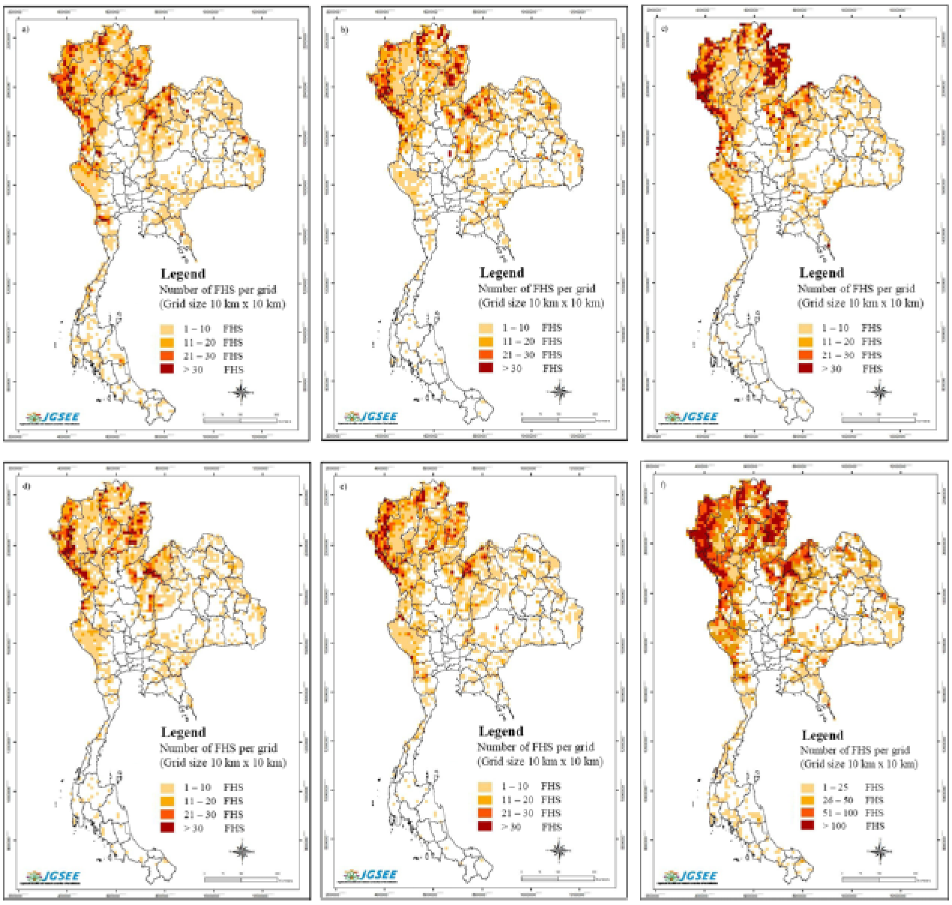

Figure 3.8. Hotspot density map from forest fires between 2005 and 2009 (a) to (e) while (f) shows the cumulated hotspot density in that time period (Junpen et al., 2013)

Aside from fire detection through MODIS and VIIRS, these instruments also have detectors used for other purposes directly relevant to the air pollution in Northern Thailand. The most commonly used tool is called Aerosol Optical Depth (AOD; also called AOT (Aerosol Optical Thickness)) which measure the attenuation of radiation caused by aerosols dispersed in the atmospheric column (Fig. 3.9). Data generally has a base resolution of 10 km/pixel and can go down to 3 km/pixel but recent methods such as the Multi-Angle Implementation of Atmospheric Correction (MAIAC-AOD) using MCD19A2 tool can provide a resolution of 1 km (Hongthong et al., 2023).

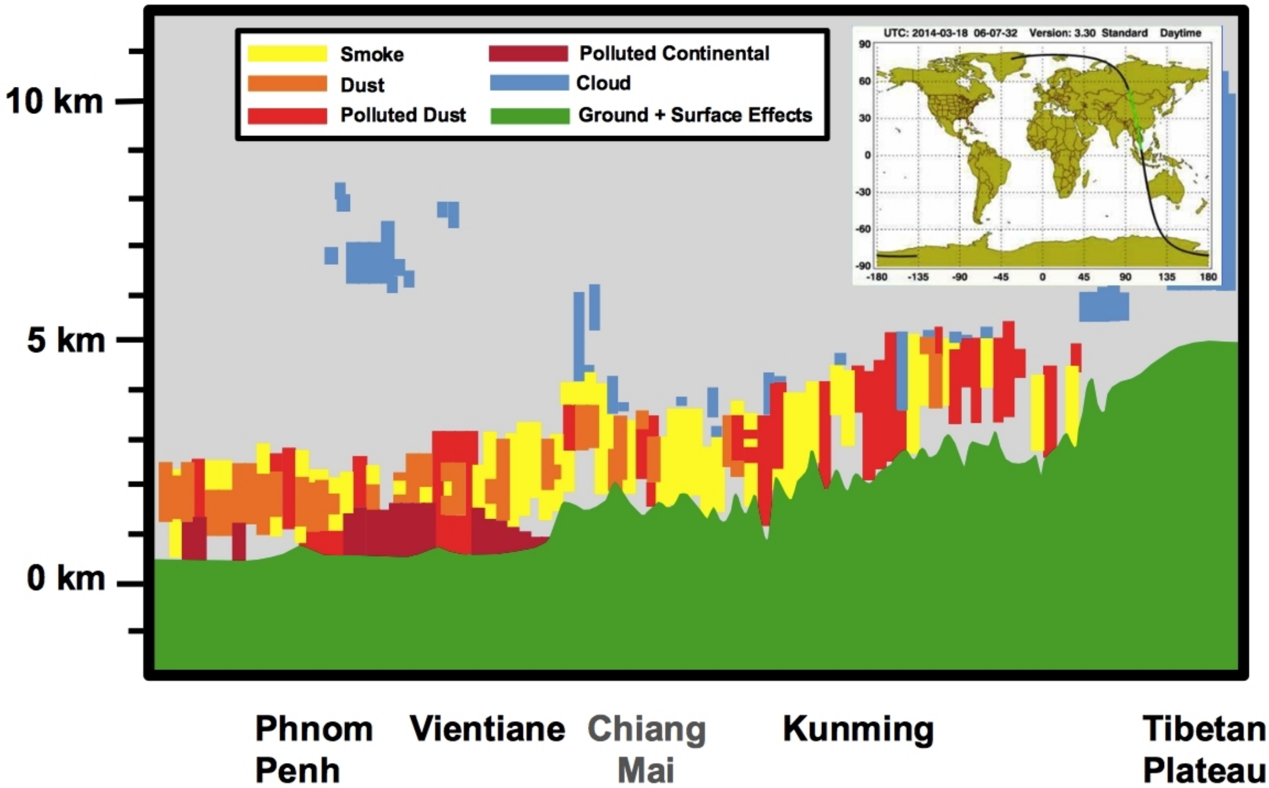

Figure 3.9. Satellite remote sensing aerosol characterization based on extinction coefficient and associated properties (LIDAR) of CALIPSO satellite. CALIPSO was then on the A-train similar to Aqua and Cloudsat satellites. The figure is a transect from South-Western China to Cambodia recorded on the 18th of March 2018. The aerosol layer is shown to be extending 2km above the ground in Northern Thailand (inspired from Pani et al., 2018)

Atmospheric transparency can be translated into an estimated level of pollution. Linear correlation with ground measurements gives a R^2 of 0.51 but additional variables such as the effect of relative humidity, mixing layer height, etc. show that a R^2 of 0.86 can be obtained for non-linear regression (Bach & Sirimongkalertkal, 2011; Chankamthon, 2012 Phayungwiwattahankoon et al., 2014; Leelaasakultum & Kim Oanh, 2017). AOD has been studied in many publications and is the main tool to provide air quality information in areas where no ground station is present (Kanabkhaew, 2013; Phayungwiwatthanakoon et al., 2014; Trang & Tripathi, 2014; Sayer et al., 2016) or to have an effective measure of the mass of particulate matter over a regional scale (Suwanprasit et al., 2018) (Fig. 3.10). MERRA-2 satellites are also of some use in the prediction of pollution by measuring the height of the planetary boundary layer and fluctuation between near ground at night and a few kilometers during the day, having a direct impact on the concentration process of aerosols near the surface (Sayer et al., 2016). On the basis of this MERRA-2 technology, some authors claims to have increased the AOD-PM correlation from R^2 of 0.21 to >0.90 (º, Chinsorn & Papong, 2021).

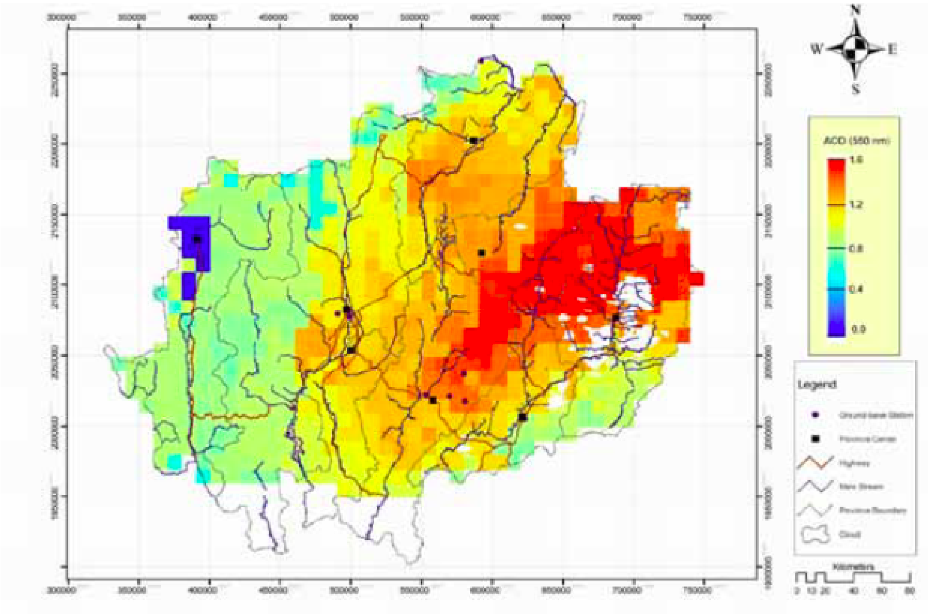

Figure 3.10. Aerosol Optical Depth map of Northern Thailand extracted from MODIS data on the 8th of April 2010. The spatial resolution is 10 km and overlaid with administrative boundaries, hydrographic data, urban centres and roads (Phayungwiwatthanakoon et al 2014).

The data provided by the National Polar-Orbiting Partnership is exploited to study land use, land cover and atmospheric characteristics and combined with other satellites data with higher spectral, geographical and temporal resolution. This information is compared with ground measurements of the Aerosol Robotic Network (AERONET) that includes sun photometers, spectroradiometers, PM laser photometers and AQI stations (Kamthonkiat et al., 2021). In the Northern provinces, all AERONET stations are within the Chiang Mai province, in Omkoi, Chiang Mai city, Fang, Chiang Dao, Doi Ang Khan and Doi Inthanon. The correlation between space-based AOD from MODIS and ground-based AOD from AERONET is very good with R^2 of 0.93-0.94. Variations are due to relative humidity, total columnar water vapour and a vertical heterogeneity of the aerosol column with more absorption near the ground surface (Sayer et al., 2016; Hongthong et al., 2023). The aerosol prediction index from MODIS reflectance data in blue (459-479 nm) and mid-infrared (2105-2155 nm) with a 10 km resolution has been compared with AOD from MODIS and AERONET giving a correlation with a R^2 between 0.62 and 0.66, leading to an error on PM10 ground estimation of 10.78% (Phayungwiwattahankoon et al., 2014).

Other atmospheric pollutants can also be studied from satellite observations, notably through the Measurement of Pollution in the Troposphere (MOPPITT). Resolution is lower for these measurements with 22 km/pixel combined with the 10 km/pixel of AOD measurements to provide estimation of CO concentration in the atmosphere. Comparison with ground measurements give a correlation coefficient between 0.69 and 0.89. The measured correlation with hotspot counts and particulate matter measurements also suggests a link between CO and biomass burning in rural areas and allow tracking down smoke plumes from fires. In urban areas, CO concentrations can be affected by traffic, coal-fired power plants and other urban sources (Sukitpaneenit & Kim Oanh, 2014; Lalitaporn, 2018).

GOME, OMI and SCIAMACHY satellites are also used to estimate atmospheric NO_2 compared to ground concentrations. OMI satellite in particular, shows NO_2 columns appearing in the afternoon, possibly from fertilizers in burning crops (Lalitaporn & Boonmee, 2019).

3.2.2. Air Pollution Detectors

Types of Detectors

The traditional method of air pollution measurement of particulate matter consists of a complicated process of accumulation of dust on different filters.The size characterisation of particulate matter is done through mass of particulate captured by different filters as a function of the air flow passing through it. It was initially mostly limited to PM10 but eventually expanded to PM2.5. PM0.1 remains an elusive fraction that brings some technical difficulties. The filtering technique is still widely used for accurate measurement of particulate matter pollution, calibration of instruments and studies on physical and chemical properties of particulate matter.

Alternatively to filtering techniques, optical methods are available to quantify particulate matter through interactions between haze and light. These techniques are equally accurate and precise but require a careful and constant monitoring and an adequate calibration to provide quantitative data suitable for the scientific community.

Among optical methods, low-cost air pollution sensors (LCS) are of a particular interest as they have become widespread in the last decade, with a considerable reduction in complexity, maintenance and price compared to research-quality instruments. LCS started to appear in the early 2010s and became commercially abundant around 5 years later, in 2017-2018 (Giordano et al., 2021).

The manufacturing and field characteristics of LCS have the advantage to produce a spatially dense network with a high temporal resolution that is particularly beneficial in low and middle-income countries where reference stations are unavailable. Another characteristic of LCS particularly beneficial for the Northern Thailand situation is the potential spatial resolution of such device network where concentration fields of pollutants with significant gradients can be recorded. However, the sensitivity of LCS to calibration requires simple (meteorology, sensor aging) and complex (aerosol properties, refractive indices) corrections to remove any bias for any application other than qualitative characterization of air pollution (Giordano et al., 2021).

Optical sensors

Optical sensors works by translating particle size and count measurements into mass concentrations using particle density hypotheses that include numerous parameters affecting accuracy and precision of interpreted data. The underlying principle is based on Mie theory of dispersion of light. As contaminated air flows through a measurement cavite, the light intensity (infrared or red light) reaching a phototransistor is modulated by the presence of particles in the light path. The scattering of light produces a nephelometric response that is a function of the mass and number of particles. Devices generally have an optical particle counter made of two detectors for coarse and fine particulate matter and use a laser beam scattered inside the measurement chamber and analysed by photodetectors. A full review on the technical aspects of these sensors has been made by Alfano et al. (2020). LCS often include other sensors for the measurement of gaseous pollutants using electrochemical gas sensors (SPEC DGS) and metal oxide gas sensors (MiCS, MQ) recording the electrical conductivity in contaminated air or at the surface of a semiconductor sensitive to gases present in polluted air (Gabel et al., 2022).

Parameters associated with the calibration of each instrument include the initial characteristics and sensitivity of sensors, particularly their behaviourial response depending on chemical composition, reactivity, refractive index, concentration, shape, size distribution, etc. and environmental conditions such as temperature and relative humidity. These parameters add to long term instrumental drifts, known interferents, non-linearities used in calibration and concept drift effect caused by incomplete models (de Vito et al., 2020).

Sensor parameters

Relative humidity can produce measurement accuracy effects for value as low as 50% (Jayaratne et al., 2018; Magi et al., 2020) but it's for relative humidity values above 80-85% that the impact on the measured PM concentration becomes significant (Crilley et al., 2018; Liu et al., 2019; Malings et al., 2020). In those conditions, non-linear behaviour is observed and quadratic functions are required to reduce the relative error on mass estimation below 10% (Zheng et al., 2018). Although meteorological conditions are relatively dry during the burning season with relative humidity between 40 and 60%, it is not uncommon to have days of high humidity in northern Thailand, particularly at the end of the burning season and it could affect the accuracy of LCS.

Temperature has an effect on sensors and the concept design of LCS but the effect is minor and can be relatively easily corrected (Giordano et al., 2021).

Size distribution is partially alleviated by the use of different sensors for different weight partition bins. However, ultrafine particulates (PM0.5) are underestimated and affect the calculation of PM1.0 or PM2.5. This can be a significant issue in urban environment where the production of ultrafines from traffic or industry can be significant. The concept design in the sampling setup can also have an effect on measurements (Lewis et al., 2019; Alfano et al., 2020) and it has been shown that PM2.5 and PM10 measurements are not two independent measurements in LCS (Giordano et al., 2020).

Concentration values are also an issue that is partially resolved by longer sampling time and calibration. Low concentrations (<30 μg/m^3) provide the worse accuracy of PM2.5 group but with a proper setup, the precision can be ±1 μg/m^3 which represent ~10% of the concentration (Malings et al., 2020; Eilenberg et al., 2020; Giordano et al., 2021). Time integration is also an important factor as errors over measurement integrated over 1h are between 27 and 46% while a 24h integration bring this error to 9-17% (Zheng et al., 2018). When concentration are above 125 μg/m^3, non-linear behaviour is observed (Zheng et al., 2018). For very high concentration, non-linear behaviour is expected and all sensors are saturated for values around 4 mg/m^3, resulting in a noise background that limit the ability to work in cleaner air (Alfano et al., 2020).

Chemical composition has been described has having a 20% difference between organic and inorganic PM and differences between inorganic compounds as high as 50% (Liu et al., 2017a; Salimifard et al., 2020).

Sensor aging is probably negligible for a 1-year use, but it depends on several parameters such as other elements of the monitor, the level of exposure to high concentration of aerosols, etc. (Sayahi et al., 2019; Tryner et al., 2020; Giordano et al., 2021).

PM sensor calibration is dependent on particle group behaviour, interactions of particle with light as a function of RH, morphology, composition, etc. (Giordano et al., 2021).

Sensor calibration

LCS are laboratory calibrated on a set of conditions that represents what the sensor is expected to measure in the future, with or without adequate corrections. In that regard, most LCS are sold without any guarantee on data accuracy and precision (Lewis & Edwards, 2016; De Vito et al., 2020). The calibration is made on a priori assumptions of particle size, properties and distribution for concentration estimation. When these assumptions are not met in the field, low accuracy, low precision and non-linearity effects occur. Ultimately, the concept drift effect caused by inadequate calibration models to allow optimal field performances directly affect the robustness of the data from LCS (de Vito et al., 2020). A wide range of sources (NaCl, KCl, $C_{12}H_{22}O_{11}$, NH_4NO_3, polystyrene spheres dust, diesel waste fumes, welding fumes, soil dust, various incenses, sucrose, cigarette, e-cigarette, various papers, candles, aroma diffusers, talcum, oleic acid, pMDIs) are used for calibration purpose of LCS and research-based sensors (Alfano et al., 2020) and are not always suitable to accurately measure biomass burning particulate matter. It is possible that from all calibration aerosol sources, incense smoke has the size distribution and behaviour that match best the haze in Northern Thailand (*).

The correlation coefficient used to estimate the accuracy of PM sensors has limited capability to show existing (corrected) biases and various errors and the robustness of LCS requires the full use of statistical errors (MSE, RMSE, CRMSE, MAPE, MAE) to provide an estimation of the quality of a sensor. Among the ~50 LCS used to assess data quality by Alfano et al. (2020), R^2 range from 0.2 to 0.99, with the majority of sensors reaching a R^2 of ~0.90 when the right calibration is used. When it is inadequate, R^2 below 0.5 is commonly observed. Once a calibration is made, correction of this calibration can go from simple linear and quadratic models to complex machine learning algorithms using nonlinear autoregressive methods through neural network and deep learning models (Zaidan et al. 2022; Giordano et al., 2021).

Several solutions are available for the increase in data robustness of LCS. Collocated sensors can have increased precision as well as adaptive calibration models when ground truth data is available. Extensive laboratory experiments in a wider range of testing scenarios with different aerosols and meteorological variables selected for the location of the LCS would considerably increase the quality of the data as would calibration periods that would cover an entire year. The uncertainty of a measurement is known to be reduced from 50% for a 1h calibration to 10% for 100 days calibration (Eilenberg et al., 2020). The design of more robust calibration with little drift except under unexpected circumstances would also provide better data in some circumstances (Alfano et al., 2020; Giordano et al., 2021).

Local spatial and temporal variations

While physical techniques are mostly limited to an hourly average of air pollution measurements, new optical detectors can provide instantaneous measurements of air pollution and with their very affordable prices, become widespread in public and private settings, indoor and outdoor to monitor air quality and the efficiency of air purifying techniques.

Some of these detectors are also connected to an online network and measurements are available for the public through dedicated websites. The abundance of detectors provides a new form of dataset that is so far not exploited in the scientific literature for Northern Thailand. There are however some common observations that can be made on these datasets. Local variations of PM concentrations (2 orders of magnitude) occur occasionally outside the haze season. In cases where the source has been investigated and found, it is the result of a proximal source that is particularly polluting near the monitor but defective monitor have also been noticed (particularly extreme punctual variations with odd patterns)(*).

Less extreme variations (1 order of magnitude over a suburb) are likely explainable by a local source (biomass burning, house fire, industrial or urban activity) and/or a specific urban feature (topography, winds, etc.) that can cause a shortly lived anomaly. Some deviation in PM10/PM2.5 can also be observed (*).

Smaller variations are the result of natural variability in air pollution, related to the local distribution of haze, the position of detectors in the urban environment (traffic, buildings, elevation, semi-closed spaces, etc.)(*). Low cost detectors also have their inherent concept issues that can create inconsistency in available data as devices used for publicly available air pollution networks are produced by low-accuracy, low-robustness detectors that have no calibration process and suffer from time drifting (Concas et al., 2021; Zheng et al., 2018).

3.2.3. Air Quality Index

Ultimately, the lack of accuracy of low-cost sensors has only a minor effect to the public. The discrepancy between reference data and measurement is significant but negligible when personal decisions are depending on it. For most applications considered, an imprecision of 20% when air pollution is quite high has little impact on basic interpretation and health decisions that would follow as particulate matter concentration are generally translated into air quality indices that would often makes the error on measurement of less importance.

The Air Quality Index (AQI) is a quick estimation tool designed by environmental authorities in different countries to inform the public of the level of air pollution. The scale is proportional to the concentration of pollutants but the index is assessed on the health effect that each measured pollutants has on the human body. For particulate matter, it takes an average of PM-related health effects measured in many parts of the world.

Components entering the AQI determination are fine particulates (PM2.5), coarse particulate (PM10), ozone (O_3), carbon monoxide (CO), nitrogen oxides (NOx) and sulfur dioxide (SO_2). In some scales (India, Australia), other pollutants such as ammonia (NH_3) and lead (Pb) are also measured. The different variables are computed into a piecewise linear function with various breakpoint (between 5 and 10) providing a result ranging from clean air to very hazardous air pollution.

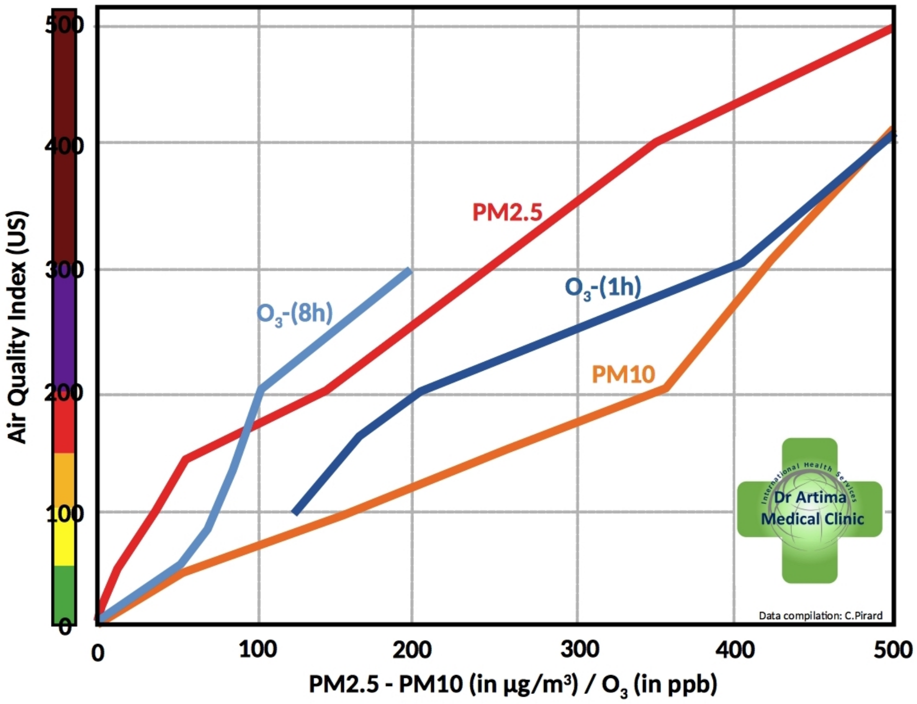

Figure 3.11. Graphical representation of the Air Quality Index (US) for its corresponding particulate matter concentration for PM10 and PM2.5 and ozone.

Many scales are used, some of them being almost but not completely identical. The American US AQI scale is very similar to the Chinese AQICN (Fig. 3.11). Vietnam, Thailand, Singapore, Japan, South Korea and India all have similar indices that broadly provide the same AQI numbers with some variations in the terminology used and some breakpoints. The typical range is 0-500. The UK, Canada and Hong Kong are using their own scales with values between 0 and 10 while the EU has a 0-100 scale and Australia a 0-200 scale. The definition of the AQI scale used and pollutants incorporated into it can reflect the public health policies of the country, its air pollution history and the overall air quality standards expected in a specific nation. Recently, a homogenisation of world data recalculated from mass concentration into the US AQI is available in realtime by the World Air Quality Index Project (waqi.info), an expansion of the Chinese network AQICN already available for the past 15 years (aqicn.org) which allow direct comparison between countries, independently of the local variation of their own air quality indices.

In Northern Thailand, the Air Quality Index is determined by the PM2.5 concentration as it is the dominant aerosol in terms of health effects. Occasionally, PM10 effects can take over but it is often a temporary event related to the proximity of forest fires. Other pollutants are almost never the main concern as moderate AQI values can occasionally be reached during the burning season while PM2.5 and PM10 are in the unhealthy to hazardous range resulting in a final AQI defined by particulate matter. Ozone often provided constantly moderate air quality during the burning season prior to 2017 but hasn't been a significant issue since then. Sulfur dioxide has, very rarely, been the source of moderate air pollution for 1 or 2 days outside the haze season but represents an accidental release rather than a seasonal trend.

The Thai AQI scale is an index that is possibly used by the government to estimate the health risk of air pollution. Since to our knowledge, no official paper makes reference to the type of index used by environmental and public health authorities and that the Thai scale is not the subject of any publication describing the data supporting the scale, it remains unclear what is the purpose and field of application of that scale. It differs from the USAQI or AQICN by having significantly higher tolerance for low and medium level of pollution, while providing higher AQI number for unhealthy and hazardous levels of pollution (Fig. 3.12). One possible political reason is that having a higher threshold embedded into moderate levels of pollution supposedly gives a scientific basis to delay action and public announcement regarding air quality (*).

In recent years, Thailand has lowered its warning level from 50 to 37.5 µg/m^3 under the pressure of activist groups. The World Health Organization (WHO) had guidelines for yearly average pollution lower than 25 µg/m^3 but following an update in 2021, guidelines are now 15 µg/m^3 for PM10 and 5 µg/m^3 for PM2.5, which are unrealistic goals to be reach in South-East Asia due to the natural background of aerosols in the atmosphere (*).

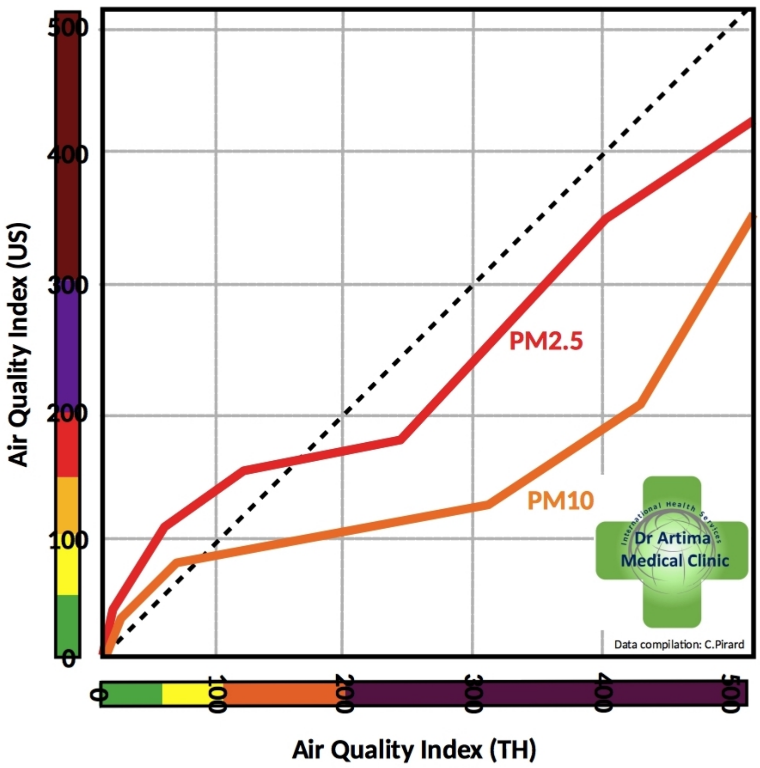

Figure 3.12. Comparison of the commonly used Air Quality Index (US) with the Thai Air Quality Index, showing an underestimation of the health effects of pollution at low concentration (AQI<200) and an overestimation of harmful effects at high concentrations.

4. Chemical characteristics of air pollution

The two components of air pollution are particulate matter and gaseous aerosols. The latter cover gases such as CO_2, CO, NO_2, NOx, SO_2, O_3 and Volatile Organic Compounds (VOC) which can be easily adsorbed on solid particles. Particulate matter is mostly carbonaceous, a term that covers a large amount of molecules, but also contains significant quantities of sulfates, nitrates and ammonium compounds and minor concentrations of metal cations.

4.1. Carbon & Organic compounds

4.1.1. Main classification

Carbon is the major component of particulate matter. It forms 50-60 wt.% (Pani et al., 2019; Kawichai et al., 2022; Suriyawong et al., 2023). It is divided into two fractions called elemental carbon and organic carbon based on their composition and various analytical properties.

Elemental carbon (EC) is a form of carbon identified by optical thermal properties. It is almost identical to black carbon (BC) which is identified by a direct optical determination (Tao et al., 2020). Its composition can be graphitic-like with a very high carbon content but it can also include some aromatic compounds. Depending on the process of formation of EC, it can be labelled as char-EC when it is a residual product of combustion or soot-EC when it forms by the precipitation of high-temperature aerosols formed during combustion. The distinction is important for optical characterization of haze as char-EC tends to absorb ultraviolet wavelengths while soot-EC absorbs large portion of the IR spectrum (Chen et al., 2017).

Organic carbon (OC) is a large group of molecules that typically scatter sunlight, in which a significant subgroup is defined by high UV absorption and called Brown Carbon (BrC) (Tao et al., 2020). Organic carbon includes most of the more complex carbonaceous compounds and its composition is often variable through time, due to exposure to the atmosphere, other pollutants and sunlight. This form of carbon is combined with other elements in order to form complex organic molecules. These elements are mostly nitrogen (5-10 wt.%) (Kawichai et al., 2022), oxygen and hydrogen.

On average, around 40-52% of particulate matter is made of organic carbon while 3-10% is made of elemental carbon (Pani et al., 2019, 2023; Suriyawong et al., 2023). Absolute concentration values in the atmosphere vary widely during the haze season in direct relationship with PM concentration but only minor relative changes in total carbon (TC) and OC/EC ratios are observed.

The ratio between OC, EC and TC is an important variable as it is a major component variable indicating if the source is biomass burning (EC/TC = 0.1-0.2), wood burning (EC/TC = 0.18-0.33) or fossil fuels (EC/TC = 0.5) (Sudheer & Sarin, 2008; Jia et al., 2016; Viana et al., 2007; Kraistinitkul et al., 2022). In Chiang Mai, the OC/EC ratio between 3.5 and 8.3 is indicative that the source is mostly biomass burning (Cao et al., 2005; Pio et al., 2008; Srinivas & Sarin, 2014; Thepnuan et al., 2019; Choochuay et al., 2020; Phairuang et al., 2022a; Pani et al., 2023). Smaller fluctuations in OC/EC ratio are mostly controlled by source material (fuel type, maturation of smoke (secondary organic aerosol), removal rate through wet deposition) (Phairuang et al., 2019; Pani et al., 2019, 2023; Song et al., 2022a) and correlations can be made between OC/EC and the number of fires from satellite data (º, Sresawasd et al., 2021) but also the severity of haze level and changes in wind patterns (Tao et al., 2020).

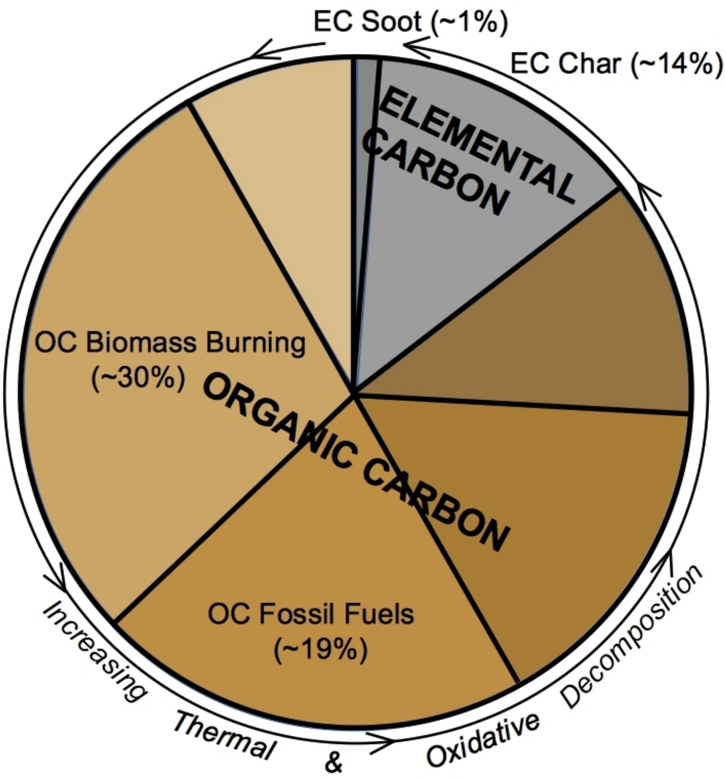

Figure 4.1. Relative proportions of carbonaceous matter in particulate matter of Chiang Mai province. The different subgroups are based on the analytical process to identify organic and elemental carbon. Preliminary interpretation identifies some categories as sourced from biomass burning or fossil fuel burning (modified and recalculated from Pani et al., 2019)

Independently from their respective composition, EC and OC concentrations are important, along with size distribution, mixing state and particulate morphology, due to their absorption and adsorption potential of other molecular compounds. EC more efficiently absorbs compounds but since OC has several times higher concentration, OC is the controlling adsorbing surface in particulate matter (Tao et al., 2020).

Ultrafine particulate matter (PM0.1) is often studied separately for analytical reasons but also because its behaviour is slightly different to coarser fractions. In PM0.1, OC is the dominant fraction (>50%) over EC (3-12%) and is interpreted as the result of lignin pyrolysis (Samae et al., 2022). The variation between haze episode (OC = 57.1±14.2 %; EC = 11.7±3.3%) and non-haze (OC = 40.7±24.4; EC= 11.0±6.3%) indicates that the increase in PM0.1 is associated with biomass burning. OC/EC ratio is high during haze and linked to biomass burning but non-haze is 1.8±0.3 which remain higher than a diesel exhaust source (0.1-0.97) (Sresawasd et al., 2021).

Carbonaceous compounds are also classified into primary and secondary organic carbon (POC & SOC). Carbonaceous precursors released in the atmosphere are modified through maturation of smoke or the effect of solar radiation and produced secondary aerosols with specific chemical characteristics (Pani et al., 2019).

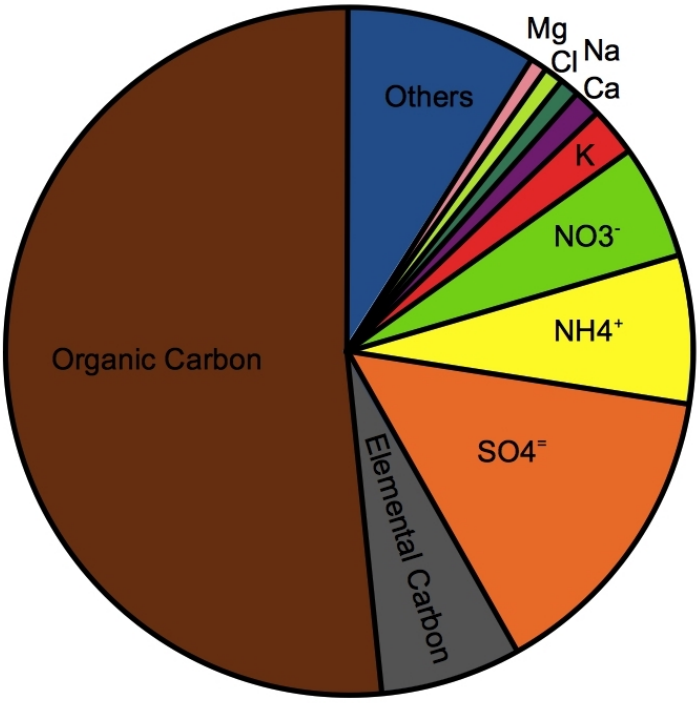

Figure 4.2. Relative proportions of all main chemical groups in particulate matter of Northern Thailand

4.1.2. Polycyclic Aromatic Hydrocarbons

Polycyclic aromatic hydrocarbons (PAH) are a group of molecules with 2 to 8 benzene cycles attached to each other and a variety of termination radicals. There are the product of incomplete burning and are of particular concern due to their carcinogenic properties. Their concentration and composition depends on the type of fuel, the combustion process, the blending ratio of oxidizer and excess air, moisture, etc. (Hata et al., 2014). PAH are particularly present in the ultrafine fraction (430-650 nm) of particulate matter and is a significant component for PM2.5 compared to PM10 (Hata et al., 2014; Insian et al., 2022).

PAH concentration in Chiang Mai varies from 0.05 to 26 ng/m^3 with an average value of 10.2±3 ng/m^3 (º, Pengchai et al., 2009; Chantara et al., 2009; Thepnuan & Chantara, 2020; Kawichai et al., 2020a; Insian et al., 2022). Variations follow haze episodes and PM concentrations and diluted mass is 10 to 20x lower during the rainy season. The highest aggregated PAH level in Chiang Mai is 25.87±10 ng/m^3 in 2010, which remains considerably lower than annual variations in Beijing (30.3-278.6 ng/m^3) (Thepnuan & Chantara, 2020).

PAH are grouped according to their mass (and structurally, according to their number of aromatic rings). Low mass PAH (2-3 rings) are in a concentration range of 50 to 150 pg/m^3 while high mass PAH (4-5-6 rings) are more abundant from 2 to 7 ng/m^3 (Chantara et al., 2009; Insian et al., 2022). Although low mass PAH are relatively equally distributed between PM fraction size (Insian et al., 2022), it has been shown that for high mass PAH, 97 wt.% is present in the fraction below 2 µm (Pongpiachan et al,, 2013; Insian et al., 2022). Light PAH have a tendency to stick to coarser particulates due to their volatility, hydrophobic behaviour, Kelvin effect, etc. (Insian et al., 2022) (Fig. 4.3.).

Detailed studies on the composition of PAH provides more information on the carcinogenic potential, pollution sources and particulate matter maturation. 2 rings PAH form 2-7% during haze episode but are mostly absent the rest of the year. 3-rings PAH form a minor fraction in fine particulate (4-8%) but can be dominant in coarse particulate matter (15-38%). 4-rings PAH are by far the dominant group with 32 to 50%. However, as single species, benzo[b]fluoranthene (BbF), a 5 ring molecule, is known to dominate with ¼ of PAH during the haze season. This fraction is reduced to 13% outside haze episode (Insian et al., 2022).

Fluoranthene and pyrene are PAH associated with diesel emission while benzo[b]-fluoranthene and benzo[a]pyrene are linked with gasoline. Fluorene, benz[a]anthracene, chrysene and benzo[g,h,i]perylene are various products of fossil fuel combustion typically associated with traffic. On the other hand, napthalene, penanthrene & anthracene are linked with wood combustion. Using emission characteristics of various sources, PAH species can be used as proxies for source identification and smoke plume behaviour. The variation in concentration of indeno[1,2,3-cd]pyrene and benzo[g,h,i]perylene as well as fluroanthene/pyrene indicate that biomass rather than fossil fuel combustion are the main sources (Wiriya et al., 2013). However, finer analysis tends to show insignificant ratio values (*, Insian et al., 2022) but the very high concentration in benzo[b]fluoranthene is said by some authors to be strongly associated with biomass burning (º, Wiriya et al., 2015). Another ratio, benzo(a)anthracene/chrysene, provides interesting differential photochemical stability. A high ratio would indicate a considerable atmospheric residence time, indicative of long-distance transport (º, Wiriya et al., 2013). Eventually, in tropical conditions, most PAH get degraded through atmospheric chemical reactions with gaseous pollutants (Pongpiachan et al., 2017).

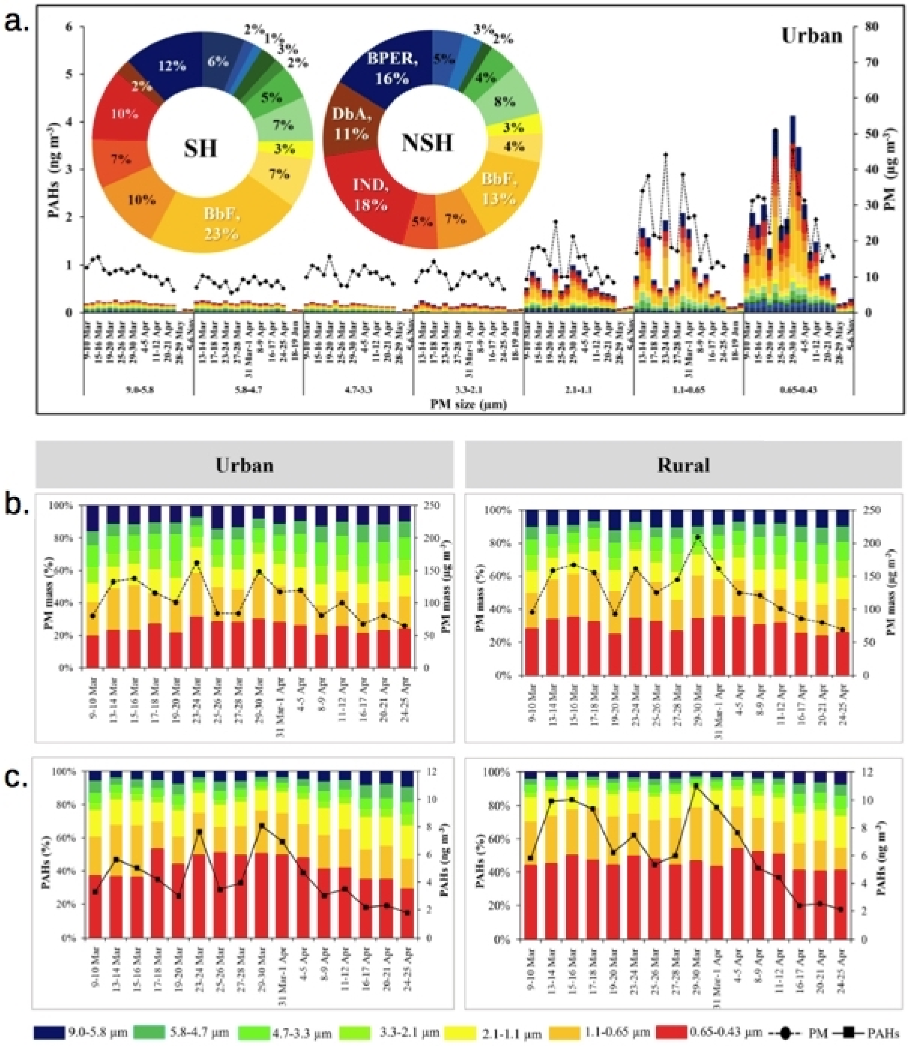

Figure 4.3. a. Distribution of PAH as a function of particulate size in an urban environement during a haze event. b. Time series of particulate size distribution in urban and rural environments. c. Time series of PAH concentration as a function of particulate size in urban and rural environments (modified from Insian et al., 2022)

On a yearly average, ~55% of PAH are produced by traffic exhaust and fossil fuel combustion with a variance of 13.1%. However, during the haze episode, the contribution from agriculture (15%) and forest (30%) burning is very significant while traffic only represents 20-25% (Pengchai et al., 2009; Pongpiachan et al., 2017; Moran et al., 2019; Insian et al., 2022).

PAH emission from biomass sources are twice higher in wood combustion than rice residues (Hata et al., 2014) and despite fossil fuel combustion being a potential important source, PAH levels of haze in rural areas is twice higher than urban pollution (Insian et al., 2022). Outside the haze season, high traffic (urban) areas have concentrations of 7.6-16.6 ng/m^3 while rural areas are 2.7-9.1 ng/m^3 when biomass contribution is minimal (Chantara & Sangchan, 2009).

Chiang Mai is the largest urban center affected by the continental South East Asia haze, along with Vientiane, Lao P.D.R.. It provides values of PAH concentration with considerable urban contamination with an average value of 10±3 ng/m^3 (Pengchai et al., 2009; Chantara et al., 2009; Thepnuan & Chantara, 2020; Kawichai et al., 2020a) similar to many European and Japanese cities (Pongpiachan & Ijima, 2016; Pengchai et al., 2009) although Choochuay et al. (2020) reports a value of 2.361±2.154 µg/m^3 in Chiang Mai which is 100x higher and in disagreement with all literature available (º). Bangkok on the other hand has average values of (45±10 ng/m^3) (Thongsanit, 2002). The carcinogenic : non-carcinogenic PAH ratio in Chiang Mai is slightly higher (3:1 to 4:1) than Bangkok but with higher overall PAH concentration in the capital, carcinogenic PAH are in similar absolute concentration. This minor difference has been associated with market cooking, specific factories and open burning (Chantara & Sangchan, 2009; Chantara, 2012).

Another group of PAH are nitrated PAH (NPAH) formed directly from combustion or by atmospheric reaction of PAHs with hydroxyls and nitrate radicals. NPAH are around one order of magnitude less abundant than PAH with peak concentration during the haze episode at 2.6-4.2 ng/m^3 but down to 200-500 pg/m^3 during the rainy season. The dominant species are equally abundant 0-nitroanthracene and 1-nitropyrene used as tracers of biomass burning with specific relative concentration changes between wet and dry season (Chuesaard et al., 2014).

4.1.3. Anhydrosugars

An interesting dominant group of organic molecules, while not being a health concern, are anhydrosugars. These chemicals are formed by the partial pyrolysis of carbohydrates such as cellulose, starch and many other saccharides (*, Chansuebsri et al., 2021). The most common anhydrosugars are levoglucosan, mannosan and galactosan and form 0.7-0.8% of PM10 (Tsai et al., 2013). Levoglucosan (1,6-anhydro-beta-D-glucospyranose) is dominant (~85-95%) among saccharides and present at 1.22±0.75 µg/m^3 (Thepnuan et al., 2019) while mannosan is around 50-100 ng/m^3 (7-9)% (Tsai et al., 2013).

Since these molecules are formed by the partial pyrolysis of polysaccharides found in vegetation, their absolute variations are indicative of fluctuating contribution from emission of biomass burning while relative variations inform us of various biomass sources and maturation in aged smoke plumes. Levoglucosan is strongly correlated to the level of particulate matter and organic carbon concentration and increase by 2 to 4x during haze episodes, clearly identifying biomass burning as the main source of pollution in the dry season (Tsai et al., 2013, Kawichai et al., 2020b; Tao et al., 2020). The presence and high level of levoglucosan in smoke also implies combustion temperature of 150 to 350ºC, characteristic of low intensity fires and exclude high intensity wild fires, wood stoves and many wood fueled heating devices as well as some agro-industrial burning that would consume anhydrosugars (*, Harrison et al., 2013).

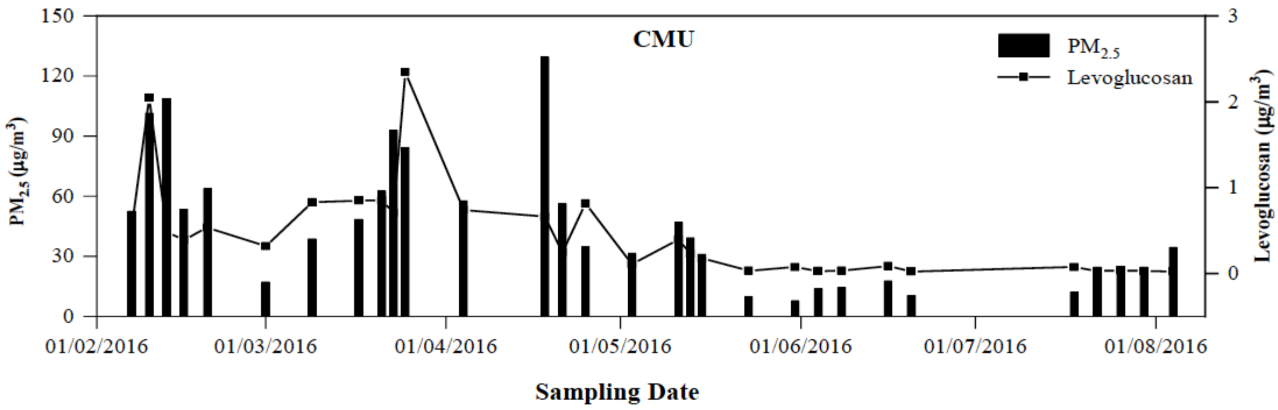

Figure 4.4. Variation of levoglucosan concentration and particulate matter levels between February and August 2016 at Chiang Mai University (Kawichai et al., 2020b).

As levoglucosan is not stable in a daytime humid atmosphere and mostly revert to fully hydrated saccharides within a few days, long distance transport can also have an effect on its concentration levels (*, Hoffmann et al., 2010).

Levoglucosan/K^+ ratio is commonly used to provide an estimation of forest vs. agricultural waste as a source of haze. Anhydrosugars are formed from unspecified biomass burning but potassium is particularly abundant in crops, due to the introduction of significant amount of potassic fertilizers into the system (Thepnuan et al., 2019). Levoglucosan/K^+ in the haze is 0.3 to 1.5, which is considerably lower than hardwood (3 to 5). Softwood emissions (0.5 to 1.3) are more appropriate but the lack of extensive burning of such sources would indicate that crops and herbaceous plants have a considerable contribution. On this basis, the contribution of hard wood to OC and EC is estimated to be 36±15% and 47±19%, the remainder seen as contributions are grassland and crops (Tao et al., 2020).

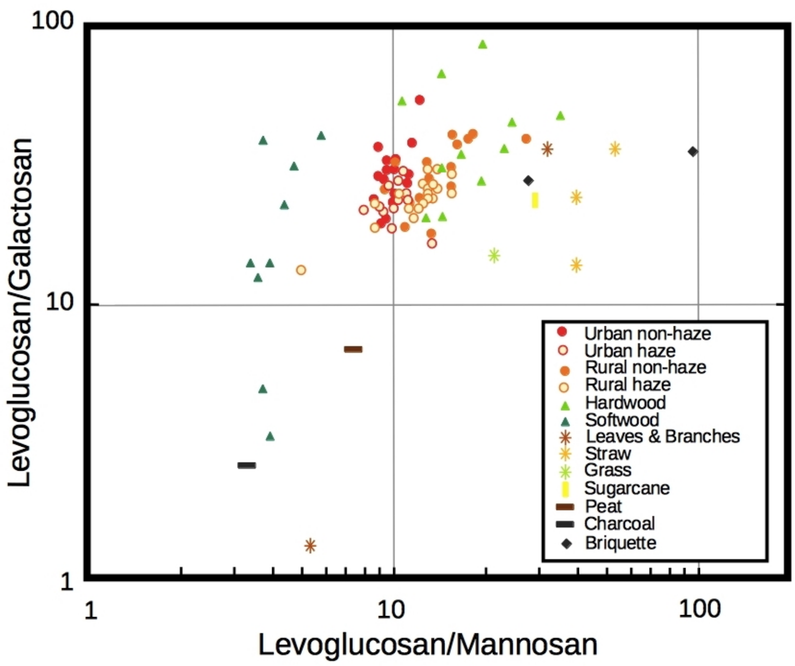

Figure 4.5. Anhydrosugars levoglucosan, mannosan and galactosan ratio in haze & non-haze air pollution compared to the combustion of various sources. Hardwood sources are the closest matching air pollution in northern Thailand (modified from Song et al., 2022).

Relative concentrations between different anhydrosugars (levoglucosan, mannosan, galactosan) as well as organic carbon indicates that hardwood is the dominant biomass type producing particulate matter. Levoglucosan/Mannosan ranges from ~6 to ~15 between non-haze and haze season, while hardwood has a ratio of 12 to 32 and softwood is 2.5 to 6 (Fig. 4.5).

4.1.4. Others

A large number of other organic chemicals are produced during biomass burning.

Carboxylic acids are important aerosol components, produced by traffic as a primary source for acetic acid while formic and pyruvic acids are photochemical secondary products (Tsai et al., 2013). Oxalic acid is the most abundant dicarboxylic acid and succinic, malonic and maleic acids are present in slightly lower concentrations (Tsai et al., 2013). The later is mostly produced by coal and wood burning (Tsai et al., 2013).

Carboxylates are very common and reach concentrations of 2-3 μg/m^3 in particulate matter (Thepnuan et al., 2019; Tsai et al., 2013). Acetates and oxalates are the most common species reaching 1 μg/m^3 each in peak haze (Fig. 4.6.). Other common carboxylic salts are formates, succinates, malates, malonate, maleates around 100 ng/m^3 and glutarates, tartarates, fumarates, phthalates and citrates at 10-50 ng/m^3 (Fig. 4.6.).

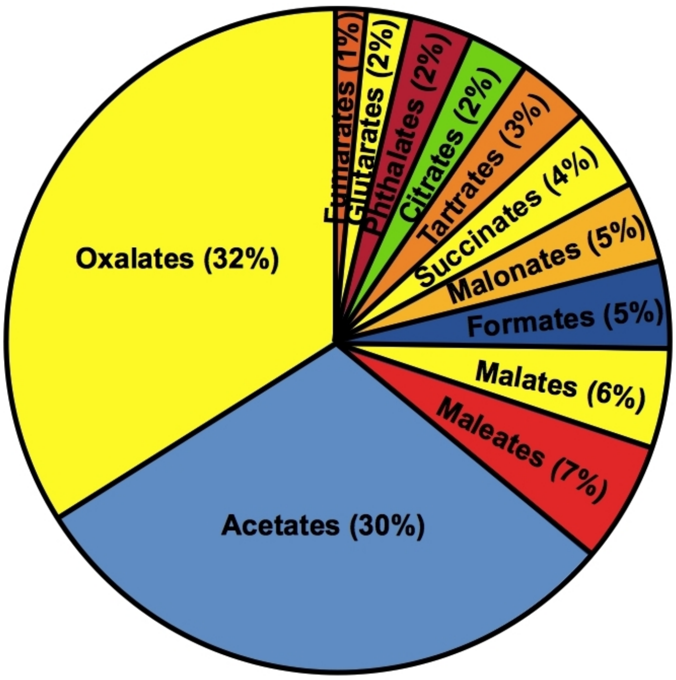

Figure 4.6. Carboxylic acids proportions in particulate matter. Oxalates & acetates represent two thirds of these chemicals. Monocarboxyl acids are in blue, dicarboxylates are yellow to red and tricarboxylates in green, (modified from Tsai et al., 2013).

Changes in respective proportion between different carboxylates occur between haze and non-haze season and provide some information on sources (Tsai et al., 2013). While acetates can be produced by biomass burning, it is also a biological and pedological product but fumarates are identified as mostly emitted by biomass burning. Oxalates have various sources, notably the photochemical dissociation of other dicarboxylic acids. Maleates and malates are common products of wood burning and the mildly low malonate/succinate ratio in particulate matter is indicative of traffic sources (low) rather than secondary photochemical production (high). Acetate/formate also indicates a primary source (>1) rather than secondary sources (<1) since particulate matter acetate/formate ratios are constantly between 3 and 9.

Saccharide polyols such as arabitol, glycerol, erythriol, mannitol and xylitol are also associated with biomass burning (Tsai et al., 2013). Sugar alcohols form up to 1 $\mu g/m^3$ in particulate matter where arabitol counts for 50-60% of it. While arabitol production is associated with bark and tree leaves, glycerol & erythriol are also linked with the soil biota combustion (Tsai et al., 2013).

Other volatile organics compounds are known to have extensive short- and long-term adverse health effects through toxicity and mutagenicity. These include benzene, toluene, acetaldehyde, xylenes, acrylonitrile. However, there is no evidence that these compounds are present in significant amount in Northern Thailand air pollution (°, Sirithian et al., 2018).

Polychlorinated dibenzo-p-dioxins & dibenzofurans (PCDD/Fs), commonly known as dioxins, are present in the air pollution of Chiang Mai but their concentrations are relatively low since significant sources are normally linked to industrial chlorinated combustion processes absent in Chiang Mai (Chi et al., 2022).

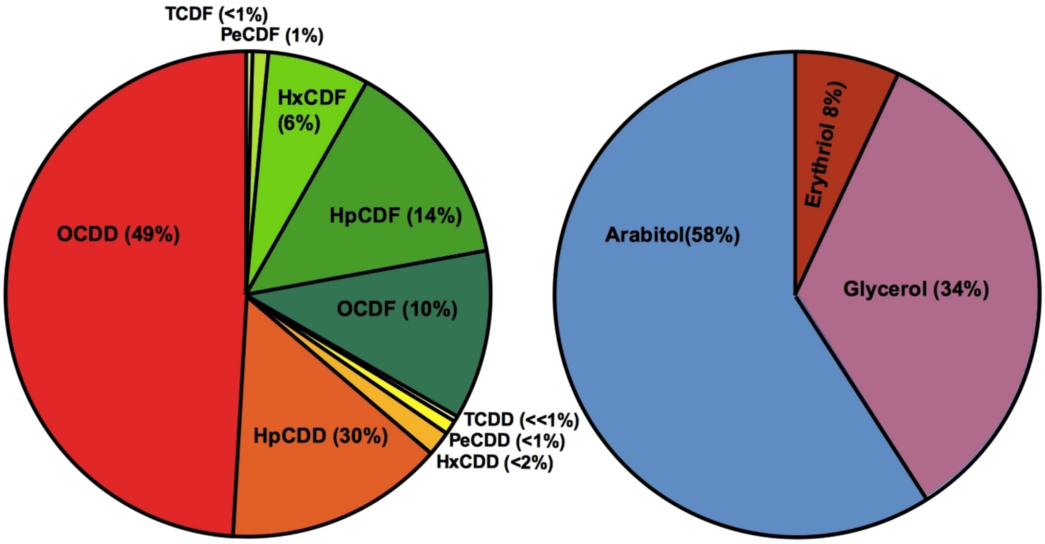

Figure 4.7. Right: Sugar alcohol composition of particulate matter in Chiang Mai (modified from Tsai et al., 2013). Left: Dioxin congeners composition of particulate matter in Chiang Mai (modified from Hsien Chi et al, 2022) . PCDDs are red to yellow colours, PCDFs are green colours.

4.1.5. Isotopic studies

Within carbonaceous compounds, a further independent characterisation can be made using isotopic fractionation of carbon, nitrogen, hydrogen and oxygen between sources.

The simplest isotopic system is the carbon-14 content of particulate matter. Carbon-14 is exclusively produced by biomass burning and any divergence from the natural abundance can be associated with fossil fuels and by-products that contain no carbon-14. Biofuel and semi-fossil organic matter are not taken into consideration and would currently represent only a minor contribution to the carbon balance. However, the increasing use of ethanol produced from sugarcane and cassava in gasoline representing 10 to 85% of the gasohol fuel would have a significant impact in traffic sources in the future (*).

Based on carbon-14 abundances in particulate matter, 3 to 8% of total carbon is produced from fossil fuels in urban areas and down to 0.1% in rural areas. Since non-fossil carbon increases by 4 to 5x during the haze episode, it is, alongside levoglucosan, the clearest chemical indicator of biomass burning as the main cause of the increase in particulate matter during the haze season (Song et al., 2022a).

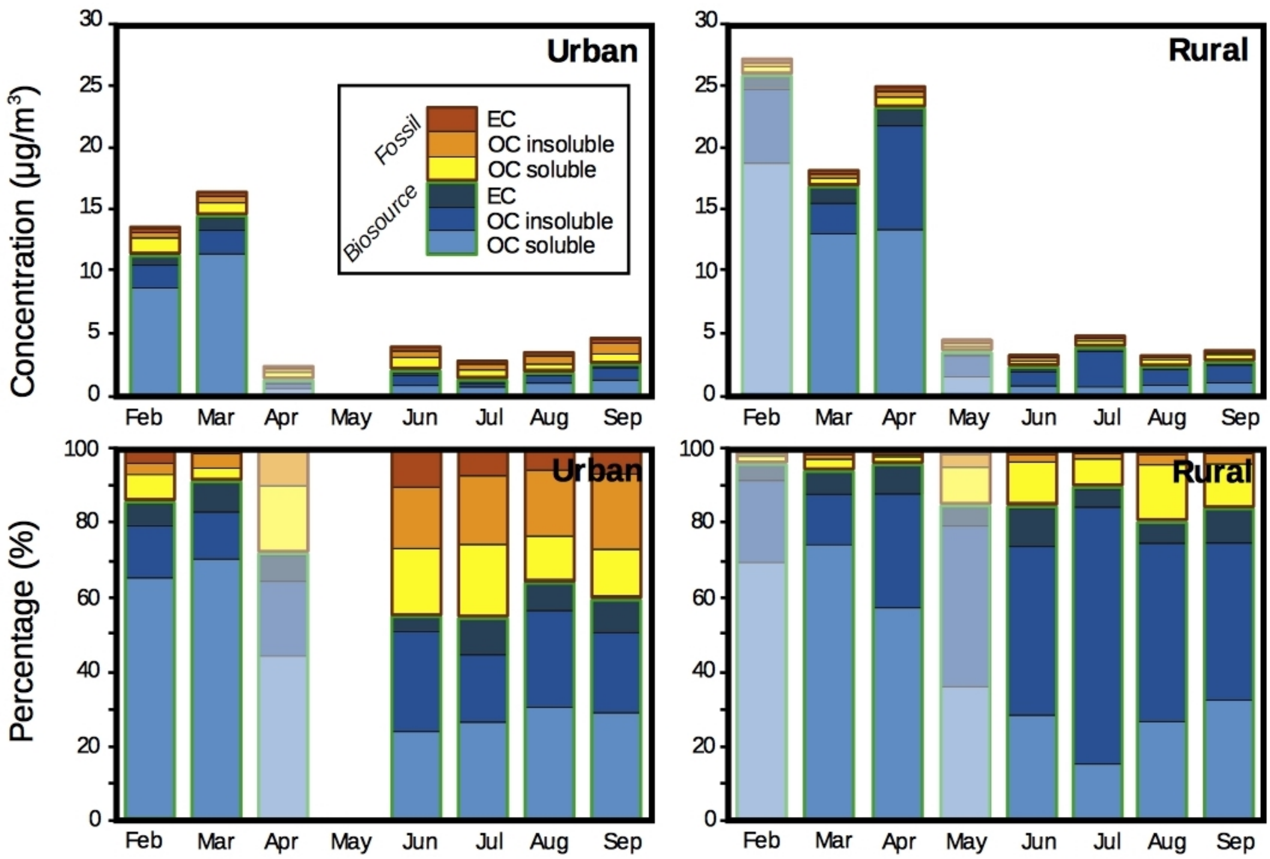

Figure 4.8. Contribution of fossil and non-fossil (biosource) carbon based on ^{14}C concentration in different elemental and organic carbon of particulate matter in urban (Chiang Mai) and rural areas. Light columns are extrapolated or interpolated data (modified from Song et al., 2022)

The two stable isotopes of carbon are also of some use to make a distinction among biosources of different plant origin. C3 carbon fixation is a metabolic process found in plants where photosynthesis will absorb carbon using specific molecules. Most plants are using C3 photosynthesis and include rice, most trees, most grasses. C4 carbon fixation is a rarer additional metabolic process to C3 which function slightly differently and is seen in important plants such as wheat, corn, Rhodes & Napier grasses, sugarcane. Since C3- and C4- metabolic processes uses different pathways to absorb carbon from CO_2, they also absorb preferentially lighter (C3) or heavier (C4) carbon isotopes. This creates different $^{12}C/^{13}C$ ratio between these different plant groups that can be transferred to particulate matter during combustion as burning is not mass dependent.

Particulate matter shows $\delta^{13}C$ between -25.3±0.46 and -27.9±0.67 ‰ slowly increasing through the haze season (Kawichai et al., 2020b, 2022) which is considerably different from C4 plants (-16 to -11 ‰) including corn (-11.6 to -16.1 ‰) and sugarcane (-12.1 to -12.9 ‰). C3 plants range from -37 to -20 ‰ and mixed deciduous forest in northern Thailand have values between -27.9±0.7 and -29.6±0.6 ‰., covering the range of values found in particulate matter (Fig 4.9).

Nitrogen isotopes have also been considered to help further source distinction and show a slow increase of $\delta^{15}N$ from 7.76±1.32 to 12.7±1.61 ‰ during the burning season (Kawichai et al., 2022). $^{15}N/^{14}N$ values are coherent with ^{14}C data and exclude a large fossil fuel component in particulate matter.

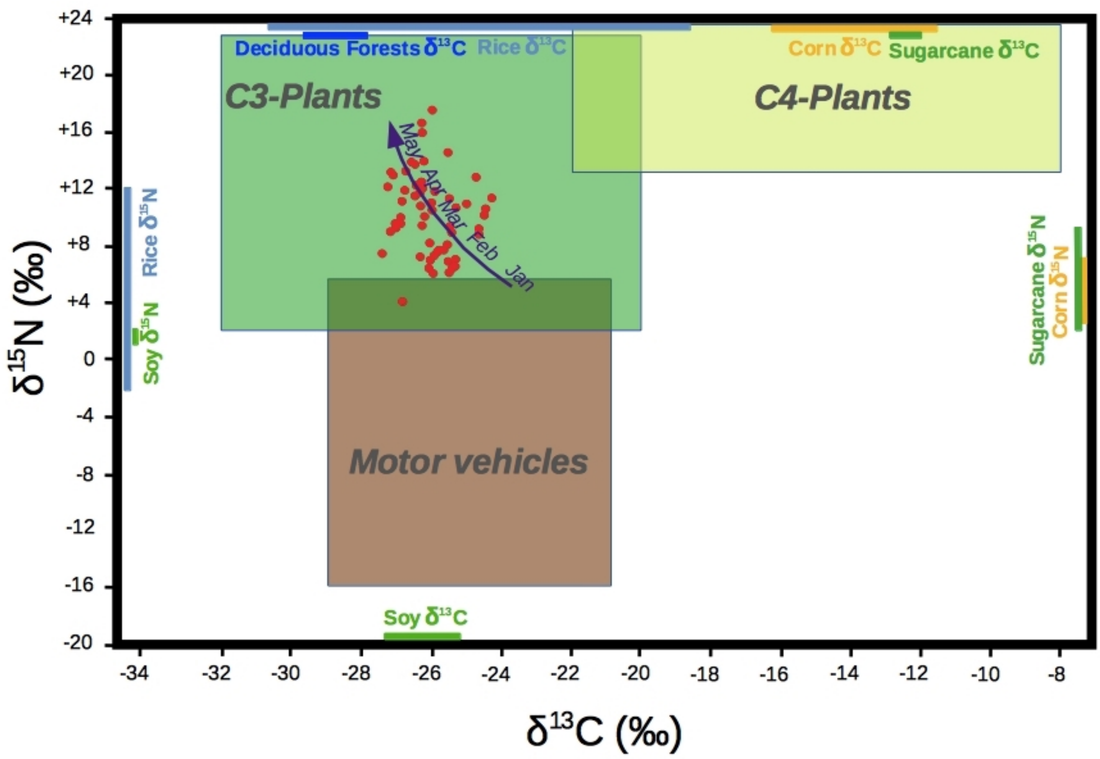

Figure 4.9. Discriminative plot of the haze carbon and nitrogen isotopic signature (red dots) and trend through time (purple arrow) compared to unspecific sources (motor vehicles, C3- & C4-plants) and potential specific sources (local deciduous forests, corn, soy, rice, sugarcane) (modified from Kawichai et al., 2020b, 2022 with additional data from Spain & Le Feuvre, 1996; Turekian et al., 1998; Yoneyama et al., 2001; Marinaeli et al., 2002; Krull et al., 2003; Kell et al., 2005; Widory, 2007; Jahren & Kraft, 2008; Das et al., 2010; Pavuluri et al., 2010; Kaushal & Ghosh, 2018; Ma et al., 2021; Kato et al., 2023.

4.2. Anionic compounds

This section covers all non-carbonaceous compounds present as anions combined with various cations. These are mostly sulfates, nitrates, chlorides and ammonium (Fig. 4.11.).

Sulfates form around 13-15 wt.% of particulate matter (Chantara et al., 2009; Thepnuan et al., 2019; Saejiw et al., 2020). Its source is diverse and is found associated with aged and urban aerosols as oxidised sulfur that can precipitate from gaseous precursors found in fossil fuel combustion (particularly diesel burning (Chantara et al., 2012)). Photochemical reactions between sulfate and ammonium produce $(NH_4)_2SO_4$ (Saejiw et al., 2020). A strong hourly correlation of ozone and sulfate concentration with peak level reached during sunny daytime indicates such atmospheric process (Tsai et al., 2013).

Sulfate anthropogenic source component makes it less variable than other components and is preponderant outside the haze episode (Sopajaree et al., 2011; Tsai et al., 2013; Khamkaew et al., 2017; Janta et al., 2020; Chansuesubsri et al., 2021a,). However, sulfate production is also found in biomass burning (Sillapapiromsuk et al., 2013) but the negative correlation with increasing particulate matter concentration indicates that biomass is possibly not the dominant source (Chansuebsri et al., 2022).

The presence of ammonium sulfate buffers the concentration of sulfuric acid, keeping the acidity of water in equilibrium with haze at a pH between 4 and 7, with most values broadly around 5 (Chantara et al., 2009). As a result, ammonium and sulfate are strongly correlated (r^2=0.79-0.88) (Tsai et al., 2013; Pani et al., 2023) (Fig. 4.10).

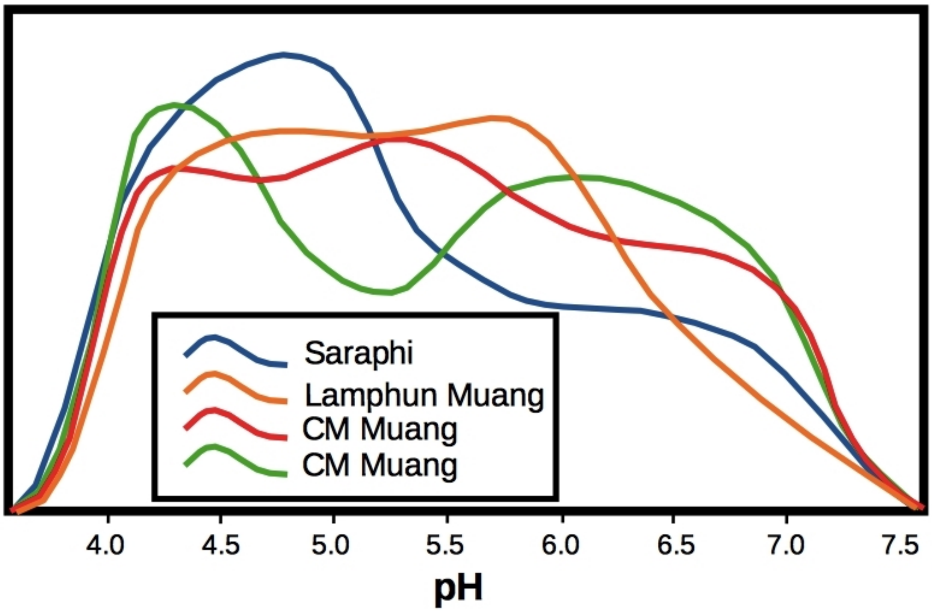

Figure 4.10. Interpolated distribution of pH of water in equilibrium with PM10 in the Chiang Mai-Lamphun basin (modified from Chantara et al., 2009; Chantara, 2012)

Ammonium forms around 4-5 wt.% (Chantara et al., 2009; Thepnuan et al., 2019; Saejiw et al., 2020; Pani et al., 2023). Its source is equally urban and associated with biomass burning as it can be emitted from the decomposition of NH_4Cl fertilisers (Khamkaew et al., 2016) or by the precipitation of ammonia precursor in urban environments (Chansuebsri et al., 2021) or livestock waste (Chantara et al., 2012).

Nitrates form around 4 wt.% (Chantara et al., 2009; Thepnuan et al., 2019; Saejiw et al., 2020; Pani et al., 2023). It is present in aged aerosols originating from biomass burning and traffic (Chansuebsri et al., 2022). The correlation between nitrate and potassium in particular, is associated with biomass burning (Saejiw et al., 2020) and is increasing when particulate matter concentration increases (Chansuebsri et al., 2022). However, its dominance during non-haze periods also suggest that traffic is a considerable source (Tsai et al., 2013).

Chlorides are generally below 1% (Chantara et al., 2009). It is mostly associated with sodium, potassium and ammonium. NaCl sources are often interpreted as long distance transport of maritime sources (º, Wiriya & Chantara, 2008; Chansuebsri et al., 2021, 2022). However, the lack of visible stoechiometric behaviour in variations cast some doubt on this potential dominant origin (*) and other origin have been suggested such as solid waste burning (Pengchai et al., 2009; Pongpiachan et al., 2022). KCl and NH_4Cl are common fertilisers and herbicides (Sillapapiromsuk et al., 2013; Khamkaew et al., 2016). However, KCl released as an aerosol makes it unstable and atmospheric aging makes chlorine being substituted by nitrate and sulfate (Freney et al., 2009; Li et al., 2015). Freed chlorine is eventually incorporated into organic molecules and various chemicals. A very small portion of KCl could also be of maritime origin (Chansuebsri et al., 2022).

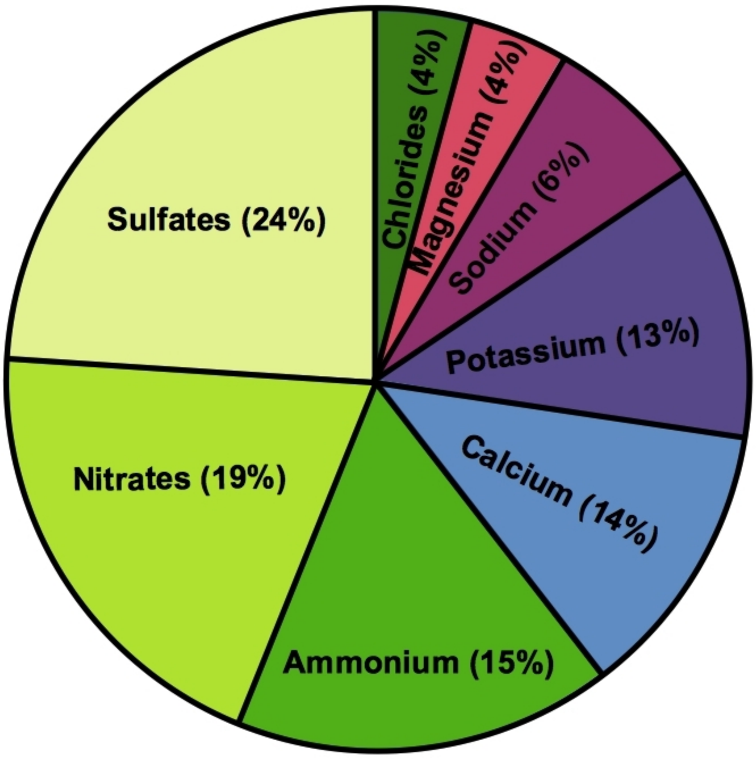

Figure 4.11. Inorganic salts proportions in particulate matter. Anionic groups in yellow-green and cations in blue-red (modified from Tsai et al., 2013).

4.3. Metals

Metals include all cations that are not dust forming (C, H, O, N). The highest concentrations are found for environmentally abundant cations such as alkali and alkali-earth metals as well as aluminium, silicon and some transition metals such as iron and manganese. These metals are typically related to soil and sub-soil chemical composition and released through combustion or wind-blown dust during the dry season. Trace metals often have more specific sources and include heavy metals that have potential health effects.

4.3.1. Major elements

Major elements typically include environmentally abundant metals. Potassium forms around 2 wt. % of particulate matter, calcium is around 1 wt.% and sodium and magnesium are 0.5 wt.% (Chantara et al., 2009; Thepnuan et al., 2019; Saejiw et al., 2020) while other lithophile elements can also be present in significant concentrations (*).

Potassium has a high concentration that correlates well with particulate matter and more particularly with organic matter and levoglucosan (see 4.1.3.) which tend to indicate a biological source. The presence of a strong positive anomaly (x10) when compared to the upper continental crustal average (Rudnick & Gao, 2014) non-biological elements (Si, Al, Ti) indicates a non-pedological source (*). Specific ratio with elemental carbon gives a high K/EC value, similar to what is produced by biomass burning, and excluding fossil fuel combustion, which is potassium-poor and producing fairly low K/EC aerosols (Pani et al., 2019).

Additional correlations with nitrate, ammonium and chlorine provide strong indication of an agricultural burning source (Sillapapiromsuk et al., 2013; Tsai et al., 2013). As many fertilizers contain large amount of potassium present as chloride or nitrate, it enriches the vegetation in these elements. However, the very high level of potassium cannot be explained by fertilizers alone and the mass of forest & grassland burning more adequately explain potassium releases in particulate matter. Although some potassium and chlorine have been identified as a marine source (°, Wiriya & Chantara, 2008), this component is estimated between 2.3 to 2.7% of K as seasalt, while 96% is biomass burning and another couple of percent from soil sources (Pani et al., 2019).

The release of potassium chloride in the atmosphere also provide some spatial source information as it has a limited atmospheric stability. While chlorides are associated with fresh aerosols, the aging of agricultural burning smoke release this potassium to be bound with nitrates (Chansuebsri et al., 2022) and sulfates. Higher levels of KCl in rural area is therefore an indication of more proximal sources (Chansuebsri et al., 2021).

Sodium has been associated with various sources. Its presence as sodium chloride has been interpreted as the result of long range transport of sea salt (Tippayawong et al., 2006; Wiriya & Chantara, 2008). However, additional research indicates that a marine source is likely a minor contributor since discriminative ratio such as Na/Mg (marine = ~8; Kayee et al., 2020) has a value of 2.22±0.98 in Chiang Mai, far below marine ratio and a selective enrichment in magnesium would be required if sodium is essentially marine (*). Other authors have suggested that various elemental correlation could be the result of solid waste incineration (Pengchai et al., 2009; Kayee et al., 2020) but a large amount could also come directly from forest burning since test burning provided very variable values between different forest types and combustible type (Chaiyo et al., 2011).

Calcium is typically seen as a soil tracer (Wiriya & Chantara, 2008; Kraisitnitikul et al., 2022) although it also has been considered in urban atmosphere as sourced from concrete and road dust (Tsai et al., 2013; Chansuebsri et al., 2021).

Silicon, aluminium, iron, manganese and magnesium are equally soil and sub-soil related and best explained by wind-borne dust and some release through soil combustion (Janta & Chantara, 2017; Kraisitinitikul et al., 2022). Some authors have quantified road dust contribution based on Mg and Ca mass balance to 22-29 % (Chansuebsri et al., 2021).

4.3.2. Trace elements

Minor and trace elements are mostly metals present in concentration inferior to 1000 ppm or less than 10 ng/m^3. It includes some environmentally common elements (Sr, Ti, …) but also transition metals (Cr, V, Zn, Cu, Co, Ni,…) and heavy metals (Pb, Cd). Without exception, all trace elements are below WHO limits for aerial toxicity (Chantara et al., 2009; Niampradit et al., 2022). It is also worth noting here that many publications have either very low concentration levels (<10 ppm or pg/m^3) or fall below detection limits for Sr, As, Se, Cr, Ti, V, Ni, Zn, Pb, Cd, Hg.

Various sources for trace contaminants can be found in the literature where reservoirs with particularly high concentrations, high capacity to be pulverized and suspended in the atmosphere are considered. As such, there is an over-tendency in the field to associate each trace element with these particular reservoirs when the reality for a lot of trace pollutants likely requires several mixing components in very different proportions (*).

	(1)	(1)	(1)	(2)	(3)	(3)	(3)	(3)	(4)	(4)	UCC
Si	**0.901**	**1.032**	n.a.	n.a.	**1.47**	**1.26**	**1.45**	**1.44**	n.a.	n.a.	311000
Al	**0.266**	0.313	**3.015**	**0.121**	**0.52**	**0.33**	**0.47**	**0.62**	**0.88**	**0.87**	81500
Mg	**0.112**	**0.14**	**0.826**	**0.044**	**0.19**	*0.14*	**0.19**	**0.18**	**0.19**	**0.13**	14900
Ca	*1.128*	**1.669**	**4.79**	**0.113**	**2.22**	**1.75**	**2.1**	**2.11**	**0.81**	**0.63**	25600
Mn	**0.016**	**0.019**	0.088	**0.007**	**0.03**	0.02	**0.03**	**0.03**	**0.03**	**0.04**	800
Fe	**0.288**	0.373	**2.126**	**0.142**	**0.44**	0.31	*0.46*	**0.59**	**0.72**	**0.39**	39200
K	0.674	0.92	**1.206**	n.a.	**1.7**	**1.39**	**1.95**	**1.66**	**0.99**	**1.81**	23200
Na	n.a.	n.a.	n.a.	0.075	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	24000
Cu	*0.011*	0.024	**0.086**	**0.003**	*0.01*	**0.02**	**0.04**	0.02	n.a.	**0.004**	28
Zn	0.069	0.201	**0.838**	**0.015**	**0.08**	0.1	*0.09*	0.08	**0.03**	**0.05**	67
As	**0.012**	**0.015**	**0.319**	**0.001**	0	0	0	0	n.a.	n.a.	4.8
Ba	0.008	*0.012*	0.001	**0.003**	**0.02**	0.01	**0.02**	0.01	n.a.	n.a.	624
Pb	**0.035**	0.049	**0.218**	**0.006**	0.05	0.04	0.05	**0.04**	**0.02**	0.01	17
V	*0.006*	*0.006*	**1.132**	**0.001**	0	0	0	0	n.a.	n.a.	97
Sr	*0.003*	*0.003*	n.a.	*0.001*	0	0	0	0	n.a.	n.a.	320
Cr	0.014	*0.016*	**0.138**	0.003	0.01	0.01	0.01	0.01	n.a.	n.a.	92
Hg	0.024	*0.027*	n.a.	n.a.	**0**	0	0	0	n.a.	n.a.	0.05
Ni	0.006	0.014	**0.269**	0.001	0	0	0.01	0.01	n.a.	n.a.	47
Ti	*0.007*	*0.007*	n.a.	n.a.	0.01	0.01	0.01	0.01	n.a.	n.a.	3600
Cd	0.001	0.001	0.001	n.a.	**0**	0	0	0	n.a.	n.a.	0.09
P	*0.008*	0.026	n.a.	n.a.	0	0.01	0.03	0.01	n.a.	n.a.	700
Sn	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0	**0.04**	2.1

Table 4.1. Elemental concentrations in particulate matter in µg/m^3. (1) Chantara et al., 2009; (2) Kayee et al., 2020; (3) Pengchai et al., 2009; (4) Kraisitnikul et al. 2022. Upper Continental crust average is in ppm (Rudnick & Gao, 2014). Elements are ordered as a function of their geochemical statistical validity when some errors are considered. Data in bold are significant numbers; Data in italics are numbers likely below the limit of quantification; Data in grey are numbers likely below the limit of detection.

As a whole, metal concentration in particulate matter of northern Thailand is systematically lower than Bangkok. The heavy traffic and intense industrial emissions in the Bangkok metropolitan zone charge the atmosphere with various metals of anthropogenic origin. While some metals have sources in common, concentrations reached in Northern Thailand are within crustal background levels when analytical procedures, propagated errors, limit of quantification and other technical parameters are taken into account. A geochemical normalization on the upper continental crust average (Rudnick & Gao, 2004) when calibrated on crustal non-mobile lithophile elements (Si, Ti, Al) shows a systematic significant enrichment in K and possibly Ca and Mn and no enrichment in Fe, Mg (considered as crustal but geochemically less robust). As, Pb, Cu and Zn have non-systematic enrichment but analytically valid data is rare. No valid geochemical data could be obtained for elements such as Ba, Cd, Cr, Hg, Ni, Sr, V and any discussion on the matter will require a more rigorous analytical approach of trace elements concentrations in haze (*. Tab. 4.1., Fig. 4.12). Correlations with particulate matter are equally poor; the most strongly correlated elements (Al, Ca, K, Mg, Mn) have a correlation coefficient between 0.1 and 0.5 while trace elements have no correlation at all (Kraisitnikul et al., 2022). However, several authors have discussed these pseudo-concentrations and their hypothetical sources with unrealistic mobilisation processes (See section 11.).

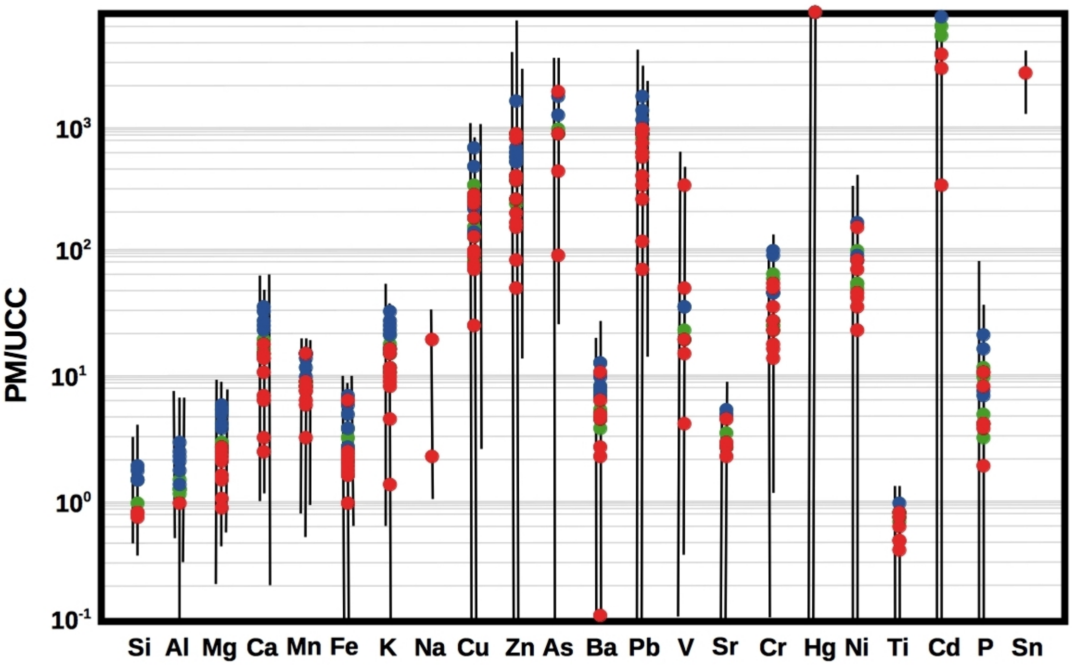

Figure 4.12. Particulate matter element concentrations normalized on Upper Continental Crust average (UCC, Rudnick & Gao, 2004) using Si (green), Ti (blue) and Al (red) as calibration reference to identify non-crustal anomalies. Elements are ordered as a function of data meaningfulness from Chantara et al., 2009; Pengchai et al., 2009, Kayee et al., 2020 & Kraisitnikul et al., 2022). Vertical black lines are associated standard deviations. Error bars reaching the 10^{-1} are potentially meaningless data.

Strontium is typically an element where relative concentration with soil-sourced aerosols gives crustal abundances (Kayee et al., 2020). There has been suggestions to link strontium to traffic such as brake pads and tire wear (°, Pengchai et al., 2009).

Nickel, vanadium and zinc have been associated with traffic emission. Zinc in particular is sourced from automobile exhaust and tyre wear (°, Kayee et al., 2020; Kraisitnitikul et al. 2022). Chromium, as well as iron and magnesium are linked to brake wear and yellow paint for road surface (º, Pengchai et al., 2009) although some articles suggest that bagasse (sugarcane pulp) has high levels and its use as biofuel could have an impact on haze composition (Samae et al., 2022).

Lead levels are higher than the expected background. Based on lead isotopes, mixing ratios gives 5-30% of crustal origin, 35-50% issued from biomass burning, and the remainder is labelled as transboundary since the isotopic signature cannot be associated with known sources in Northern Thailand (Kayee et al., 2020).

Cadmium is supposedly related to diesel burning (Pengchai et al., 2009) although an article suggests that bagasse (sugarcane pulp) has high levels (Samae et al., 2022).

Mercury is produced by hazardous waste incineration (Pengchai et al., 2009) while tin has been associated with a range of sources, but garbage burning is a likely source in Northern Thailand (Christian et al., 2010; Zhang et al., 2021; Kraisitnitikul et al., 2022).

Some burning sources are capable of providing relatively high level of trace metals such as sugarcane residues which are known to have high levels of V, Cr, Co, Ni and Pb (Pongpiachan et al., 2022). However, not all tracers indicate that sugarcane pulp is participating in any significant manner to the pollution in Northern Thailand (*).

4.4. Gaseous components

This section includes all major gaseous components. Although the definition is clear for common compounds such as SO_2, NO_2, NH_3, CO, CO_2 and O_3; for complex molecules, there is a grey zone between the finest particulate matter (<100nm) and the heaviest volatile compounds. It becomes increasingly undefined when PM0.1 can be of secondary origin and precipitates from gaseous precursors (Phairuang et al., 2022b). With the exception of local, short-lived spikes occurring at random times, the concentration of the main gaseous pollutants in Northern Thailand is always very low as they quickly react with particulate matter to form solid compounds.

SO_2 is produced from diesel burning (Chantara et al., 2012) which can contribute up to 59% through traffic and another 39% from various electricity generators & motors (Sopajaree et al., 2011; Khamkaew et al., 2017). Background levels during the rainy season are around 2 ppb and 10-day average rises a little bit during the haze season to 3-4 ppb (º, Chantara et al., 2012). In April 2014, the highest weekly level of SO_2 of the last decade was recorded with 18 ppb (*). Rare short-lived spike at 60 ppb have been observed but are unrelated to the haze season and are of local incidence (*). Due to the accumulation of SO_2 and NOx in the atmosphere during the haze episode, the pH of water in equilibrium with particulate matter is mildly acidic and the first rains in April have a pH around 5.6±1.5 (Wiriya & Chantara, 2008) (Fig. 4.10.).

NH_3 is a gas production from livestock and crop fertilizers (Chantara et al., 2012) but it is also emitted in significant concentration during the smoldering stage of biomass burning (Pani et al., 2019). Peak concentration of ammonia reaches 6 to 13 ppb on a 10-day average while the annual average is 2 to 4 ppb (º, Chantara et al., 2012).

CO is a product of incomplete combustion in oxygen-deprived environments. Around 20% of atmospheric CO is covered by forest fires (Sukitpaneenit & Kim Oanh, 2014) and correlates relatively well with particulate matter variations, reaching 3.4 ppm (Tsai et al., 2013). Carbon monoxide is unstable and go through photochemical reaction producing ozone with a half life of a few months (Sukitpaneenit & Kim Oanh, 2014; Adam et al., 2021). Past published data of CO concentration in Chiang Mai gives 691±434 ppb for February 1998 (Pochanart et al., 2001). Data available between 2014 and 2016 indicates that daily CO concentration can reach 2.1 ppm with a monthly average of 1.3 ppm during the peak of haze season. Occasional random spikes at 3 or 4 ppm occur but are not related to haze (*).

Nitrogen dioxide (NO_2) and monoxide (NO) are gases produced by various industrial and combustion processes. In Northern Thailand, it is estimated that 90% of NO_2 is produced by biomass burning (Khodmanee & Amnuaylojaroen, 2021). Haze-related NOx have decreased over the last decade (Sukkhum et al., 2022) and are generally not an issue. High levels (40 ppb) are reached at random times during the year in Chiang Mai, possibly due to a local pollution event. Without these events, 10-day average concentrations during the haze episode are between 2 and 7 ppb (º, Chantara et al., 2012) with daily concentrations rarely reaching 20 ppb and remain below 5 ppb in the rainy season. Real-time records in burning seasons 2014 to 2016 have monthly average of ~35 ppb (*). The atmospheric chemical lifetime of NO_2 is relatively short from a few hours to a few days (Lalitaporn & Boonmee, 2019) as it is oxidised into nitric acid, forming nitrates in particulate matter. The concentration of NOx is also in equilibrium with ozone levels which are directly affected. High level of NO_2, like other pollutants, is mostly due to stagnant air & radiative inversion (calm winds, clear skies, low mixing height) and subsidence inversion (NE monsoon with cold dry air). OMI detectors on the Aura satellite show that NO_2 plumes tend to appear in the afternoon and are likely associated with combustion of fertilizer in crops rather than transportation (Lalitaporn & Boonmee, 2019).

Volatile Organic Carbon can be produced along with CO during incomplete combustion (Sukitpaneenit & Kim Oanh, 2014) but these VOC compounds can be photochemically sensitive and the aging of biomass burning plumes modify their abundance and composition (Fujiwara et al., 1999; Real et al., 2007).

HCl is a minor gaseous component with a yearly average between 340 ppt and 1090 ppt. 10-day average concentration increases to 1.47 - 5.02 ppb during haze episodes (Chantara et al., 2012).

Ozone in the boundary layer varies between 9 and 65 ppb for a yearly average of 27 ppb with peak concentrations in March-April (Pochanart et al., 2001). 8-h average ozone concentration used for air quality monitoring provides similar values, where 2016 (and 2014) burning seasons had abnormally high levels of ozone (up to 67 ppb) and a monthly average for April at 60 ppb (*). As it is the case for NOx, these years were exceptions and since 2017, ozone minima and maxima are 6 to 46 ppb with the highest monthly average below 30 ppb, indicating that ozone pollution has considerably improved in the past 6-7 years and is directly linked to lower atmospheric content in NO_2 (*) since ozone is directly buffered by NO_2 availability (Khodmanee & Amnuaylojaroen, 2021)

Seasonal variation of ozone are marked as it is mostly a secondary product of biomass burning. Atmospheric levels are 4-5x higher in the haze episode than the middle of the rainy season. During the haze season, around 13 ppb are suspected to be transboundary with a marine contribution (Pochanart et al., 2001).

Daily diurnal variation are very significant for ozone due to dynamic and photochemical effects. After sunrise, ozone increases and doubles its concentration as the stable nocturnal layer is disturbed and some vertical mixing occur. Concentrations steadily increase until mid-afternoon as photochemical processes transform other gaseous component such as NO_2, CO and VOC into ozone (Fujiwara et al., 1998; Pochanart et al., 2001; Real et al., 2007; Khodmanee & Amnuaylojaroen, 2021, Sukkhum et al., 2022)). At night, ozone in the surface atmospheric layer is decomposed through dry deposition and surface chemical reactions (Pochanart et al., 2001) (Fig, 4.13.).

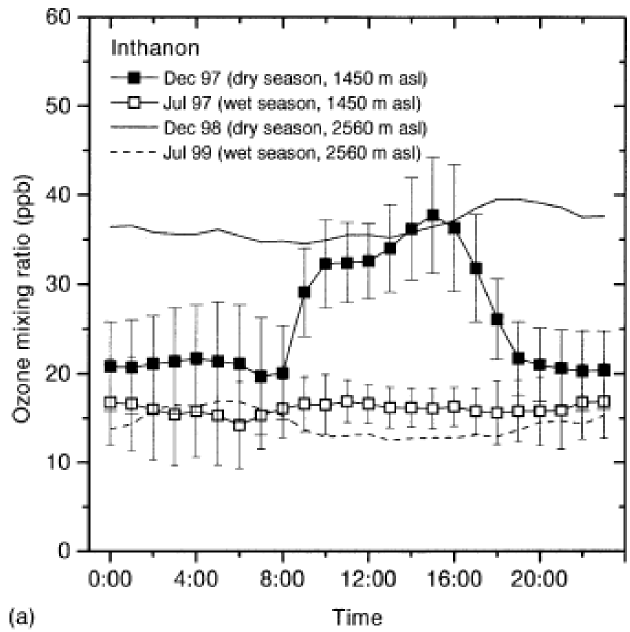

Figure 4.13. Daily ozone concentration variation in Doi Inthanon range and comparison between rainy and dry season in 1997 and 1998. Medium altitude measurements in the dry season show a doubling of ozone concentration during daytime (Pochanart et al., 2001).

4.5. Radioactive components

Radon pollution has been studied in Chiang Mai as a tentative explanation for the anomaly in lung cancer rates in the province and in some districts of the province (See 7.4.2.). Radon is an odorless, colorless dense inert gas that can accumulate in closed space (basements, caves, mines, indoor in general). It is an endogenic gas that has nothing to do with other type of air pollution seen in Northern Thailand. The only interesting isotope is radon-222, which is a short-lived daughter isotope in the uranium-238 decay series with a half life of 3.82 days. It goes through alpha decay into polonium-218 and -212 and eventually decays completely into lead-206.

There has been a few studies on radon indoor (and outdoor) concentration all over Thailand and more particularly in Chiang Mai area due to the public health concern. Average value for Chiang Mai province are between 48 to 57 Bq/m^3 (Autsavapromporn et al., 2018; 2022; Thumvijit et al., 2020). Between districts, variations of averages are minor (Mueang, Hang Dong, Saraphi, Sanpatong: respectively 47, 43, 49, 50 Bq/m^3), however, outliers with high readings occur in some dwellings (209, 219, 405 Bq/m^3). These are true outliers since they represent 1 or 2% of all measurements and are separated from all other measurement by ~200% (*). Although levels in Northern Thailand are among the highest in East Asia, the average indoor radon values worldwide is 39 Bq/m^3 while Thailand is 16 Bq/m^3. The highest recorded value indoor in Thailand is 1974 Bq/m^3 (Wiwanatade, 2011) and Bangkok has more than 20% of buildings with concentrations above 155 Bq/m^3, up to 1870 Bq/m^3 (Polpong et al., 1994).

In the North, outdoor values are 5x lower than indoor and average at 66 nGy/h, slightly higher than the worldwide average of 59 nGy/h. Locally, concentrations have been measured in waters of wells in Doi Saket Hills at 52 Bq/l, 30 Bq/l in springs, 0.5 Bq/l in streams and 0.18 to 1.13 Bq/l in tap water (Thumvijit et al., 2020). As a comparison, this is 2 to 10x lower than tap water in the UK and all measurements are well below US (148 Bq/l) or EU (100 Bq/l) limits. Some hot springs in Thailand however, can have very high level up to 7220 Bq/l (Wanabongse et al., 2005) but these are not used for consumption for various reasons.

During the burning season, indoor radon increases to 63±33 Bq/m^3 compared to 46±19 Bq/m^3 outside the haze episode with maximum levels around twice higher (Autsavapromporn et al., 2022). Hourly variations are important and it has been recorded that indoor radon rises from 55 to 362 Bq/m^3 between 5pm and 7am, then drops sharply and stabilizes for the morning at 100 Bq/m^3. Outdoor radon increases overnight from 12 to 67 Bq/m^3 then drop back progressively during the day. These values are 4x higher than the world average (Autsavapromporn et al., 2018) and likely related to atmospheric conditions but no relationship with particulate matter has yet been made.

Wider study on Northern Thailand have modeled indoor radon concentrations based on locations in Doi Saket (Chiang Mai), Hang Chat (Lampang) and Ban Tak (Tak) (Wattananikorn et al., 2008). It was done through soil measurements, soil permeability measurement and uranium-238 aerial surveys and predicted an average of 44 Bq/m^3 with no higher values than 74 Bq/m^3. Radon hotspots were detected in Mae Cham (MHS), Phrao (CM), Chun (CR) and northernmost Phayao province and Song (Phrae) with an upper limit of 240 Bq/m^3. In Chiang Mai province, the highest levels of radon were found in Hang Dong, San Pa Tong and Doi Lo (Rankantha et al., 2018).

Radon is ultimately related to geological and hydrogeological sources where uranium-238 in soil, rock and eventually water produces radon. As a result, soil average activities have been measured for common radiogenic isotopes giving 346±90 Bq/kg for ^{40}K, 56±16 Bq/kg for ^{238}U and 43±14 Bq/kg for ^{232}Th, which is slightly higher than worldwide average for ^{238}U and ^{232}Th (resp. 35 and 30) while ^{40}K is above worldwide average 38% of the time (Autsavaprompron et al., 2022).

In theory, the aerosolisation of soil during the haze season would carry ^{238}U, ^{235}U, ^{232}Th and ^{40}K in suspension. However, when considering the modeled quantity of radiogenic isotopes based on a granitic crustal component and silicon and aluminium as the standardization value, the activity of particulate matter on a very hazy day is around ~4 μBq/m^3 which is expectedly completely negligible (*).

Potassium-40 can also be considered independently, considering its natural abundance in the potassium that compose 2 wt.% of particulate matter. Again, activity due to biomass burning potassium is in the order of one mBq/m^3, therefore completely negligible (*).

5. Atmospheric factors

As important as the source of aerosols, the state of the atmosphere is an essential factor to create weather characteristics that will make burning of biomass possible but more importantly, it will also generate conditions allowing transportation, trapping and accumulation of aerosols in valleys close to the ground, considerably increasing the resulting air pollution.

5.1. Climate conditions

5.1.1. Intra-annual variations

The main seasonal pattern starts to show above background PM concentrations around the first week of December, followed by a more drastic increase in mid-January, reaching a peak in March and often decreases by mid-April with a gradual to sharp drop in May-June. This pattern is observed for all atmospheric pollutants except SO_2 (Song et al., 2022a; Sukkhum et al., 2022; Suriyawong et al., 2023).

This curve is clearly linked to agricultural fires (December-January) followed by forest fires (February-April) but also coincides with the dry season (winter and hot seasons) which is characterised by the dominance of thermal lows over India, West China and Northern Thailand with hot, dry stagnant air and clear skies, light wind, a low mixing height and low dew point at that time (Kim Oanh & Leelasakultum, 2011).

Weather modeling of the atmosphere during the first few months of the year has provided 4 possible patterns. A first situation with high altitude clouds, a high mixing layer, a high dew point and high visibility with variable wind speed, all acting into dispersing pollutants. A second pattern includes a low pressure system, with low dew point, dry weather, minimum cloudiness and low mixing height in the morning with wind speed below 0.2 m/s, creating the poor aerosol dispersion seen in March-April. A third pattern can rarely occurs during the burning season with high winds (1.9 m/s) creating a turbulent layer with high cloudiness, high mixing layer in the morning, high dew point and high visibility, making the dispersion of pollutants possible and a fourth model provides a high pressure system with very calm winds, clear sky and dry air, a low dew point and a low dispersion vertically and horizontally, which is often seen in February (Kim Oanh & Leelasakultum, 2010; 2011; Moran et al., 2019).

Atmospheric modeling through backward trajectories (ECMWH, Hysplit and others) is done at different altitudes to investigate the behaviour of atmospheric flow when surface friction is an important factor (~10m AGL), below the mixing layer (<1000m) and above (>1500m). Models almost systematically show NW to SW sources for the western part of Northern Thailand (Punsompong & Chantara, 2018). A significant proportion of smoke plumes produced by biomass burning are also rapidly uplifted in the free troposphere and available for long range transport reaching Southern China and the Chinese coast as well as Taiwan (Dong & Fu, 2015).

5.1.2. Inter-annual variations

Next to the annual onset of the haze episode, some parameters at a larger scale also have an influence between one year and another. The variations in seasonal average of PM levels are important and while some years (i.e. 2003, 2011, 2017, 2018, 2022) had very mild haze episodes, bad years (i.e. 2007, 2010, 2014, 2015, 2023) can have integrated PM concentrations twice higher than an average year (Fig. 5.1.).

These variations are mostly related to the weather phenomenon known as El Niño Southern Oscillation (ENSO) that affects relatively strongly all regions around the Pacific Ocean. During El Niño, the warming up of oceanic masses creates dry conditions in South East Asia. With a drier atmosphere, conditions for widespread open burning are optimal and atmospheric conditions also help in accumulating aerosols. The opposite weather system is La Niña, which has an impact on precipitations and air flow in East Asia and as a consequence, direct effect on air pollution (Kraistnitikul et al., 2022). Annual PM2.5 averages for La Niña are 44-55±25 μg/m^3, 60-65±30 μg/m^3 in a neutral ENSO and 65-80±40 μg/m^3 during El Niño (Yabueng et al., 2020).

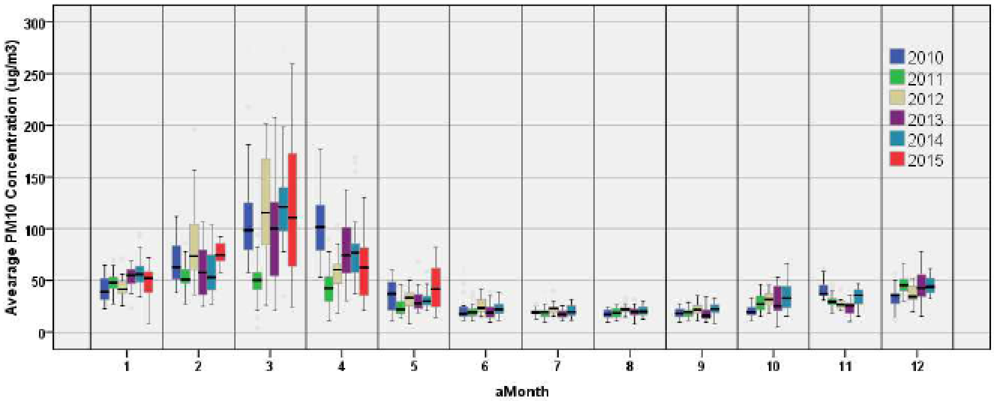

Figure 5.1. Average monthly PM10 concentration between 2010 and 2015. 2011 is clearly visible in this plot with concentrations twice lower than other years during the dry season (March-April) (Punsompong & Chantara, 2018).

During La Niña, integrated peak particulate matter production can be 3 to 5x lower than an average (neutral ENSO) year. It was the case in 2003, 2011 (Fig. 5.1.) and 2022 when the haze season was barely perceptible by the public (*, Yabueng et al., 2020; Phairuang, 2021). In addition to a higher amount of precipitation and atmosphere humidity during La Niña event, atmospheric flow in those years is more erratic and no medium-distance source of aerosol has a high probability (Punsompong & Chantara, 2018) (Fig. 5.2.).

During El Niño, the dry season can be prolonged and extreme. In 2007, no rainfall occurred between November 2006 and April 2007, creating conditions that allow record PM10 levels of pollution (Wiriya et al., 2013; Pimpunchat et al., 2014). El Niño and neutral ENSO also give a dominant air flow with a clear NW-SW trend that accentuate the haze situation in Northern Thailand (Punsompong & Chantara, 2018).

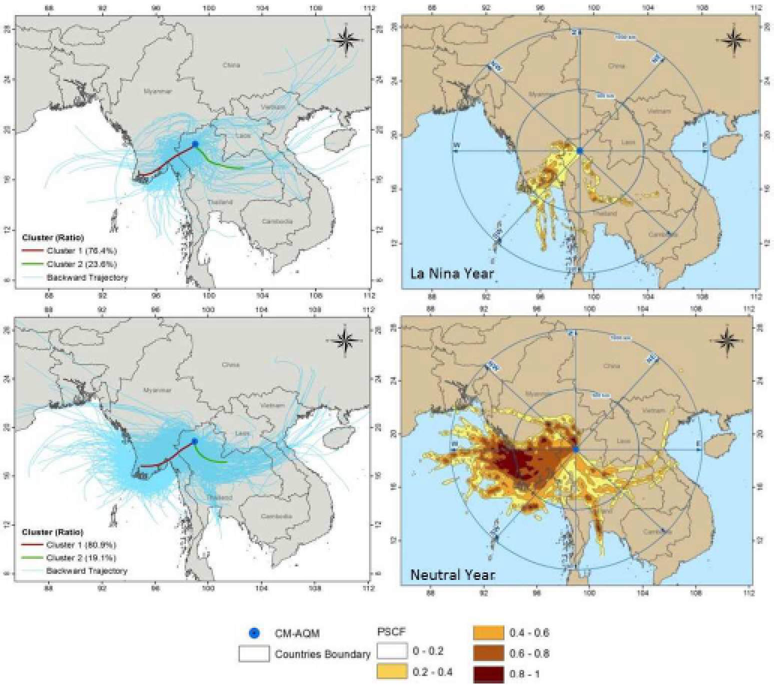

Figure 5.2. Hysplit three-days backward trajectories of air masses for Chiang Mai during haze events between 2010 and 2015. Upper plots are during a La Niña event while bottom figures are during a neutral ENSO (Punsompong & Chantara, 2018).

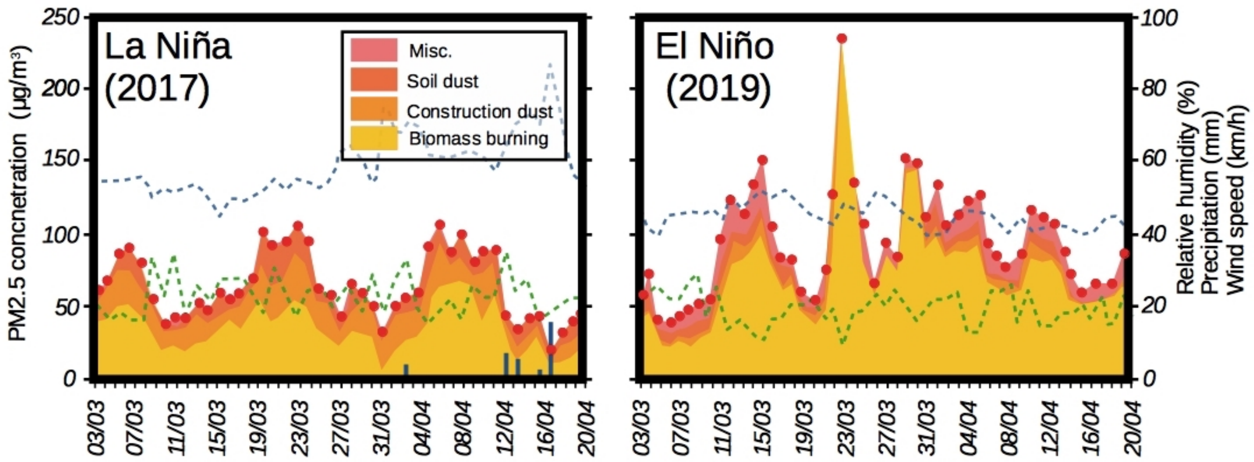

Figure 5.3. Comparison of haze episodes during La Niña (2017) and El Niño (2019) with various meteorological parameters and estimated contributions of aerosol sources in particulate matter (modified from Kraisitnikul et al., 2022).

5.2. Local atmospheric conditions

The general structure of the troposphere during the burning season consists of a persistent stable boundary layer close to the ground which is limited to night time in normal conditions and a convective boundary layer (mixing layer) lies above it but is of limited extend. These layers represents the planetary boundary layer, the column of atmosphere that is under the influence of ground effects such as temperature variation, topography, etc. Above the planetary boundary layer is the free troposphere with the entrainment zone between the two where clouds usually forms (*, Prasad et al. 2022).

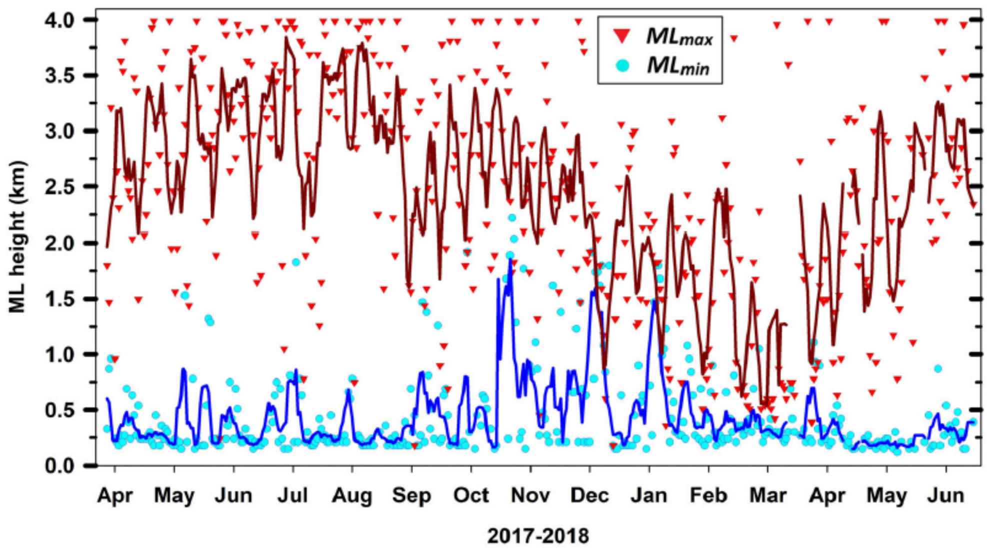

Figure 5.4. Variations of daytime maximum (red triangles) and night-time minimum (blue circles) mixing layer in Chiang Mai basin between April 2017 and June 2018. Solid lines are 5-day moving average of maximum and minimum elevations (Solanki et al., 2019).

The mixing layer is a turbulent atmospheric layer where vertical mixing occurs by convection and mechanical turbulences. Factors at play in the dynamic of this layer include frictional drag, evapotranspiration, heat flow, cloud cover, relative humidity, pollutants, synoptic wind flow, soil moisture and the stratification in the free troposphere.

Between April and December, the mixing layer varies in thickness from 300 to 3500 m throughout a full day (Solanki et al., 2019). During the burning season, the height of the mixing layer is considerably reduced. It reaches height of 2000m in January & February and April, and is eventually down to 1.5±1 km in March as an upper limit, reaching values as low as a few hundred meters during daytime (Vinitketkumnuen et al., 2002; Khamkaew et al., 2016b; Solanki et al., 2019) (Fig. 5.4).

In some high altitude places such as Doi Inthanon, Doi Ang Khang, etc., the ground surface penetrates through the mixing layer and these mountains are more or less within the free troposphere at night time, helping the dispersion of pollutants (Khamkaew et al. 2016b, Solanki et al., 2019). In valleys however, the confinement of the mixing layer is induced by topography through rotor, waves, temperature and slope winds. It produces high air pressure forming an inversion layer trapping pollutants in the lowermost atmosphere (Pongpiachan & Paowa, 2015; Punsompong & Chantara, 2018). The mixing layer which varies from a couple of thousands meters to 50-100m at night time (Ruttanawongchai et al., 2018) can have 24h variation as low as 500m. It has been established that the smallest these variations are between day time and night time, the strongest the thermal inversion is and with a constant source, the highest the pollution will be at ground level (Solanki et al., 2019).

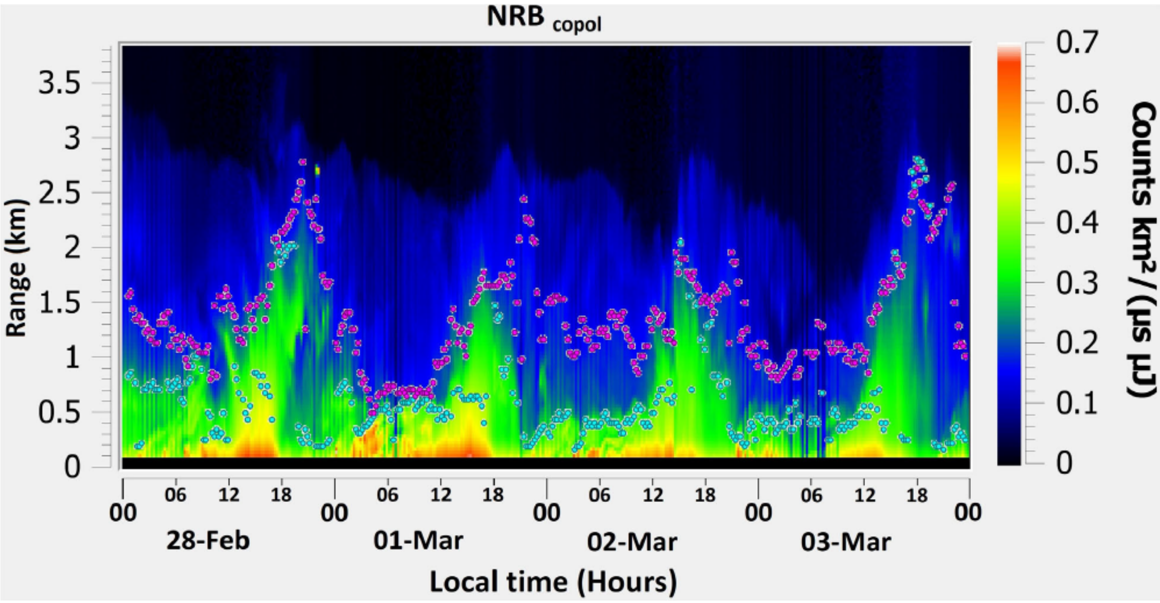

Figure 5.5. Estimated height of mixing layer (blue circles) and aerosol layer height (purple circles) over 4 days during the burning season of 2018 in Chiang Mai basin based on LIDAR measurements (Solanki et al., 2019).

The temperature inversion produces a thick persistent stable boundary layer inside the mixing layer (Prasad et al., 2022). Thermal profiles in the lower atmosphere show that the inversion layer is present up to 900m in early February with a gradient from +13ºC to +18ºC. In mid-March, the situation is 17ºC of ground temperature and 26ºC at 1000m, sometimes with even stronger gradients while by the end of April, the profile is mostly isothermic as the ground temperature is 26ºC with a minor increase with altitude (Kim Oanh & Leelasakultum, 2011, Sresawasd et al., 2021) (Fig. 5.6.).

On average, the temperature inversion peaks at +800m and is the strongest in the early morning, only to dissipates in the afternoon as the ground atmosphere heats up (Amnuaylojaroen & Kreasuwun, 2012; Ruttanawongchai et al., 2018). The ground thermal inversion, combined with weak winds make aerosols unlikely to be dispersed upwards or blown away from the basin (Amnuaylojaroen, 2009). As a consequence, when abundant aerosol sources are present, regional PM2.5 levels above 100 µg/m^3 are obtained when the mixing layer fails to reach 1800 m anytime during the day (Solanki et al., 2019) with a PM10 trend that shows a decrease of 0.05 µg/m^3 per meter of ground elevation (Trang & Tripathi, 2014).

Another related factor is the humidity saturation which requires less than 4ºC difference between air temperature and dew point to allow precipitation. In conditions of strong temperature inversion in the dry season, such situation is unlikely to arise within the stable boundary layer and the removal of particulate matter through rainfall is not possible (Amnuaylojaroen, 2009).

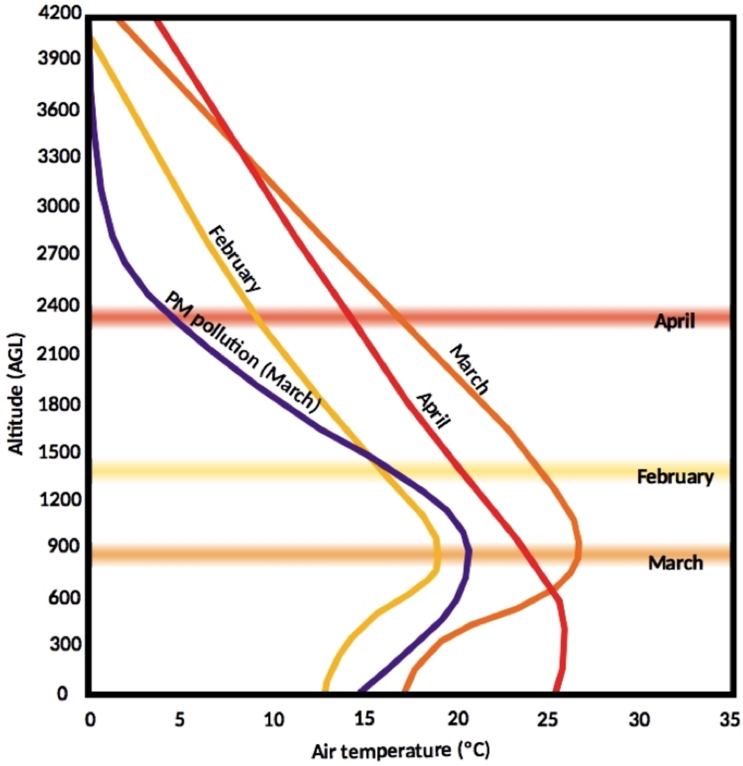

Figure 5.6. Temperature profiles of the lower troposphere during the dry season of 2007. Qualitative distribution of particulate matter pollution over the atmospheric column is given for comparison (modified from Kim Oanh & Leelasukultum, 2011).

5.3. Correlation between pollution and weather parameters

Aside from broadly similar sources that are found in other regions of South-East Asia (Kalimatan, Sumatra) that sees large amounts of biomass burning (agricultural waste, uncontrolled burning and forest fires), the case of Northern Thailand is exacerbated by medium size mountain ranges, a strong stability of the troposphere between 0.6 and 1.2 km and strong atmospheric inversion (Amnuaylojaroen, 2009; Othmann et al., 2022).

A strong correlation is established between fire hotspots and PM concentration (Phairuang et al., 2017, Sritong-aon et al., 2021). The relationship is strengthened in atmospheric conditions of low wind speed, high stability, temperature inversion and local topography (Nakapan & Choopun, 2018; Punsompong & Chantara, 2018). A 6-day lag also seems to be present in the correlation between hotspots and PM levels that might be related to transborder sources (Sritong-aon et al., 2021).

Particulate matter is positively correlated with atmospheric pressure with a lag of 6 to 7 days. The high pressure is inducing the stagnant atmospheric conditions and the accumulation of pollutants close to the ground (Ruttanawongchai et al., 2018; Vongruang & Pimonsree, 2020; Sritong-aon et al., 2021). Temperature on the other hand, is negatively correlated with a R^2 of 0.624. This is due to the thermal homogeneisation of the lower troposphere at the hottest time of the day, which allow pollutants to be dispersed over a thicker layer of atmosphere (Anusasanan et al., 2021; Sritong-aon et al., 2021; Sirithian & Thanatrakolsri, 2022)

Rainfall is strongly negatively correlated with PM2.5 with a R^2 of 0.85 (Anusasanan et al. 2021) (Fig. 5.7.). The correlation is due to particle movement when precipitation conditions are possible and the coalescence and settling of particulate matter during rainfall (Giri et al., 2008;

Kayes et al., 2019; Sirithian & Thanatrakolsri, 2022). The relationship between rainfall and lower PM2.5 concentrations has a lag of 7 to 8 days, indicating that a significant rainfall event can have an effect for a week (Sritong-aon et al., 2021). The rainfall correlation is absent for PM0.1 although relative humidity has an effect due to the short life of nanoparticulates, agglomerating and coalescing into larger particulates (Berube et al., 1999; Avino et al., 2011; Chuang et al., 2016; Sresawasd et al., 2021)

Wind speed during haze episodes has been measured as 0.72±0.77 m/s (Janta et al., 2020), 1.4 m/s (Punsompong & Chantara, 2018), 1 to 4 m/s (Ruttanawongchai et al., 2018) or higher (Fig, 5.3, Kraisitnikul et al., 2022), all indicating low wind speed but still sufficient to carry pollutants over a couple of hundred kilometers per day. Within the haze episode, there is no strong correlation with particulate matter when wind speed variations are between 0 and 2 m/s (Sirithian & Thanatrakolsri, 2022) as it will not affect significantly the atmospheric mixing height (Sritong-aon et al., 2021). Over a year however, trends show that a decrease of 1 m/s in average wind speed increases PM10 by 86.37 μg/m^3 (Trang & Tripathi, 2014).

Overall, the combination of all meteorological parameters shows that air pollution peaks in moderate temperature conditions, high pressure systems with low humidity and low wind speed, in a static lower atmosphere characterised by a strong thermal inversion. This situation is reached in March potentially causing extreme pollution in valleys and basins (Chunram et al., 2007a; Sritong-aon et al., 2021).

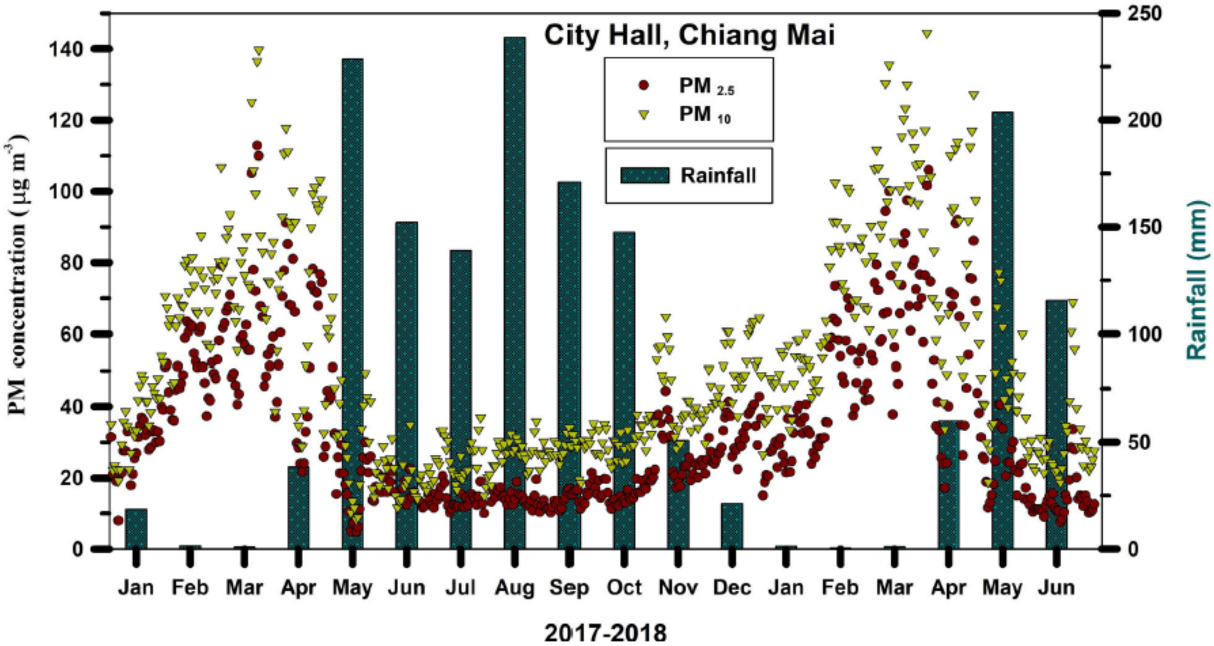

Figure 5.7. Daily mean concentration values of PM2.5 (red circles) and PM10 (yellow triangles) in 2017-2018 and monthly accumulated rainfall in Chiang Mai (Solanki et al., 2019).

5.3.1. Daily variations

The change in atmospheric conditions throughout the day has a direct impact on air pollutants and daily variations from 70 μg/m^3 to 600 μg/m^3, dependent on emission sources, have been recorded (Amnuaylojaroen, 2009). Particulate matter highest concentration in February-March occurs at 9:00 and shift to earlier time (6-7:00) by mid-April while the lowest concentration are met around 15:00 (Anusasanan et al., 2021; Othman et al. 2022). This is directly related to the state of the stable boundary layer. As the sun rises, higher atmospheric layers are warmed up while the ground in valleys is still in the shade, producing a strong thermal inversion layer trapping pollutants that couldn't escape during the night due to the suppression of the mixing layer (Monkonnen et al., 2004; Tippayawong et al. 2006; Anusasanan et al., 2021; Othman et al. 2022). By 8 to 10 am, the atmosphere is warming up, initiating a slight decrease until the mid-afternoon, to increase again in the evening (Punsompong & Chantara, 2018) (Fig. 5.8.).

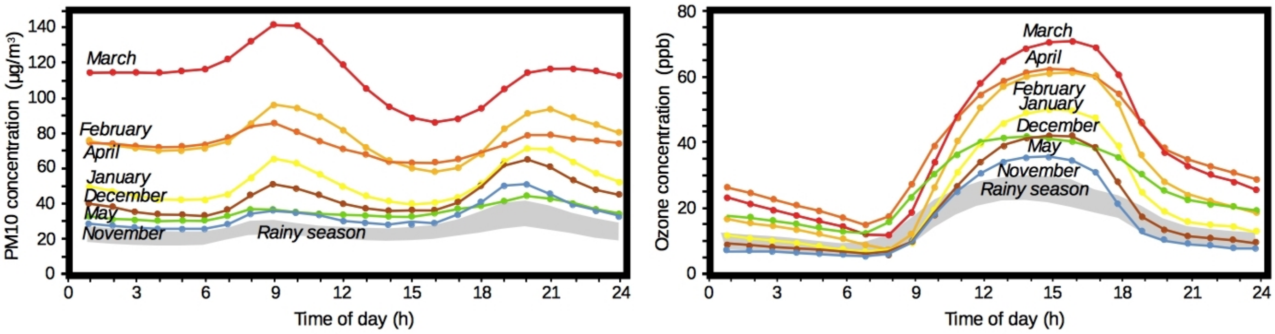

Figure 5.8. Hourly variation of PM10 and ozone over a day in different months between 2006 and 2016 (modified from Janta et al., 2020).

Ozone has a concentration of 10 ppb in the rainy season but the dry season naturally increases the background level to 20-30 ppb (Pochanart et al., 2001). Daily variations are the opposite of particulate matter and peak at 15:00. It increases from 20 ppb right after sunrise due to some vertical mixing when the stable nocturnal layer breakup to 50-60 ppb in the afternoon (Fig. 5.8.). Photochemical reactions during the day increase ozone level. During the night, ozone is destroyed under the nocturnal layer through dry deposition and surface chemical reaction (Pochanart et al., 2001; Janta et al., 2020).

5.4. Atmospheric feedback from particulate matter

Particulate matter has an impact on local (and global) climate change by modifying the albedo of the lower atmosphere through absorption and scattering of solar radiation (Xing et al., 2020; Pani et al., 2023; Song et al., 2022b) and cloud condensation nuclei properties when these are applicable (Cattani et al., 2006). Aerosols modify cloud optical properties and radiative forcing (Wang et al., 2015), which combined with the dynamic nature of particulate matter, can cause direct and indirect effect on meteorological conditions (Wang et al., 2014; Liu et al., 2016, 2021; Bran et al., 2022). It is estimated that in South-East Asia, carbonaceous aerosols contribute to up to 75% of radiative forcing and has an important role in the solar irradiation budget in the regional climate (Pani et al., 2016).

Cloud formation is a minor factor in Northern Thailand due to the low humidity of the dry season. In high humidity conditions, carbonaceous aerosols would act as cloud condensation nuclei and would influence the albedo through cloud cover and lifetime (Leaitch et al., 2010; Ramana et al., 2010; Phairuang et al., 2019). Nevertheless, atmospheric absorption of haze changes the vertical heating rate and thermal distribution in the lower atmosphere, accentuating, in some aspects the lack of heat reaching the ground and the thermal inversion layer of the lower troposphere (*, Adam et al., 2021).

These atmospheric 'brown clouds' composed of carbonaceous aerosols induce surface cooling which weaken the boundary layer turbulence, convection and advection and height by 21%, strengthen the atmospheric stability with lower wind speeds and ultimately, conditions favorable for aerosol stagnation (Bran et al., 2022). As absorption and scattering reduce solar insolation by up to

26%, it also reduces surface temperature by 3.9%. This in turn reduces the evaporation of water, bringing an increase in relative humidity by 13% (Bran et al. 2022).

Carbonaceous aerosols have a complex response to sunlight depending on their composition and through time. Overall, the absorption is strong for short visible wavelengths and ultraviolet. While black carbon absorbs solar radiation, organic carbon as well as sulfate absorbs and scatters sunlight with secondary organic carbon mostly scattering (Adam et al., 2021; Sresawasd et al., 2021). The absorption contribution of organic carbon in particulate matter range from 20 to 50% between 370 and 880 nm (Tao et al., 2020) and at a specific wavelength (400 nm), organic carbon contribute to 1/3 of the absorbance while black carbon is 60-67% (Sresawasd et al., 2021; Pani et al., 2023). The aerosol single scattering albedo at 550 nm for all pollutants is 0.75 to 0.84 in Chiang Mai area providing a negative top of the troposphere wavelength dependent simple forcing efficiency of -102±24 W/g resulting in atmospheric cooling while the absorption by elemental carbon is lower resulting in atmospheric warming (Pani et al., 2016, 2018, 2023). Black carbon absorbance is estimated to be the third greatest contribution to global warming with a radiative forcing of 0.4 W/m^2 (Moosmuller et al., 2009; Bond et al., 2013; Zhang et al., 2021)

Atmospheric absorption is a land-based and satellite-based method to estimate levels of pollution. In Doi Ang Khang, the mean aerosol extinction profile show a maximum altitude of haze at 5.5 km with most of it being at 2 to 3.5 km high, which is higher than usual due to the altitude of the mountain (Pani et al., 2016)(Fig. 5.9.). The average continental extinction coefficient in Northern Thailand is around 2 km high (Pani et al., 2018).

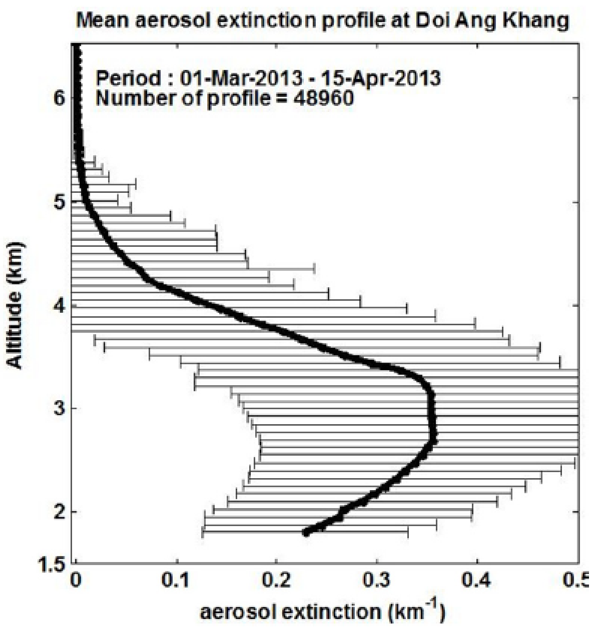

Figure 5.9. Mean aerosol extinction profile and standard deviation in Doi Ang Khang in March 2013 (Pani et al., 2016).

Time is also a factor in absorbance of particulate matter. Flaming stage smoke, which has a higher absorbance than smoldering smoke, has a half-life absorbance decay of 2 to 3 h in sunlight and 5 h at night time (Liu et al., 2021). It results that organic carbon subject to 8-9h of sunlight has its absorption properties considerably decreased compared to fresh smoke. The effect is even more evident in conditions of high relative humidity where the color of haze quickly degrades and are only maintained by NOx (Zhong & Jang, 2013; Chuang et al., 2016). However, even NO_2 has a relatively short lifetime of a few hours to a few days (Lalitaporn & Boonmee, 2019). PAH also have some role in fluorescence but bleaching occurs rapidly (Zhong & Jang, 2013).

5.4.1. Atmospheric effects at ground level

The absorption and scattering properties of carbonaceous matter are particularly strong in the red part of the visible spectrum. From the ground, sunlight transmission appears brownish (Liu et al., 2016) and the resulting thick haze has an orange tinge. Scattering within smoke plumes makes the sun appears redder than normal due to the Tyndall effect (*). PM10 has less absorption properties (Zhang et al., 2021) however, and the colour of haze formed by larger particulates tend to be rather black than brown (Liu et al., 2016). The resultant absorption and modification of the incident light spectrum from near-infrared to ultraviolet leaves less available sunlight at ground level, making photosynthesis less efficient and induces lower crop productivity (Deng et al., 2008; Pimonsree & Vongurang, 2018; Adam et al., 2021). While the absorbance of black and primary organic carbon produce warming over the atmospheric column, secondary carbon has a tendency to produce cooling (Chaiyo et al., 2011; Pani et al., 2019),

Visibility is also an obvious ground effect of haze and has been noticed for the past two decades (Chunram et al., 2007a, b). The reduction of visibility provides a direct perception of haziness (Tippayawong et al., 2006) and an approximate estimation of particulate matter concentration (Panyaping, 2009). It also varies greatly with altitude; while the visibility on Doi Inthanon or Doi Suthep can be above 10km, at the same time, Chiang Mai city centre has a visibility below 3 km. As the altitude decreases, the correlation between visibility and PM2.5 becomes stronger with R^2 >0.96 in low level basins (Pengchai et al., 2009; Jeensorn et al., 2018) (Fig. 5.10).

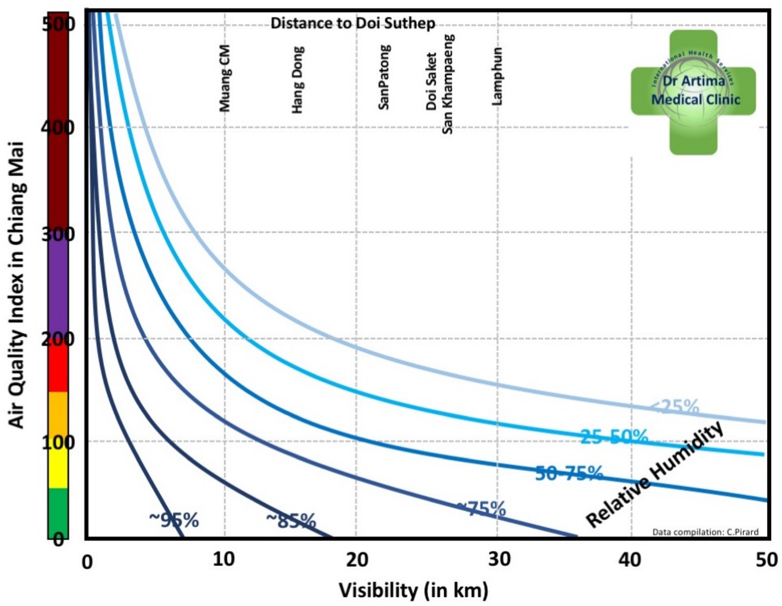

Figure 5.10. Correlation between Particulate matter concentration and visibility for different relative humidity in the atmosphere (•, Chen et al., 2016; Fu et al., 2016)

The radiative forcing of carbonaceous matter produced by biomass burning in Chiang Mai is measured to be -45.3 to -103.4 W/m^2 at ground level while it is -1.7 to +6.2 W/m^2 in the free troposphere (Pani et al., 2016; 2018; Sresawasd et al., 2021). When PM2.5 is below 12.5 µg/m^3, the loss in irradiation is minimal. However, for PM2.5 > 33.5 μg/m^3, the observational irradiation is decreased by 5% and it reaches 12.5% for each 100 μg/m^3 of PM2.5 added to the atmosphere. These lower insolation values can give 25 to 35% lower solar output which has an effect on photosynthesis and the power production of photovoltaic devices.

The electrical response of solar panels to air pollution varies depending on the type of device used as different systems have different limitations on their sensitivity to the solar spectrum. When the latter is shifted due to absorption and fluorescence of air pollution, it can affect systems differently, particularly in the near-infrared wavelengths (Song et al., 2022b). For conditions at 50 μg/m^3, polycrystalline silicon panels will show a 6% lower output while monocrystalline are 8%. Similar values are found for CIGS thin films. Silicon and CdTe thin films are respectively 9-10% and 10-11% lower. This is due to the lower spectral range (300-900 nm) of these panels compared to standard crystalline panels (300-1150nm).

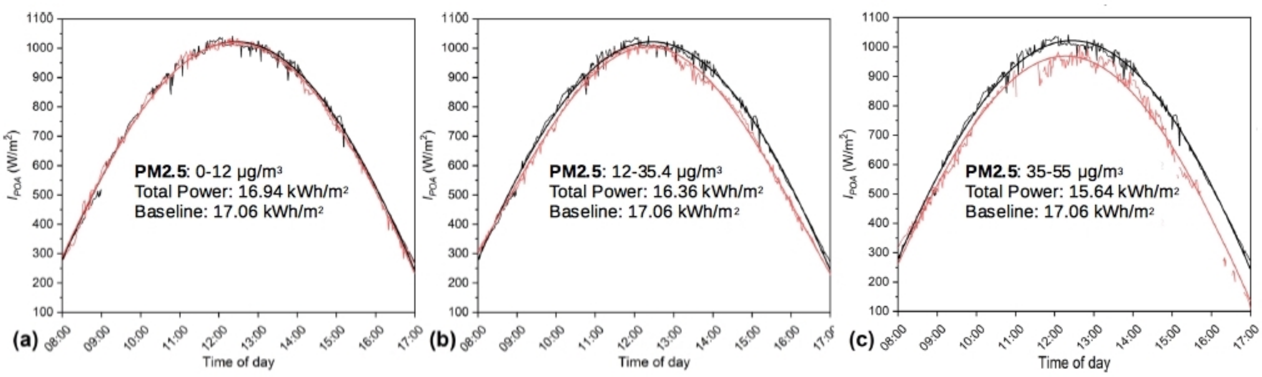

Figure 5.11.Comparison of daily total power produced by photovoltaic sources between clear day (black curve) and days with particulate matter air pollution (red curves) (modified from Song et al., 2022b)

6. Sources of air pollution

Historical data and more recent scientific reports have identified the source of air pollution in Northern Thailand as biomass burning (forest & grassland fires, agricultural residues). It is the main source of particulate matter and various gases (Christopher et al., 1998; Pochanart et al., 2001; Sopajaree et al., 2007; Liang et al., 2019; Moran et al., 2019; Phairuang et al., 2019; Suriyawong et al., 2023). It is estimated that without these anthropogenic and human-related biomass burning smoke emissions, the background level of particulate matter in the atmosphere of northern Thailand is 2 to 3 μg/m³ (º, Pinichka et al., 2017).

In 2002, the PCD has found that 97% of particulate matter originates from area sources and 2.5% from mobile sources (º, PCD, Khamkaew et al., 2016). Among area sources, 80% are forest, 5.5% are rice paddies and 4.5% are crops and subsequent estimation gave 89% of particulate matter produced by forest fires, 5.4% from solid waste burning, 2.6% from traffic, 2.3% from agriculture resides, 0.08% from industry and 0.56% from other sources (º, PCD, Kim Oanh & Leelasakultum, 2011; Khamkaew et al., 2016; Phairuang et al., 2019).

With more accurate data available over large areas due to extensive surveys and remote sensing, the contribution of biomass burning has been estimated as 85% of PM10 and 89% of PM2.5 in urban centres such as Chiang Mai (Pimonsreee & Vongruang, 2018; Othman et al., 2022) while the biomass contribution to particulate matter below 1 micron is 60-80% and <30% for PM0.1 (Phairuang et al., 2022c). The remainder finds its cause mostly in traffic and urban sources. High spatial resolution also shows considerable heterogeneity with smoke plumes generated by biomass burning creating strong concentration gradients within 50 km of major sources (Pimonsree & Vongruang, 2018) (Fig. 6.1.). As a consequence, a large amount of studies have focussed on the various contributions of crops, forest and grassland to particulate matter but other sources are still studied due to the toxic chemicals they can potentially produce.

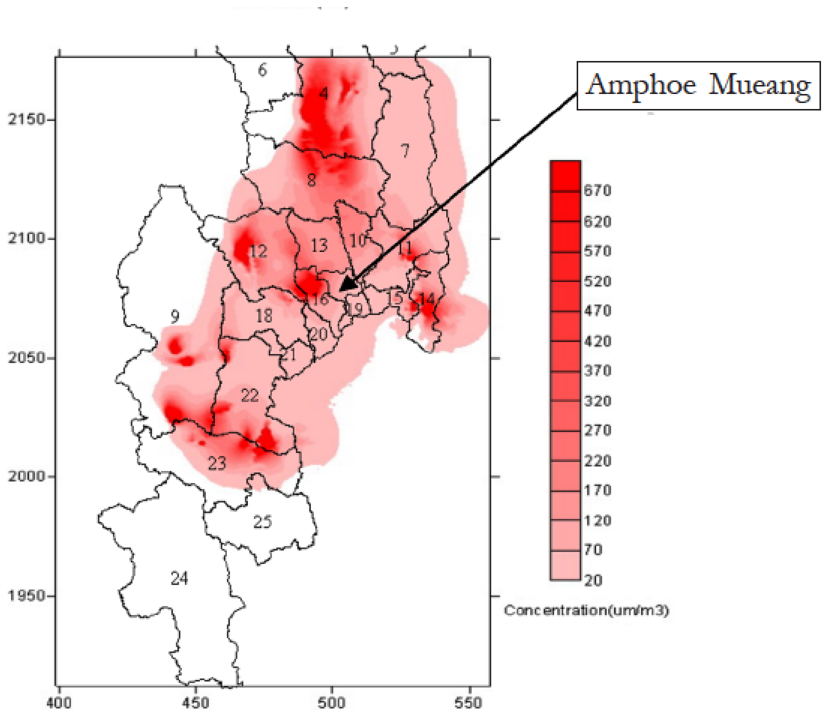

Figure 6.1. Modelisation of 24 h average PM10 distribution over Chiang Mai province on the 11th of March 2007 at 5m AGL (Amnuaylojaroen, 2009)

6.1. Biomass burning

6.1.1. Contribution of biomass burning

The detailed study of biomass burning follows two main pathways, a bottom-up approach through land use, ground surveys, emission inventory, laboratory data on combustible biomass, etc. and top-down approach using remote sensing, atmospheric patterns, hot spot identification, land use, pollution composition etc. modeled into emission potential and source distribution. Both approaches have positive and negative aspects such as spatial accuracy and precision, time resolution, sampling biases and becomes a truly solid investigative tool when combined together.

The evidence of biomass burning as a major contributor to air pollution is confirmed by molecular tracers, diagnostic ratios, positive matrix factorization models, principal component analysis, stable isotopes, emission inventories, etc. (Song et al., 2022a). Levoglucosan, a marker for biomass combustion, increases by 14.2 to 21.8x when PM increase by 3.5x (Tsai et al., 2013) and the correlation is very systematic. Estimation of biomass burning varies from 25 to 79% based on levoglucosan concentrations (Pani et al., 2018; Chansuebsri et al., 2021a).

PAH on the other hand, have contents and composition during the haze season which identify them as 51.6-55.2% from vehicular exhaust, 16.2-15.3% from biomass burning, 10.6% from diesel emission; 5.2% from marine sources, 3.7% from fertilizer volatilisation and 12.7% of unidentified sources such as incinerators, incense, cooking (º, Pongpiachan et al., 2017; Choochuay et al., 2020). Similar values were found by Pengchai et al. (2009 with 20-25% of total PAH released by biomass burning and the rest associated with traffic and energy production. Outside the haze episode, research results diverge and while some authors place traffic as the main source of PAH (Song et al., 2022), a study has found that 52.6% of PAH are produced by biomass burning, 22.5% from sugarcane and 14% from diesel during non-haze months (Pongpiachan et al., 2017). In all cases, however, absolute concentrations of PAH during this non-haze period are considerably lower.

More specific laboratory tests on the source of PAH show that low-mass PAH are linked to industrial emission and some types of biomass burning (i.e. maize, Sirithian et al., 2017). Direct comparison between biomass burning and waste combustion of paper and plastic tend to show the latter as a dominant source of PAH pollution (Park et al., 2013; Pongpiachan et al., 2015). In combustion chambers, biomass burning shows a considerable contribution to low molecular weight (3-4) PAH (Hall et al., 2012) while gasoline appears to produce heavier molecules (Miguel et al., 1998). PAH composition in haze seems to indicate a heavy influence from biomass and coal burning and less petroleum (Yabueng et al., 2020) (Fig. 6.2.). PCDDs in Chiang Mai are produced at 77% by biomass burning, and the rest by traffic. The overall relatively low concentrations are linked to the lack of large industrial complexes or intense traffic in Northern Thailand urban centres (Chi et al., 2022).

Carbon speciation between organic and elemental carbon shows that biomass burning contributes for 40.2% of PM10, while 31.5% are sourced from the industry, 17.1% from traffic and 10.9% from power plants (Vongmahadlek et al., 2009). This early result is not particularly confirmed by later analyses of carbonaceous matter in Northern Thailand haze, among other, carbon-14 content, that gives a biomass burning contribution in urban area of 63.8±9.0% and 71.7±12.2% in rural areas during haze season, and down to 40 to 47% in non-haze season (Song et al., 2022a) (Fig. 4.8) and some papers put the biomass contributions based on other calculations to much higher levels such as 98% in Phayao (Pimonsree & Vongruang, 2018).

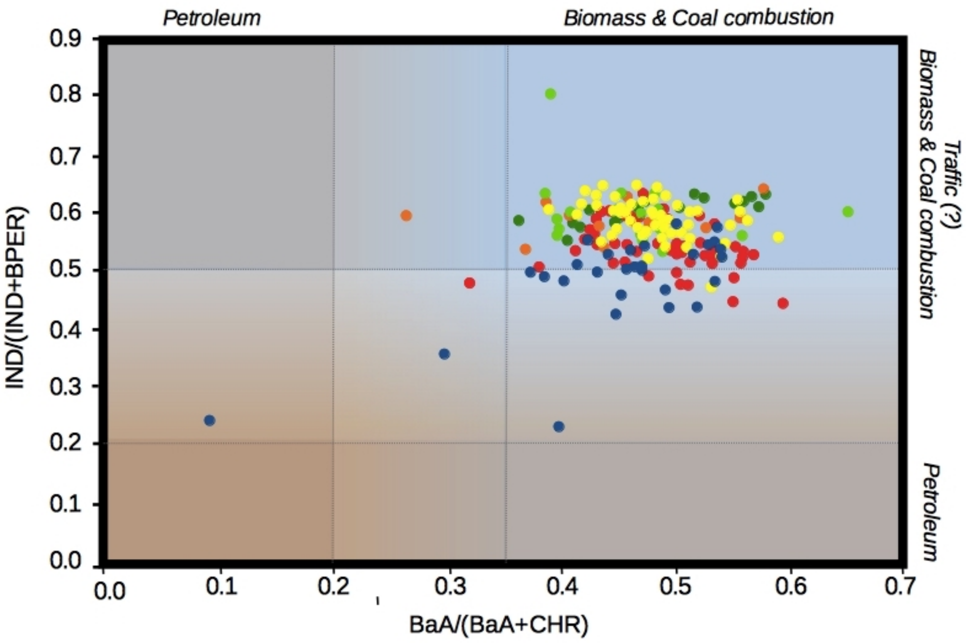

Figure 6.2. Discrimination of sources based on PAH ratio. Red, orange and yellow circles are Chiang Mai data in 2016, 2017 and 2018; green circles are Nan province data in 2017 and 2018; blue circles are unspecified northern Thailand in 2018 (IND: Indenopyrene , BPER: Benzoperylene, BaA: Benzanthracene, CHR: Chrysene) (Kawichai et al., 2020; Kongpran et al., 2020; Thepnuan & Chantara, 2020; Yabueng et al., 2020)

The contribution of biomass burning varies between regions and years and is relatively well correlated with the concentration in particulate matter. In Chiang Mai city, based on positive matrix factorization of chemical data, an El Niño year (2019) gives 79% of biomass burning, 4% of soil contribution, 5% of construction dust and 12% of unidentified source during the haze episode while a climatic system of La Niña (2017) has 50% of PM associated with biomass burning, 32% with construction, 17% with soil dust and 1% unidentified (Kraisitnikul et al., 2022) (Fig. 5.3.). Although traffic is not present in that analysis, it is known to be a significant contributor in Chiang Mai (Kawichai et al., 2020a). In Chiang Rai during the burning season of 2021, contributions, based on the same estimating principles but different proxies were 52% of biomass burning, 30% of soil and secondary aerosols, 10% of rubbish burning and 10% traffic (Duc Luong et al., 2022). Other estimations in the area based on various analytical methods broadly give similar values with 50-70% of biomass burning and 10% of diesel contributing to haze (Rayanakorn et al., 2014; Sirimongkonlertkun, 2018a). The soil component, mobilized through combustion and suspension from wind & soil displacement is a significant particulate emitter in some areas as well as sea salt carried by western and southwestern winds (Chansuebsri et al., 2022).

The contribution of biomass burning to the ultrafine fraction (PM0.1) is slightly different. PM0.1 increases from 4.4±1 μg/m^3 to 12.1±4 μg/m^3 between non-haze and haze season. This 3-fold increase is not comparable to the 7-8x increase of PM2.5 or the dramatic increase in levoglucosan concentrations. Fluctuations, correlations with other size fractions, hotspots, humidity, etc. and chemical composition indicate that biomass burning is the main producer of PM0.1 during haze season but other source such as traffic contribute to the ~30% background present all-year round (Sresawasd et al., 2021).

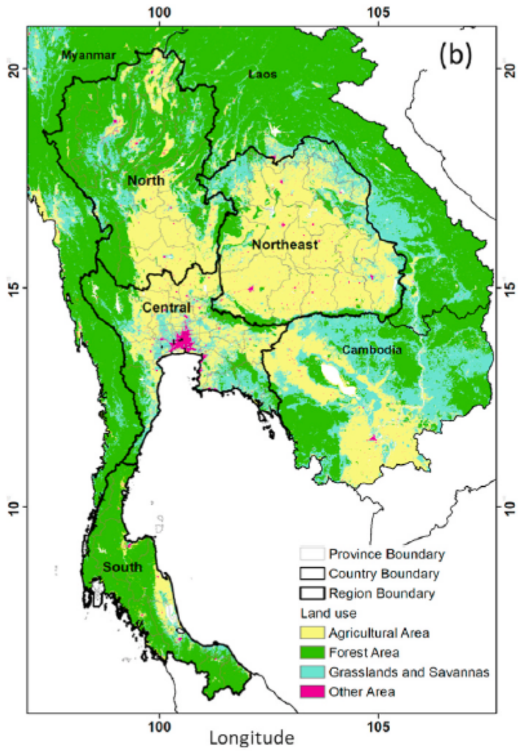

Figure 6.3. Simplified map of land use in Thailand. The northern region is characterised by a large area of forests as well as some grassland (Tak, Sukhothai). In some provinces, agriculture also represents a large surface (Chiang Rai, Phayao) (Punsompong et al., 2021).

6.1.2. Characterisation of biomass burning

Emission inventory based on satellite data (VIIRS) for northern Thailand gives a broader view and regional estimation of sources of biomass burning by identifying hotspots and their position regarding to land use. Results on hot spots counts show around 70-80% of forest fires, 5-10% of grassland fires and 5-22% due to agriculture (Kim Oanh & Leelasakultum, 2011; Silapapiromsuk et al., 2013; Khamkaew et al., 2016; 2017; Punsompong et al., 2021). The situation is slightly different when taking contribution to haze into account. Through laboratory combustion-emission studies for various types of biomass, the PM emission contribution of forest and savannah fires is 71 to 92%, 7 to 15% from crops and 2 to 5% from rice fields (ratio crop:rice of 3:1) with contributions depending on climatic conditions, boosting forest fires emission during El Niño (Silapapiromsuk et al., 2013). Other emission contributions studies have shown an even lower contribution of agriculture (1-2%) and 86-92% of emissions carried by forest fires and 7-12% by grassland fires (Hongthong et al., 2022). However, higher spatial resolution shows that a significant disparity exists between Mae Hong Son, Chiang Mai & Tak provinces where forest and savannah fires are abundant while Chiang Rai & Phayao have more significant agricultural fires (Sirithian et al., 2017; Hongthong et al., 2022).

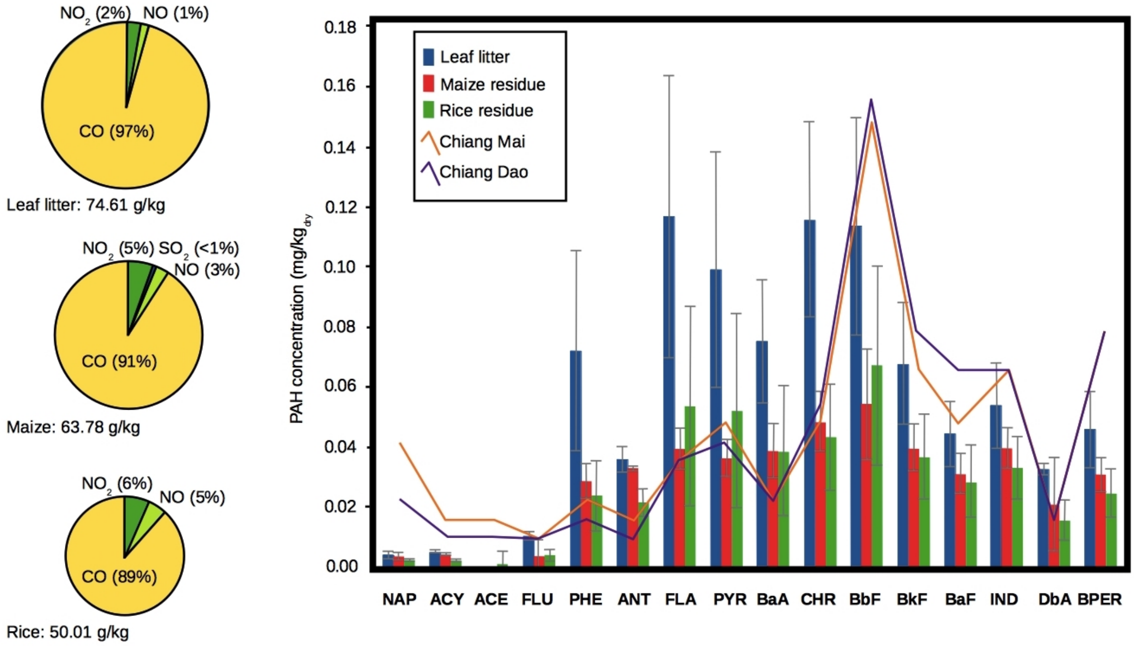

Figure 6.4. Combustion laboratory-measured emissions of forest litter, maize and rice residues of CO, NO, NO_2 and SO_2 as well as PAHs. For comparison, a qualitative concentration of PAH for urban (Chiang Mai) and rural (Chiang Dao) particulate matter is provided (modified from Wiriya, 2015; Insian et al., 2022).

Carbon speciation studies also show these variations in haze composition between provinces. The very high OC/BC ratio (2-4x higher than average) is in line with strong contributions from forest fires (OC/BC = 6.75) when compared to rice residues (3.88) and corn residues (5.81). Highest OC relative concentrations are found in heavily forested Chiang Mai and Tak provinces while BC emission are similar to the Thailand average (Phairuang et al., 2019).

Air pollution levels in the North typically increase in mid-January, reach a peak in March and often decrease by mid-April (Song et al., 2022a), fueled by open fires of biomass such as forest & grassland fires and crop residues (Phairuang et al., 2017; Thepnuan et al., 2019; Kayee et al., 2020). Particulate matter levels are strongly correlated with hotspots monthly counts. Over the haze season (Jan-Apr), the hotspot distribution is 5-12-51-31% which represents relatively accurately the monthly average PM levels (Sirimongkonlertkun, 2018a). The good correlation between hotspot counts and particulate matter concentration can be further modeled using emission inventory based on laboratory estimation with a R^2 of 0.92 to 0.94. Details show that most of the haze production occurs between February and April with a peak in March for forest fires while crop burning have a broader peak in December-January (Phairuang et al., 2021a) (Fig.6.5.).

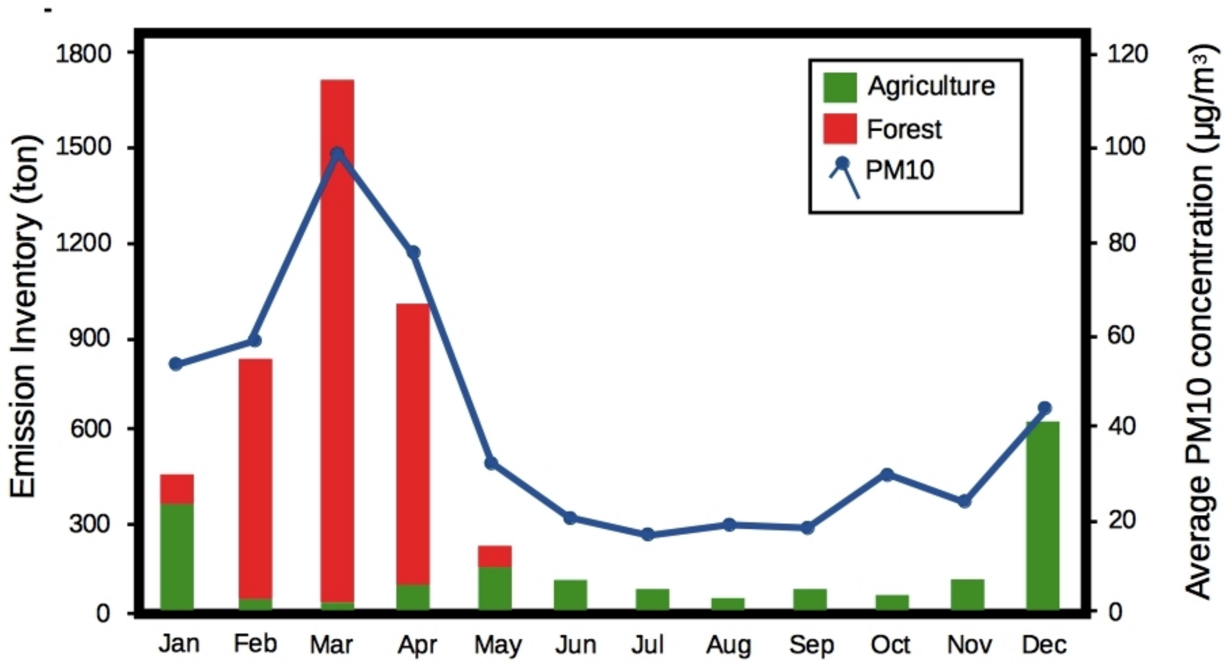

Figure 6.5. Comparison of monthly average PM10 variations and emission inventory for forest and agriculture in Chiang Mai for 2013 (modified from Phairuang et al., 2021a).

6.2. Forest Fires

Forest fires as defined by the Royal Forest Department is a fire that occurs on forest land, for any reason and in the absence of any control. Aside to this category, there are some prescribed fires initiated by forestry or communal fires under the control of village community, even if the burned land is *de jure* state or public land (Rakyutidharm, 2002). The correlation between forest fires and haze has been established for decades with zero fires between June and November, a handful in December and May, hundreds in January, February and April and thousands in March (Vinitketkumnuen et al., 2002) (Fig. 6.6.).

Forest fires are a significant contribution to haze and it is estimated that 46% of forest-related haze is produced by local (within Thailand) forested area (Punsompong et al., 2021). According to Sresawasd et al. (2021) based on satellite imagery, 1 Mha of land can be burned in a single year in Northern Thailand and 90% are forested areas. However, estimations by other techniques such as emission calculation give a lower figure of a few 100000s ha (Junpen et al., 2013a). In 2010, it is estimated that 28% of forested areas were burned during the smoky season (Wiriya et al., 2015). At a national level, around 2/3 of all forest fires occur in northern Thailand, mostly in mixed deciduous forests (FFCD, Junpen et al., 2013a, b). At a provincial level, forest fires are particularly abundant in Chiang Mai, Tak and Mae Hong Son regions (Phairuang et al., 2019) but savannah fires can also be a significant contributions of wildfires (Hongthong et al., 2022) as well as urban fringe and roadside burning of grass (Hoare, 2004). More information of forest fire characteristics is available in section 8.1.

6.2.1. Causes of forest fires

In Northern Thailand, forested area covers 50 to 80% of provinces (Fig. 6.3.). Around 50% of these forests are deciduous dipterocarp, 36% are mixed deciduous, 5% coniferous, 5% dry evergreen. It means that 86% of forest annually shed leaves and are subject to potential fires (Janta et al., 2020). The FFCD has roughly similar values and estimates that 70% of forested areas in Northern Thailand are subject to fire (Thammanu et al., 2021).

Among forests subject to fires, there used to be a distinction between conservation forest, which are usually evergreen, dense and humid, often in a watershed area and occasionally protected by religious and traditional beliefs and production forests on the other hand, that are dipterocarp and mixed deciduous forest used as a source of food, firewood, fodder, etc. where burning was a common practice to accelerate the germination or growth of forest products and facilitate hunting (Rakyutidharm, 2002). The current administrative subdivisions would include national parks, protected forests, private & commerical forests, etc.

Surveys in the past two decades have identified more precisely the causes of forest fires in dipterocarp and mixed deciduous forests (Fig. 6.6.). In 2011, the FFCD saw that the collection of non-timber products such as fuel wood, mushroom, honey, bamboo, represents 39% of the factors driving undergrowth burning, hunting (24%), land clearing for agriculture (19%), incendiary fires (10%), illegal logging (2%) and 6% of other causes (Junpen et al., 2013a, b).

In 2014, the reasons for forest fires estimated by the FFCD were collection of forest products (37%), incidents (12%), land clearing for cultivation (11%), hunting (11%), animal farming (4%), illegal logging (1%) and other causes (24%) (Phairuang et al., 2016).

In 2016-2018, reasons for forest fires are for collection of forest products (62.94%), hunting (10.2%), slash & burn (4.45%), animal farming (1.15%), conflicts (0.66%), incidents (0.33%), illegal logging (0.18%) and 20.07% of other causes (Suriyawong et al., 2023) or alternatively 75.21% for non-timber forest products, hunting (7.76%), agricultural clearing (4.04%) and 12.99% for other reasons (Department of Forestry, Outapa & Ivanovitch, 2019).

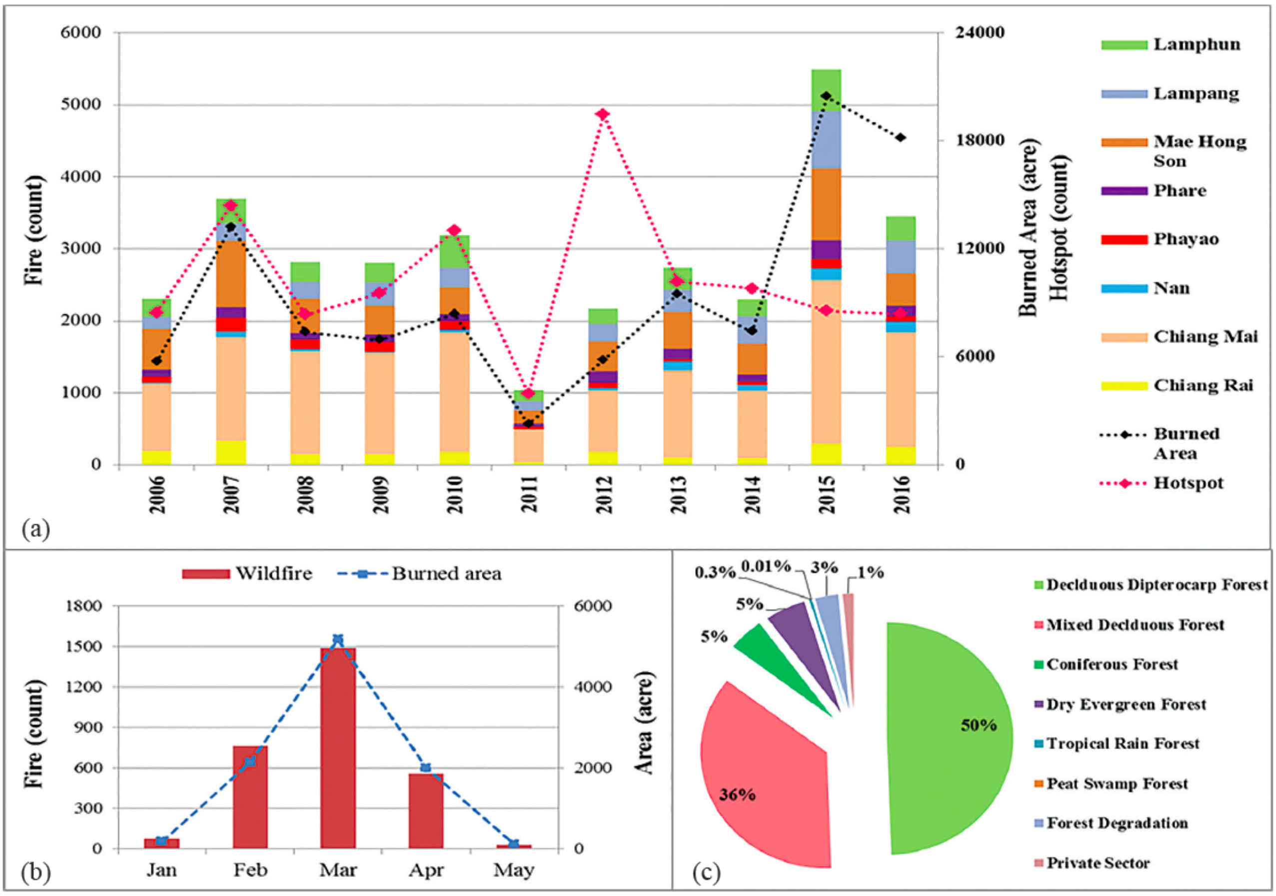

Figure 6.6. (a) Yearly variations of wildfire frequency based on burned area, number of fires in northern provinces and number of hotspots. (b) Monthly variation of wildfire frequency and burned area. (c) Proportion of different type of burned areas (Janta et al., 2020).

Overall, these successive surveys show that the collection of non-timber forest products (plants, mushrooms and hunting) represents 50 to 75% of all reasons to start fires in these forests. The most well-known forest products is a group of mushrooms call earthstars as it is believed that forest burning enhance the fruiting of *Astraeus sp.* (see section 8.2.). Other edible plants such as star gooseberries (*Sauropus androgynus*) and phak waan paa (*Melientha suavis*) are commonly harvested (Kamthonklat et al., 2021). Other plants where fires are of some uses are the harvest of thorny bamboo (*Bambusa arundinaceae*) and *Vietnamosasa pusilla;* promoting the germination of teak trees (*Tectona grandis*), managing the growth of tiger grass (*Thysanolaena maxima*) to produce brooms and production of Cogon grass (*Imparata cylindrica*) used for thatching roofs. Among animals hunted following forest fires are pigs (*Sus scrofa*), bark deers (*Muntiacus muntjak*), Bengal monitors (*Varanus bengalensis*) and a variety of wild fowls. Forest fires are also made for land preparation, grass for livestock and clearing where young shoots and grasses are used as fodder for domestic animals (*; Makarabhirom et al., 2002; Rakyutidharm, 2002).

6.3. Agricultural Fires

Agricultural fires include the burning of farming residues, clearing of cultivated fields and some pre-harvest crop preparation (i.e. sugarcane) and is a very common practice that can cover up to 50% of all crops (Wiriya et al., 2015). There are various poorly substantiated claims over the role of agricultural fires in the Upper Northern Thailand haze season, often inferred from comparisons with Central and North-East Thailand (*). Among them is its identification as the main source of particulate matter (Sirimongkonlertkun, 2014; Pasukphun, 2018) or that March haze is due to land preparation in highlands for corn planting ((Sirimongkonlertkun, 2018b). Some of these claims are in strong contrast with all other published materials on this subject.

While the overall situation regarding haze in northern Thailand can be considered in a single approach, the investigation of sources and particularly the role of agriculture requires to differentiate Northern Thailand from other regions and different provinces & basins within Northern Thailand as agricultural practices and the importance of agriculture in land use vary considerably.

Although agricultural burning can occur at any time of the year, rice burning itself is identified as a large source of particulate matter in December-January. 60% of rice residue burning occur during that time compared to only 3% in the February-April period (Phairuang et al., 2016). It is followed by a second harvest and burning period in April-May and eventually June, representing another 30% (Kim Oanh & Leelasakultum, 2011; Cheewaphongphan & Garivait, 2013) (Fig.6.7). Overall, the drop in rice burning residue at the peak of the haze season (when PM > 60 $\mu g/m^3$) is in agreement with projections that ~95% of haze is produced by forest fires during that period (Phairuang et al., 2016). However, there are considerable variations over the region and while it is established that air pollution in western provinces in the upper north is mostly controlled by forest and grassland fires, Nan province has modeling showing that 60% of particulate matter during heavy haze (67% of hotspots) is associated with agricultural land while less than 20% are linked to forest burning (Kamthonklat et al., 2021). In Chiang Rai province, agricultural burning is also predominant over forest burning and maize residue has been considered as one of the most significant source of air pollution during haze season (PCD, 2016; Sirithian et al., 2017).

Comparatively to the rest of Thailand, rice burning is not an important source of aerosols in the North. It is estimated that around 6 to 11% of total rice straw produced is actually burned and the rest recycled or left in the field (Wiriya et al., 2015; Junpen et al., 2018). This data contrasts with other studies where 47% of rice farmers burn their residue in the field (Cheewaphongphan & Garivait, 2013). Other parameters to consider is the potential for rice residue to produce pollution due to climatic conditions, agricultural practices and spatial heterogeneity. The combustion factor is lower in the North, producing more particulate matter due to incomplete combustion compared to other regions (Junpen et al., 2018) despite having a lower moisture content (41-42%) than other regions (58-85%). Post-fire analysis of burned residue shows that only 15 wt.% is calcined (Cheewaphongphan & Garivait, 2013). Contract farming also has an indirect effect on combustion efficiency as the pace imposed by this type of agriculture push producers to quickly prepare their field for the next crop, leading to less than ideal burning conditions for agricultural waste products (Pongpiachan et al., 2013; Pongpiachan & Paowa, 2015). Finally, wide variations also exist in the distribution of rice fields in Northern Thailand. In terms of aerosol production, it is measured that Uttaradit & Chiang Rai provinces alone produce more than ¾ of rice residue air pollution in Northern Thailand (Fig.6.7.).

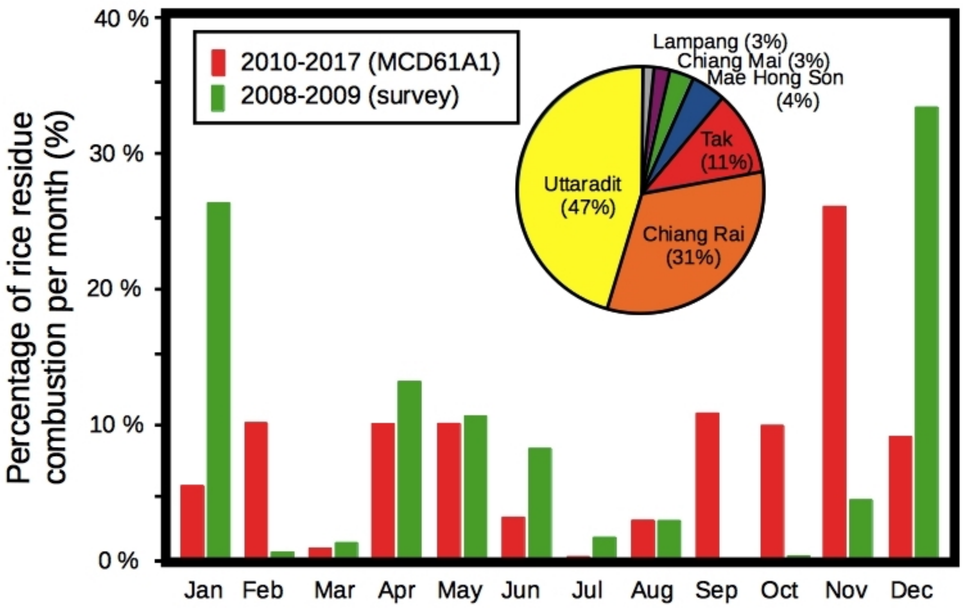

Figure 6.7. Percentage of rice residue burned per month in Northern Thailand during the 2010-2017 period based on land use and hotpsot counts and 2008-2009 based on land and farmers survey. The pie chart represents the mass of rice residues burned in the 9 northern provinces with Uttaradit & Chiang Rai representing more than ¾ of rice-produced pollution (modified from Cheewapongpan & Garivait, 2013; Junpen et al., 2018). Discrepancies between satellite data and land surveys could be related to the heterogeneous distribution and agricultural practices of rice crops in the north.

Corn is another commonly mentioned crop for its role in air pollution. On average, 40% of maize residue in Chiang Mai are burned (25 to 75% depending on regions, Arunrat et al., 2018) but its relatively low surface area makes it a minor emission source. Carbon-nitrogen isotopic studies have also shown the dominance of C3-plants in biomass burning and C4-plants (i.e. corn) is at best a minor component (Kawichai et al., 2022) (Fig. 4.9). However, the significance of corn can be different in other provinces such as Chiang Rai where agriculture and maize crops are more common (*).

Sugarcane burning is a pre-harvest process with a high emission factor that occur during the haze episode. However, while it is a very significant source of pollution in Isaan and the central plains, the production of sugarcane in northern provinces is limited to the southern fringe with small fields in Tak, Phrae and Uttaradit provinces (Pornprakun et al., 2019; Jarumaneeroj & Akkerman, 2021; Pongpiachan et al., 2022) and has an insignificant impact on the air pollution of most of Northern Thailand (*).

6.3.1. Causes of agricultural fires

All kinds of crops are subject to burning before or after harvesting. It includes rice, sugarcane, cassava, corn, soybean and potatoes (Phairuang, 2016). Open burning is a very common crop management in Thailand, Myanmar, China, India, etc. (Junpen et al., 2018), practiced for its economical benefits, rapidity of field clearing, absence of alternatives, alleged soil improvements, etc.

Rice straw and corn burning to clear fields is done a few weeks after harvesting, often in the early morning or in the afternoon, to facilitate a full burn in suitable meteorological conditions (wind & temperature) (Arunrat et al., 2018). In the highlands, some grass burning also occurs in March to prepare the land for corn planting (º, Sirimongkonlertkun, 2018b) as part of the slash-and-burn process of Swidden cultivations (fire-fallow cultivation method). It consists of cutting trees and plants and let it dry and burn it before the start of the rainy season to then use the cleared land for a few years of cultivation before recovery (Wanwongwatana, 2020).

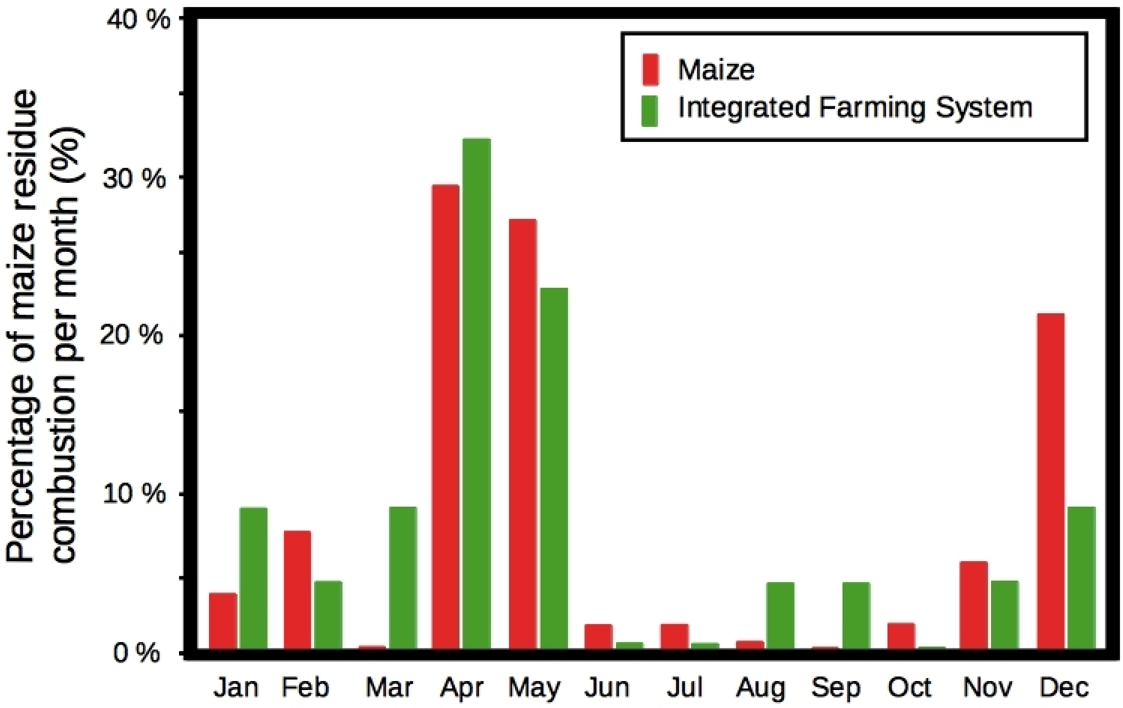

Figure 6.8. Percentage of maize residue burned per month Mae Chaem, Chiang Mai province following single crop system and basic integrated farming systems (modified from Arunrat et al., 2018)

The reasons for burning fields is to facilitate tilling and tillage efficiency and controlling insects, diseases, weeds and animals (Arunrat et al., 2018; Suriyawong et al., 2023). Open burning also eliminates a large part of residues that would be more costly to be mechanically removed (Pasukphun, 2018; Narita et al., 2019; Wangwongwatana, 2021) and prepares for the next crop cycle. It is also believed to provide higher yields and in the case of sugarcane, it's a pre-harvest procedure to remove sharp leaves from canes and accelerate harvesting (Wangwongwatana, 2021). Studies on open-burning have shown that alternatives such as soil incorporation of rice straw are conducive of crop diseases (Hrynchuk, 1998) and affects short-term yield due to nitrogen immobilization (Buresh & Sayre, 2007) supporting some claims of the benefits of open-burning. Finally, the booming of contract farming in the last few decades to facilitate market exchange (Sriboonchitta & Wiboonpoongse, 2008) push farmers to have short rotation between harvesting and cultivation and open-burning imposes itself as an adequate and cheap solution to prepare the land (Chiaranakun, 2017; Junpen et al., 2018).

However, next to some uncontested positive aspects of open-burning, it has been demonstrated that the loss of nutrient (OC, N, P, K) through burning directly affects soil fertility, leading to a higher need of fertilizers. The loss of active beneficial soil micro-organisms and the general biodiversity along with a degraded soil structure through hardening and compacting and decomposition of humus and organic matter leaves a more acidic soil and also lead to lower crop yields. The risk of fire spreading to other fields, forests, sensitive ecosystems and infrastructure is also not negligible as is the increased risk of soil erosion due to lack of vegetation coverage, poor soil aggregate stability (Arunrat et al., 2018; Wanwongwatana, 2020) and contribution to air pollution and global warming.

6.4. Industry

There are no large industrial complexes in Northern Thailand. Most factories in Chiang Mai (the largest urban centre) are located in Amphoe Muang, San Kamphaeng and Saraphi (in 2009; more recently, Lamphun would have to be considered*) with 2126 units recorded, among them 115 are non-metal (ceramic, concrete, pottery), 88 are metal producing and 22 are chemical (Pengchai et al., 2009). Their number and size is not considered a significant source of particulate matter or specific chemicals such as PAHs or PCDDs. However, during the haze season, energy production through gas, coke and charcoal burning can locally produce large amount of gases and aerosols, including PAH (Pengchai et al., 2009). Lampang has some industry such as tobacco curing, ceramic manufacturing and the lignite-fired power plant of Mae Moh that are potentially minor source of particulate matter during haze season (Uttajug et al., 2021) (Fig.6.9).

No relationship has been found between air pollution and busy commercial or industrial areas in the north (Tippayawong et al., 2006) but garbage burning, which is more widespread, can locally be a source of smoke with a considerable concentration of toxic components (*, Charoanmuang, 2007; Bach & Sirimongkalertkal, 2011).

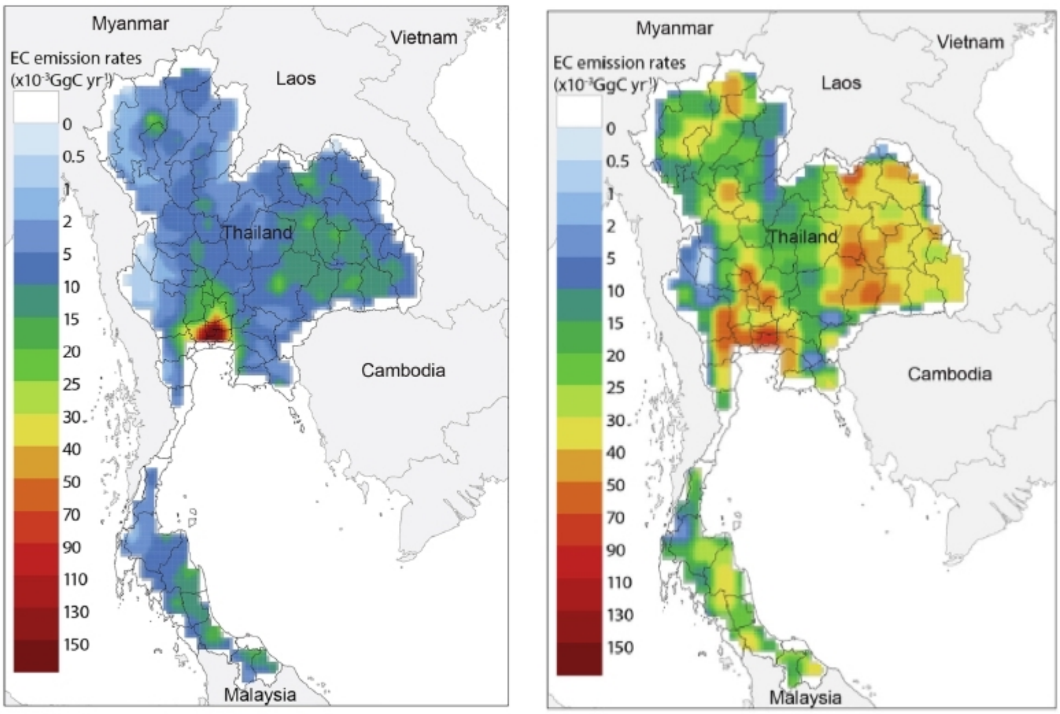

Figure 6.9. Regional map of Thailand for industrial (left) and traffic (right) emission rates of elemental carbon (modified fromXing et al., 2020).

6.5 Traffic

In large urban centres such as Chiang Mai, the presence of traffic can have a considerable influence on air pollution and its composition. Early studies did not identify a relationship between coarse particulate matter and traffic despite more than 1 million registered motorcycle in Chiang Mai at the time (Tippayawong et al., 2006). Since then, the use of private vehicles has dramatically increased in Thailand, including Chiang Mai (Pongthanaisawan & Sorapipatana, 2010; Pongpiachan & Paowa, 2015).

Carbon-14 measurements are arguably the most robust proxy to estimate vehicle-derived carbon in air pollution. The estimation was 41.5±4.4% in urban areas when biomass burning contributions are low (Kawichai et al., 2020b; Song et al., 2022a) but becomes of low significance during heavy haze episodes (Fig 4.8.).

PM0.1 is an exception as it is dominated by traffic in the wet season and maintains a relatively high background through the haze period despite the substantial contribution of forest fires (Phairuang, 2016). PM0.1 levels are mostly associated with diesel exhaust (Phairuang et al., 2019).

PAH is also a component of air pollution where traffic has considerable influence and is the main contributor outside the haze season. In the burning season, traffic still represent 20 to 25% of PAH emission (Pengchai et al., 2009; Song et al., 2022a) although some estimation are up to 55.2% (Pongpiachan et al., 2017). Hopanes & steranes, which are similar groups of molecules are also used as tracers for motor vehicle exhausts due to the specific lubricant oil used in diesel and gasoline engine. Their presence allows to estimate the contribution of engine exhausts to air pollution (Sricharoenvech et al., 2020).

6.6. Transboundary

Transboundary influence on air pollution is known all over the world for a long time as aerosols are produced in adjacent countries (sometimes continents) and get carried hundreds of kms away by prevailing winds. Such situation is particularly well known in South East Asia and has reached a climax in 1997 Indonesian forest fires creating heavy pollution over the Malay peninsula. In Northern Thailand however, the situation, precise identification of sources and quantitative contributions have been unclear for a long time.

The general seasonal atmospheric pattern in the region displays two main aeolian channels associated with the Asian winter monsoon. A circulation from Taiwan and Eastern China towards Laos and Northern Thailand is present as a continental, diurnal, low level (<500m) weak winds and has an impact to the eastern part of Northern Thailand. The other current is dominantly North-West, from India and Myanmar and can travel at higher altitudes (~3000m) (Amnuaylojaroen et al., 2020).

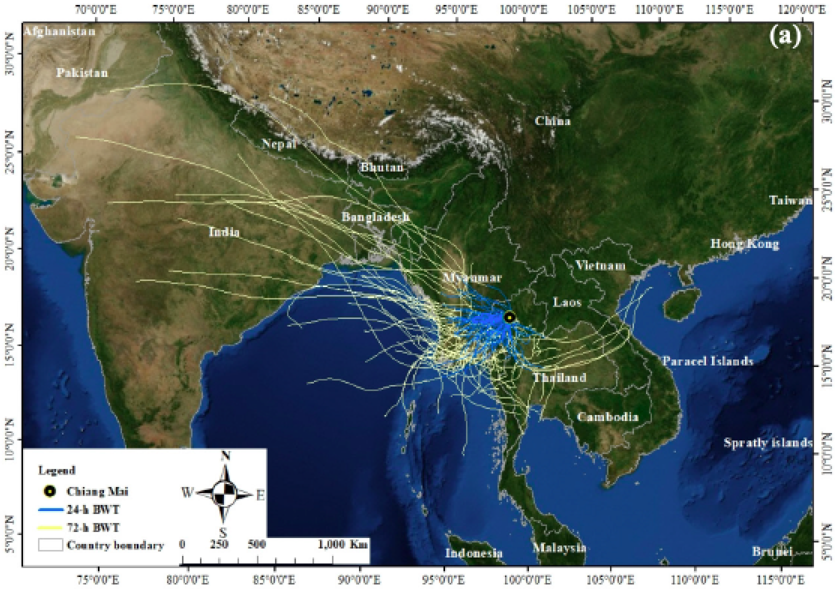

Figure 6.10. Dominant transboundary wind backward trajectories from Chiang Mai, in the western part of Northern Thailand at an altitude of 1500m AGL during the 2018 haze season. Trajectories in blue are 24h displacement while yellow are 72h of displacement. Contribution from eastern China is minimal in Chiang Mai (Choomanivong et al., 2019)

6.6.1. Backward trajectory models

The first referenced work on reverse atmospheric flow applied to air pollution is a ECMWF atmospheric model showing the influence of the SW monsoon during the dry season, that would indeed bring air from India and be a potential source of pollution (Pochanart et al., 2001). Since then, the HYSPLIT atmospheric model (Draxler & Rolph, 2003) has tools that can provide backward trajectories for pollutants found in Northern Thailand and has been used and sometimes abused to make various claims on the origin of air pollution in the region (*).

Based on this model, the average daily travel of an aerosol is 318±106 km and 1125±649 km in 3 days from Chiang Mai at 1500m high. At a ground (10m) altitude, daily distances are found to be 145±79 or 545±356 km (3 days) (Choommanivong et al., 2019). These travel distances, albeit quite large, are still considerably less than what can be found for Bangkok (60% smaller) or Kohn Kaen (52% smaller) (Punsompong et al., 2021).

A very large number of publications show, with variable contribution (30 to 70%), that air masses arriving in Chiang Mai from all altitudes (10 to 3000 m) comes from the South-West and ultimately from Mae Hong Son province (Kim Oanh & Leelasakultum, 2011; Sirithian & Thanatrakolsri, 2022) and Myanmar (Kim Oanh & Leelasakultum, 2011; Pani et al., 2016 ; Phairuang et al., 2016; Kiatwatannacharoen et al., 2017 ; Sirimongkonlertkun, 2018a ; Thepnuan et al., 2019; Thepnuan & Chantara, 2020; Chansuebrsri et al., 2021, 2022; Niampradit et al., 2022; Song et al., 2022a; Sirithian & Thanatrakolsri, 2022) during the peak of haze season. The common interpretation is that these winds passed through coastal Myanmar and various border states (Shan, Kayah, etc.) and Mae Hong Son; all areas with considerable biomass burning, producing aerosols that would be carried to Northern Thailand.

Some backward trajectory models also give some significant contributions from the NW (Khamkaew et al., 2017) and from the Andaman sea (Kim Oanh & Leelasakultum, 2011 ; Pani et al., 2016; Khamkaew et al., 2017; Pani et al., 2019 ; Thepnuan & Chantara, 2020) while the higher altitude transport (>2000m) could also be considered as it would bring air from India, Bangladesh or even Arabia as potential contributors with 3 to 5 days of travel time (Kim Oanh & Leelasakultum, 2011; Pani et al., 2016; Khamkaew et al., 2017; Pani et al., 2019).

Analysis of time-dependent pollutants and extensive dataset also provide some indication that a significant part (11 to 90%) of 1-2 days air masses are local (Chantara et al., 2012; Khankaew et al., 2016; Thepnuan & Chantara, 2020; Punsompong et al., 2021) and extensive rapid transborder movement is not a constant throughout the burning season (*).

6.6.2. Temporal variations

In itself, all these robotically applied models have little direct use other than reaching a strong consensus on the patterns of transboundary haze. However, intra- and inter-annual variations carry some interesting patterns capable of explaining some features of haze distribution over Northern Thailand. Air flow in March is clearly defined as coming from NW to SW direction with a minor contribution from Central Thailand and the Andaman Sea, while wind patterns in April are similar or event stronger towards the SW. Early haze season however, has random sources in Chiang Mai with a dominant direction from the south (Kawichai et al., 2020a) (Fig. 6.11). This is related to the strengthening of the SW monsoon during the dry season, giving westerly winds passing through coastal areas and regions of high biomass burning of Southern and Western Myanmar (Punsompong & Chantara, 2018; Othman et al., 2022). By May, the winds are defined enough that 48 to 61% comes from the Andaman Sea (Kawichai et al., 2020a).

Inter-annualy, variations are equally important. While the situation described above represents mostly neutral ENSO and El Niño events, during La Niña years, backward trajectories tend to provide low probability sources with random patterns and in general, shorter transport ability from transborder sources (Wiriya et al., 2013; Punsompong & Chantara, 2018; Yabueng et al., 2020) (Fig. 5.2).

6.6.3. Spatial variations

Another factor worth considering when detailed atmospheric patterns are studied is the geographical position of a station within Northern Thailand. The situation in Chiang Mai city and Doi Ang Khang, a major topographic prominence at the Thai-Burmese border is dependent on some parameters stated above. In Doi Ang Khang, due to its proximity to Myanmar, it is estimated that 23% of sources are local (Khamkaew et al., 2016) with a very large contribution from coastal Burma and eastern Myanmar as well as India but also a significant but minor source from Central Thailand, Isaan and Cambodia (Pani et al., 2019).

In Chiang Rai, although the burning season shows an important contribution from Myanmar and eastern India, the early haze episode in January-February also has significant contribution from Northern Laos, Vietnam and eventually Southern China (Sirimongkonlertkun 2018b; Kayee et al., 2020; Duc Luong et al., 2022; Othman et al., 2022).

By comparison, elsewhere in Thailand the situation is different and in Central Thailand, 55% of air masses originate directly from the South and SE and 45% from Isaan; In Bangkok, during the Northern Thailand burning season 55% of air masses come from the Andaman Sea, 19% from the gulf of Thailand and 26% from South China Sea while Vietnam, Cambodia and southern Laos can also contributes at other time of the year. In the Isaan region, 62% of air masses originate from the NE (Kayee et al., 2020; Punsompong et al., 2021).

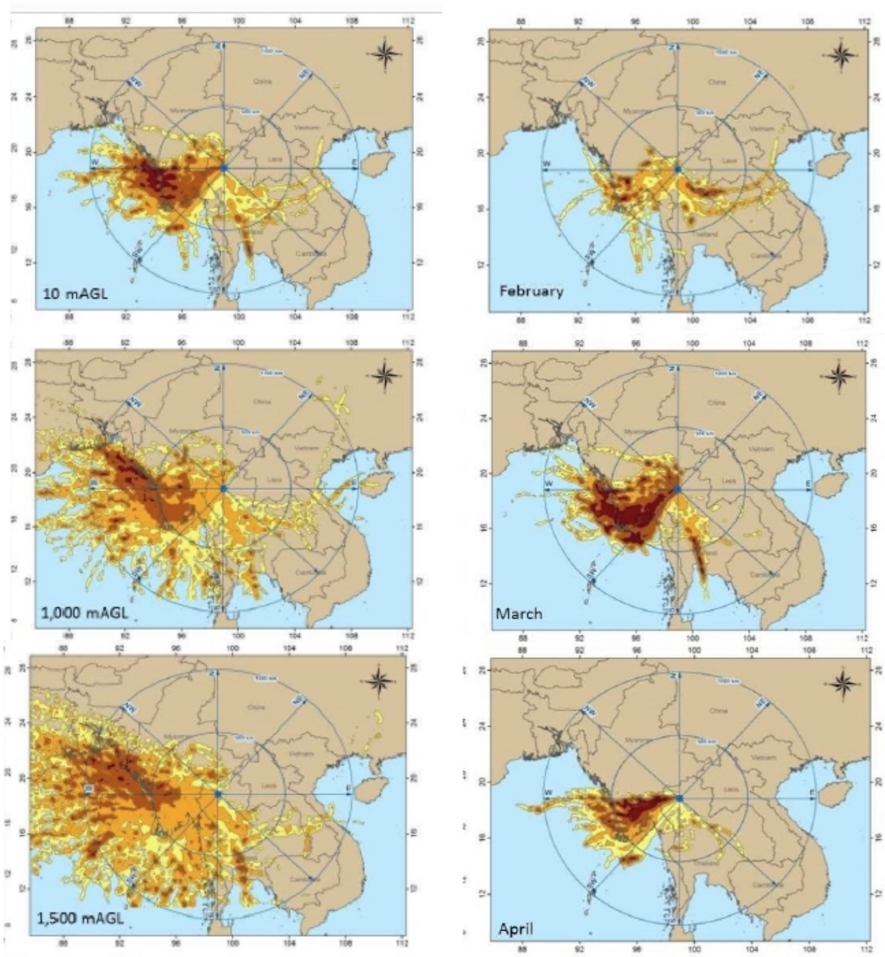

Figure 6.11. Hysplit backward trajectory models and probability maps for Chiang Mai at different altitude (10, 1000 and 1500 m AGL) and through the burning season (February, March, April) between 2010 and 2015 (modified from Punsompong & Chantara, 2018).

6.6.4. Transborder emission source

The actual proportion of transborder aerosols into the air pollution over Northern Thailand will require further research. It has been demonstrated that a significant part of 1-2 days old air masses are of local provenance (Chantara et al., 2012; Khankaew et al., 2016; Thepnuan & Chantara, 2020; Punsompong et al., 2021) but variations are important depending on weather and local conditions. The absolute concentration of aerosols as transborder pollutants dominate the background pollution during the haze season, with an estimated 11% linked to local sources. During peak haze events when hazardous AQI levels are reached, these local sources can represent 39 to 90% of air pollution (Chansuebsri et al., 2021a; Punsompong et al., 2021). However, as these interpretations are based on the estimation of background levels and that so far, little has been published on chemical constraints to these long-range provenance models, uncertainty remains important (*).

Based on models, satellites and ground monitoring and some properties of air pollution, the average proportion of local forest fires contributing to pollution is 46% (while 54% are transborder), 39% of local agricultural burning and 19% of grassland, leaving 61% of agricultural residue and 81% of grassland burning aerosols originating from longer distances (Punsompong et al., 2021). Similarly, weakly constrained PCSF models give a range of 25 to 45% of PM10 finding its source locally (Punsompong & Chantara, 2018). Emission inventories for Myanmar and Laos are poorly identified making quantified transboundary contributions difficult to calculate (Phairuang et al., 2019). There are some data that provide some constraints such as nitrate levels finding an important source in India and Myanmar while sulfate concentrations are more likely to be locally found within Thailand from anthropogenic emissions but overall, more research is required to shed some light on this subject and provide fully quantitative estimations (*, Pani et al., 2019).

6.6.5. Transborder local situation

Despite the lack of precise quantification of the contribution of Myanmar to the pollution in Northern Thailand, there are some parameters that show that if anything, the situation is worse over the border. On average, the number hotspots in Myanmar is 3x higher than Northern Thailand (Bach & Sirimongkalertkal, 2011; Punsompong & Chantara, 2018; Sirimongkonlertkun, 2018a). While Thailand has a hotspot density of 0.021 fires/km^2 (up to 0.06 in rural areas), Laos is 0.075 and Myanmar 0.063 (Pimonsree & Vongruang, 2018) and the regional contribution of Laos and Myanmar in hotspots is above 66% in March-April compared to Thailand 11 to 20% (Amnuaylojaroen et al., 2020) (Fig.6.12). Earlier in the haze season, Cambodia can also be a significant hotspot producer while Laos tend to dominate at the end of the dry season (Bach & Sirimongkalertkal, 2011).

Myanmar has some very large forested area and despite showing a decline in the number of fires over two decades, 44.7% of fires are occurring in forested area with deciduous forest the most affected. 65% of these forest fires are persistent hotspots that will appear every year with another 15% regular hotspots, mostly in SE Shan State, Kayah and Northern Kayin state. In states adjacent to Thailand, the percentage of burnt forest ranges from 8 to 58% with Shan and Kachin states the two regions with serious fires (Myint, 2018; Unnikrishnan & Reddy, 2020). JAXA land use map shows that deforestation is relatively intense in Eastern Myanmar while it is very mild in Northern Thailand (Trisurat et al., 2010). Around 46.54% of the area is covered by forest (2020) and an estimated decrease of 19% occurred between 1990 and 2010 (Yadav et al., 2017), another decrease of 7.29% between 2008 and 2016 and 13.8% is expected by 2030. Deforestation occurs around population centers and roads to create new rubber and palm plantations, mines, hydroelectric projects and charcoal production. In flat lands, forest is mostly lost to croplands such as rice and maize (Yang et al., 2019; Sharma et al., 2020).

Burning practices are similar to Thailand and is done traditionally for hunting and slash & burn agricultural methods but large scale agricultural development is seemingly an important fire risk now. Not much is known about the enforcement of protected areas in Myanmar but satellite data show that fire have twice less occurrence in those forests (Biswas et al., 2015).

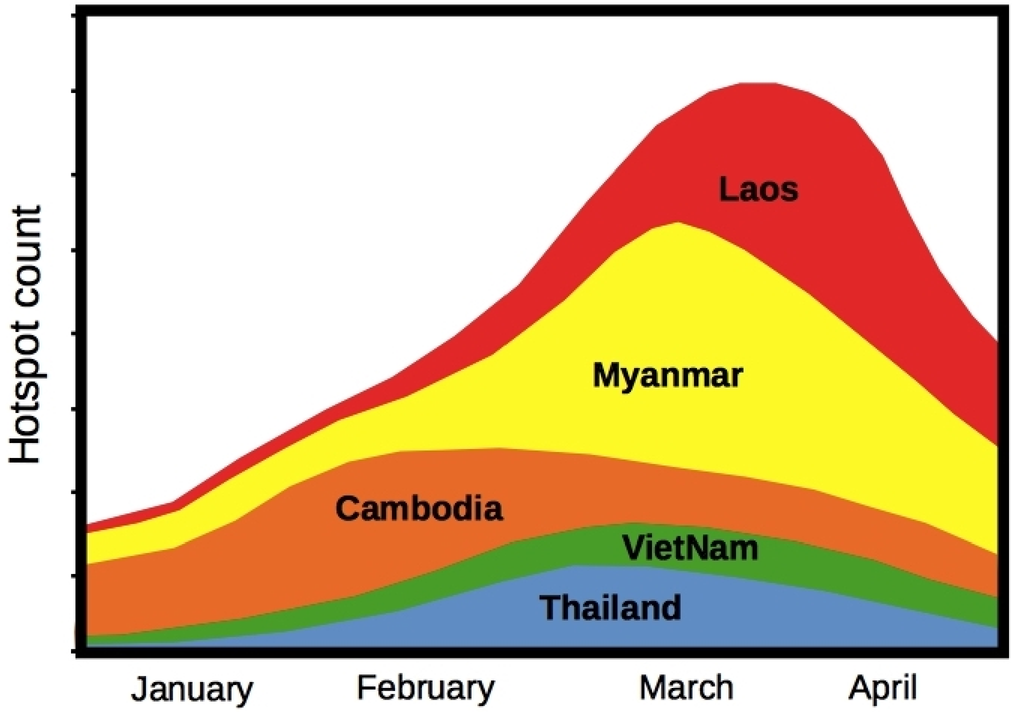

Figure 6.12. Qualitative time distribution of hotspot counts based on data from MODIS and VIIRS for 2016 and 2018 (Choomanivong et al., 2019; Amnuaylojaroen et al., 2020).

6.7 Comparison with other regions

Globally, continental South-East Asia burning season is on the same emission level than burning seasons in Australia or boreal North America; slightly less than Southern South America and Equatorial Asia and a lot less (3 to 5x) than central and southern Africa burning seasons (Yadav et al., 2017). In terms of ground pollution however, these other regions do not have the meteorological conditions that allow the accumulation of aerosols and haze is not a major concern. In the same context of global comparison, Northern Thailand does not stand out as a particularly heavily polluted region when annual averages of PM2.5 concentrations are considered and areas such as the Ganges valley, North China plains, Tarim basin, Saharan and sub-saharan Africa and the Arabic peninsula all suffer of higher annual averages. The specific characteristic of Northern Thailand and surrounding regions is the high level of pollution systematically reached every year for a couple of months.

Regionally, there are major variations in sources of pollution between Asian countries with intense industrial and power generation outputs in India and China while biomass burning is a dominant source in less developed countries such as Myanmar, Laos and Cambodia. Over Thailand, the national average is 40.2% of air pollution from biomass burning, 31.5% of industrial origin, 17.1% from traffic emissions and 10.9% associated with energy production (Vongmahadlek et al., 2009), indicating that sources varies wildly outside the northern region. Transborder pollution is also identified as an important source in different regions of Thailand (Surussavadee & Noosok, 2020; Reddington et al., 2021; Marks & Miller, 2021).

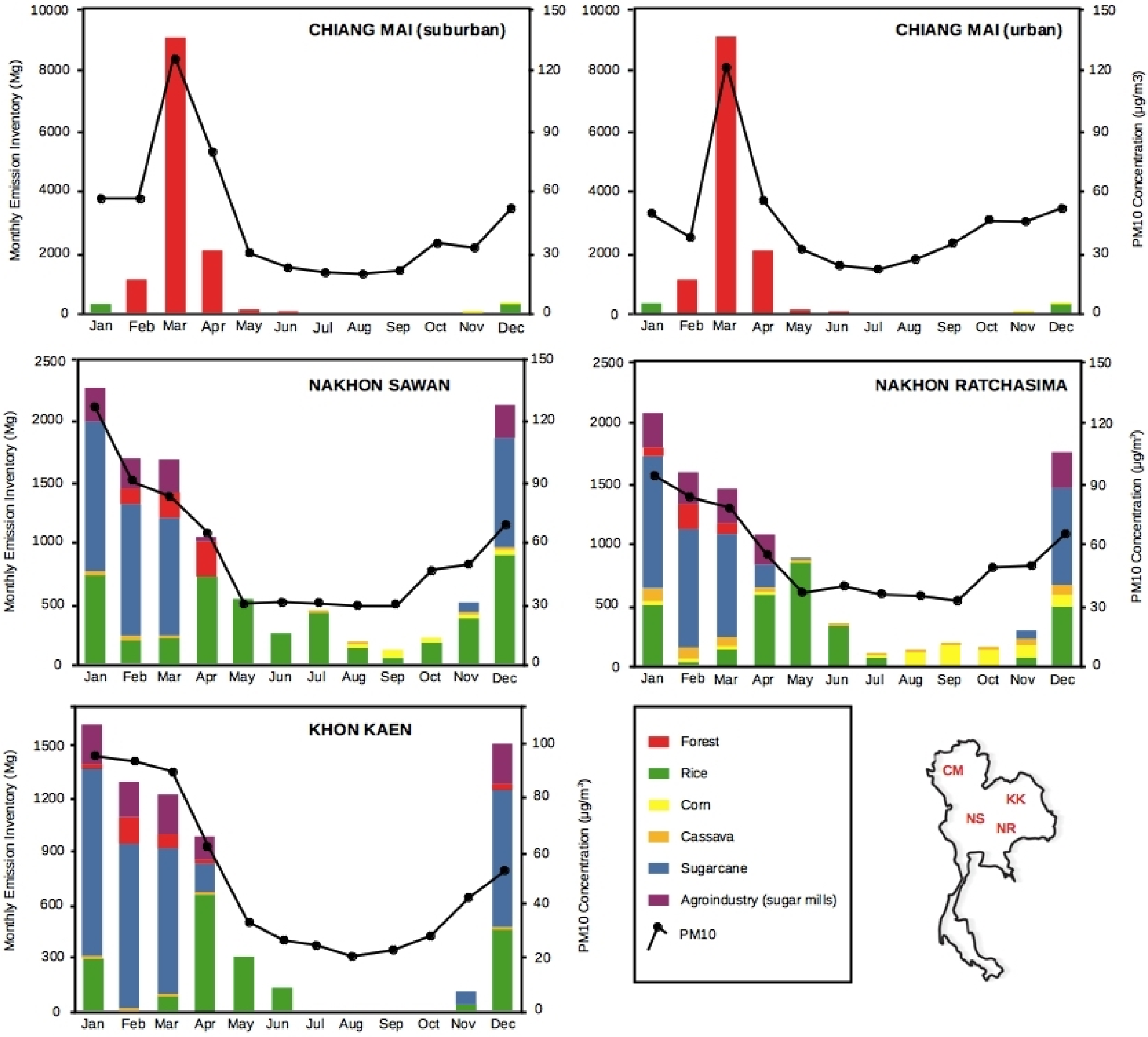

Figure 6.13. Monthly average emission inventory of various crops, forest and agroindustry in Chiang Mai and major towns in Central and northeastern plains of Thailand as well as PM10 average values for 2014 (modified from Phairuang et al., 2016).

The situation in Central and North-East provinces is dominated by biomass burning of rice residues which represent a significant part of air pollution all year long and sugarcane burning during the smoky season (Phairuang et al., 2016). In those regions, annual contributions are 51% from rice major crop post-harvest and 20% from the second rice post-harvest; 21% from sugarcane pre-harvest, 6% from forest, 1% from cassava and 1% from other crops (corn, soybean, potato) (Phairuang, 2021; Suriyawong et al. 2023). In some areas, agro-industrial burning, used as a source of energy, can also be associated with significant particulate emissions (Chomanee et al., 2018; Phairuang et al., 2019) (Fig. 6.13).

Different meteorological conditions and agricultural practices also provide different timing for potential haze seasons. While in the North, forest burning, crop residue and transboundary sources are an issue mostly from January to April, in Isaan, crop burning and minor amounts of transboundary aerosols occurs in January-March while in some areas of the central plains, November to February is a time when crop burning occurs as well as accumulations of pollutants from transports and industry. Southern Thailand has a more equatorial climate influence and peat burning, agro-industry and transboundary pollutants are an issue mostly between June and October (Vongmahadlek et al., 2009; Suriyawong et al., 2023).

The Bangkok Metropolitan Region has its own air pollution characteristics inherent to its status as a primate megacity. With its size one order of magnitude larger than Chiang Mai, urban sources such as traffic, industries, biomass burning and secondary pollutants from gaseous emissions are very significant (Phairuang et al. 2019; Narita et al., 2019; Wang et al., 2020). In consequence, there is no specific haze season in Bangkok but background levels constantly remain at a level that can be concerning. In addition, the dominance of traffic, combustion of fossil fuels, urban sources and heavy industrial contributions produce an air pollution with higher amounts in toxic compounds that what is commonly found in Northern Thailand.

7. <u>Health effects of air pollution</u>

One of the most concerning aspect of air pollution is its effect on health. In the northern region, it is estimated that air pollution causes more than 50000 premature deaths annually (Ruchiraset & Tantraskarnapa, 2018; 2020; Muller et al., 2020, 2021; Reddington et al., 2021) with modeling of overall mortality suggesting that it reduces life expectancy by 3 to 4 years in Northern Thailand (Attavanich, 2019). Economically, in Thailand alone, it is estimated that 2 to 3 billion baht are spent annually on healthcare costs and prevention such as masks and purifiers (Chairattanawan & Patthirasinsiri, 2020) although other less conservative figures place the impact of air pollution by 2030 to be 2% of the Thai GDP, amounting to 500 billion baht nationwide (Kiesewetter et al., 2023).

A very large number of scientific publications exist on the health effects of air pollution, including research on particulate matter (PM) which is the type of pollution seen in Northern Thailand. However, most studies are focused on urban pollution (traffic, industrial & other urban sources), which present similarities but also a lot of differences compared to biomass burning, the main source of pollution seen in Northern Thailand. The differences lies in the size distribution of particulate matter, heavy metal contents and proportions, the concentration of organic carcinogenic components, etc. In order to avoid possibly misguided conclusions based on analogy with urban pollution, even the earliest studies on pollution in Chiang Mai and Northern Thailand (Matsushita et al., 1989) were already focused on assessing local characteristics of air pollution rather than assuming an equivalence with urban pollution to estimate direct health impact. Since then, Chiang Mai has been a reference site for urban activities where biomass burning pollution is dominant and serves as a comparison with other urban pollution studies.

Despite two decades of research, it remains unclear if the very high concentration of particulate matter in Chiang Mai and the region is more, less, or roughly similarly toxic than the average urban pollution of large Asian cities (Johnston et al., 2019; Muller et al., 2020). It has been suggested that biomass burning-produced aerosols have higher concentration of reactive oxygen species in particulate matter, therefore increasing the oxidative stress on the organism (Pavagadhi et al., 2013; Adam et al., 2021). The formation of secondary organic carbonaceous aerosols is enhanced by a high relative humidity, creating conditions that would be worse for health (Song et al., 2022a). However, humidity is not particularly higher in the North and secondary aerosols formed in aged smoke, known to be more harmful than primary emissions, are relatively less present in biomass burning. As a general observation, urban pollution has higher levels of heavy metals and carcinogenic organic substances than biomass burning and induces a greater inflammatory response than rural-sourced haze for similar level of particulate matter (Maciaszek et al., 2023). Finally, detailed studies on hospitalization often show a lag response following PM level variations, which could indicate that biomass burning is less harmful than traffic and industrial sources (Muller et al., 2020).

7.1. Causative agents

Particulate matter toxicity arises from two modes of actions, infiltrating the deep respiratory system and circulatory system leading to potential alveolar obstruction and the harmful effect of adsorbed and absorbed toxic substances on the surface of particulate matter. These processes lead to health effects through stimulation of oxidative stress, causing inflammation and genotoxicity (Johnston et al., 2019).

7.1.1. Carbonaceous particulate matter

Particulate matter is theoretically mostly inert but act as a mild irritant in upper and deep respiratory airways through a series of reactions that are a result of defense mechanisms from the human body. In that context, particulate matter size distribution is a very important variable to consider as the dynamic properties of particulate matter change for different fractions, allowing deeper penetration but also because size is inversely proportional to the potential surface area of particulates. In theory, at same atmospheric concentration, finer particulate implies a larger surface available for the absorption of pollutants and a potential increase in toxicity (i.e. ultrafine carbon black is more cytotoxic than PM2.5 or undifferentiated diesel combustion products (Maciaszek et al., 2023)).

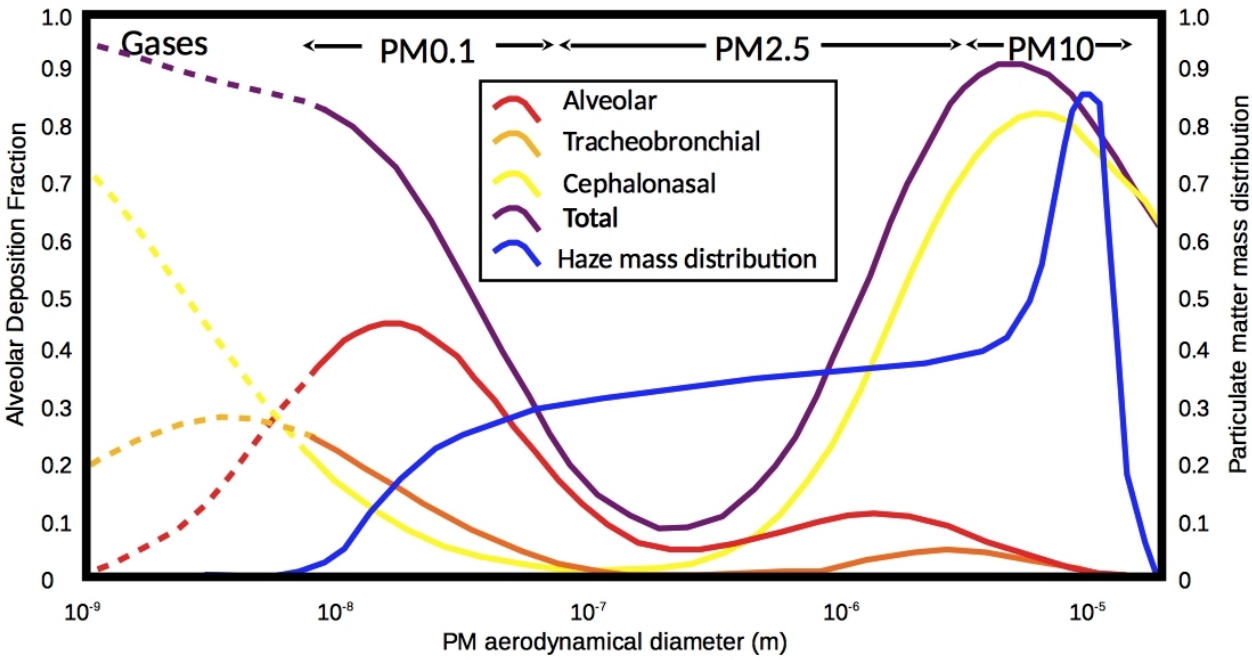

Figure 7.1. Modeled deposition curves from the International Commission on Radiological Protection with calculated total deposition, head/nose, tracheobronchial and alveolar regions with a comparison with the mass distribution of particulate in Northern Thailand haze (modified from Kodros et al., 2018).

Very coarse & Coarse Particulates (>PM10, PM10) are known to be eventually stopped in the naso-pharyngial and uppermost respiratory tract so that their impact on sensitive individuals is negligible (Pongpiachan et al., 2013). Their accumulation in upper respiratory airways increases the levels of proinflammatory cytokine, inducing a response from neutrophils and eosinophils, leading to an inflammatory response and the regulation of histamine receptors (Wu et al., 2018). This process causes allergic rhinitis and particulate contaminants are eventually removed through sneezing and coughing.

Fine Particulates (PM2.5) have a deeper penetration and their abundance in air pollution gives the highest deposition rate with the median value of mass fraction reaching the alveoli being around 4 µm (Connelly & Jackson, 2013; Othman et al., 2022). An estimation of the amount of PM2.5 inhaled over 25 years in Chiang Mai is estimated to be 1 to 3 g and twice higher in Mae Hong Song (º, Pongpiachan et al., 2013). This particulate fraction can eventually be removed from the tracheobronchial region through mucus adhesion and the motion of cilia (Finlayson-Pitts & Pitts, 1999). PM2.5 induces an antigen cell-mediated inflammatory response and induces oxidative stress. Since PM2.5 is cytotoxic to lung cells and alveolar macrophages, it can cause apoptosis and autophagy as well as an imbalance in T helper cells (Vinitketkumnuen et al., 2007; Wu et al., 2018).

Very fine particulate (PM1.0) can easily enter pulmonari alveoli (Schraufnagel, 2020) as their size escape mucociliary clearance and ingestion by alveolar macrophage scavenging (Phalen, 2009; Wu et al., 2018). As a consequence, their deposition is deep within the alveoli with a long residence time in an area where gas exchange occurs. The large surface area of these particulates bring adsorbed chemicals that can be transferred through the alveolar membrane into the blood circulation (Chomanee et al., 2020; Niampradit et al., 2022; Almeida-Silva et al., 2022).

Ultrafine particulate (PM0.1) below 100 nm are so small they can directly penetrate through the alveolar membrane into the blood circulation where they remain for several hours, causing eosinophilic inflammatory response and eventually, an ingestion by various cells (Wu et al., 2018; Phairuang et al., 2022a). There is no evidence that PM0.1 can cause acute health symptoms (Phairuang et al., 2022c) and their health impact remains unclear (Kwon et al., 2020; Schraufnagel, 2020; Sonwani et al., 2021) but the very large surface area associated with these ultrafines and the high potential to adsorb toxic substances and transfer them directly into the bloodstream (Phairuang et al., 2022b) might represent the fraction that cause the highest health risk (Kumar et al., 2013; Kwon et al., 2020; Phairuang et al., 2021b). While in the bloodstream, PM0.1 size also allows translocation into the central nervous system by crossing the blood-brain barrier and potentially causing brain damage (Cheng et al., 2016; Jew et al., 2019; Morris-Schaffer et al., 2019; Hahad et al., 2020; Potter et al., 2021; Sresawasd et al., 2021).

7.1.2. Adsorbed compounds

Although most of the carbonaceous matter can be considered as chemically inert towards the human body, it is not the case for a large number of trace amounts of chemicals present in the atmosphere and on the surface of particulate matter.

Polycyclic Aromatic Hydrocarbons (PAH) are among the most studied compounds in that category. Around 80% of PAH are carried by particulate matter, mostly the heavier fraction, while light mass PAH (2-3 rings) can be in gaseous phase. Many of the heavy mass PAH are carcinogenic. Once transferred in the alveola and bloodstream, they can penetrate cells and metabolites, causing alteration in the replication and transcription processes of DNA by creating covalent bonds with cellular macromolecules (Callen et al., 2014; Moran et al., 2019; Yabueng et al., 2020). In order to quickly assess the health impact of the numerous chemical species of PAH, a benzo[a]pyrene equivalent (BaPeq) is used (Chantara & Sangchan, 2009) so that a single concentration is representative of the carcinogenic potential of the whole PAH panel. Although PAH composition and concentration have been extensively studied in Chiang Mai pollution, their content per volume is 2 to 9x lower than Bangkok and similar to many European and Japanese cities (Pengchai et al. 2009; Chantara et al., 2009; Kawichai et al., 2020a; Thepnuan & Chantara, 2020; Choochuay et al., 2020). Nevertheless, PAH have been detected in the urine of rural schoolchildren in a mostly Karen inhabited zone of Chiang Mai province and shows relatively high levels (higher than Bangkok) suggesting that PAH concentration in human bodies could be related to lifestyle (Naksen et al., 2017) rather than air pollution. Other authors have however expressed their view that since a non negligible proportion of PAH exposure is non-dietary, it remains a health issue (Pongpiachan et al., 2015). The overall risk associated with PAH in air pollution is around 1/10000 of developing a cancer after 70 years of exposure (Thepnuan & Chantara, 2020).

Polychorinated-dibenzo-p-dioxins, more commonly shortened as dioxins or PCDD, have a wide range of toxicity applied to aryl hydrocarbon receptors. The health concern is related to their carcinogenic, developmental and immunotoxic properties and their stability and ability to bioaccumulate. However, in Chiang Mai, the concentration of PCDDs is considerably lower than large Asian cities such as Hanoi (6x higher; Hsien Chi et al., 2022) due to the lack of extensive industry but waste burning can locally remain a significant source.

Metals are a source of oxidative stress to the human body. Some heavy metals also have carcinogenic properties. Biomass burning does not release large amounts of metals compared to urban sources (traffic, industry) so Bangkok has systematically higher level of heavy metals than the thickest air pollution in Chiang Mai. However, although concentration in northern Thailand haze are relatively average compared to large cities, heavy metals are subject to bioaccumulation and can cause some damage to organs where they have a tendency to concentrate.

Endotoxins are bacterial products carried by particulate matter that can cause detrimental health effects. These have a minor impact and are more abundant outside the haze season (Maciaszek et al., 2023).

7.1.3. Gaseous components

With the exception of volatile organics compounds (VOC), which can be gaseous molecules, precipitates as secondary aerosols or adsorbed on the surface of particulate matter, other gases (O_3, SO_2, NO_2, NOx, CO, HCl,…) are not present in sufficient quantities in Northern Thailand to have a dramatic effect on health. Although concentration spikes do occur independently of the haze episode, these are short lived and rarely reach concentrations that would affect anyone other than the most sensitive individuals.

Some studies have identified acute symptoms related to ozone (º, Vajanapoom & Kooncumchu, 2019; Varapongpisan et al., 2023), NO_2 and SO_2 (º, Wiwatanadate & Liwsrisakun, 2011; Varapongpisan et al., 2023) and CO (º, Pongpiachan & Paowa, 2015) but their low levels and correlation with particulate matter levels and all chemicals associated with it makes the identification of specific health effects difficult and sometimes of doubtful significance (*).

7.2. General symptoms

Medical symptoms will depend on the level air pollution, the sensitivity of the individuals and eventually any pre-conditions or combination of factors that can result in different severity of symptoms. Among the common pre-conditions are children and the elderly who are more sensitive to health issues (Samet et al., 2000; Pope et al., 2002). For healthy individuals, at moderate to high level of pollution, the effect is often limited to allergic reactions with mild to very mild symptoms that include allergic rhinitis, congestion, sore throat, nose and eye discomfort, headache, more rarely skin reactions and when air pollution is high to very high, shortness of breath (Wu et al., 2018; Johnston et al., 2019; Prapamontol et al., 2023). Regular exposure to particulate matter also indirectly leads to aeroallergen sensitization, making individuals more prone to develop a histamine intolerance from other allergens (Sompornrattanaphan et al., 2020).

Historically, the Chiang Mai Public Health Office has shown that 42.7% of the population suffered of respiratory problems in 1999, up from 33% in 1994 (Sriyaraj et al., 2007). More recent assessments have observed a potential decrease in morbidity in the last few years (Chi Htwe et al., 2023) and have concluded that 33.1% of individuals report a respiratory symptom when the PM2.5 average value is 35 $\mu g/m^3$ (2 to 128 $\mu g/m^3$). These individuals described their symptoms as 14.2% of runny nose; 10.2% of nasal obstruction; 9.4% of cough; 7.9% of sputum production 7.1% of allergic rhinitis and 6.3% of breathlessness and an additional 15.7% of abnormal lung function reported (Ruchiwit et al., 2022). Another earlier study found that the 5 main symptoms were 34.8% of blocked nose, 33.7% of tiredness, 32.9% of body itch, 30.7% of burning & itchy eyes and 28.7% of running nose (Wiwatanadate, 2014). Finally, rhinitis and atopic dermatitis are reported as slightly higher in urban schools compared to rural locations due to higher pollution, with the allergic rhinitis symptoms peaking in October-January (º, Sriyaraj et al., 2008).

The constant exposure to smoke haze is also associated with mild psychological stress and cognitive impairment causing recurrent thinking about haze, irritability, insomnia and poor concentration (Ho et al., 2014). These psychosomatic symptoms may be attributed to changes in cerebral hemodynamics due to exposure to particulate matter (Tan et al., 2019).

Another issue from prolonged high PM levels is the health effect caused by the atmospheric absorption of sunlight. As a consequence, for PM2.5 at 35-100 $\mu g/m^3$, vitamin D production is 8.45 to 19.82% lower than for PM2.5 between 6 and 35 $\mu g/m^3$. When air pollution is high (100-161 $\mu g/m^3$), this reduction in vitamin D production is 21.6 to 50.64% lower (Wang et al., 2020). However, increased absorption of UV by aerosol reduces radiation impact at ground level, giving a lower risk of sunburn (*, Deng et al., 2008; Pimonsree & Vongruang, 2018).

7.3. Short term diseases

The toxicity of particulate matter regarding short-term exposure is quite established and known to increase morbidity and non-accidental mortality risk (Pothirat et al., 2016, 2021; Othman et al., 2022) with significant effects for respiratory diseases morbidity, cardiovascular morbidity, and adult mortality in high-risk groups (Johnston et al., 2019; Uttajug et al., 2021, 2022; Vajanapoom et al, 2020; Chinsorn & Papong, 2021; Ngamsang et al., 2023; Rotjanabumrung et al., 2023). Health issues affect particularly children due to their underdeveloped respiratory system and higher breathing rate (Lipsett & Materna, 2008; Uttajug et al., 2021; Amnuaylojaroen & Parasin, 2023) as well as the elderly (Samet et al., 2000; Pope et al., 2002). Haze penetration into the respiratory system leads to mucus secretion, inflammation and mural fibrosis, inducing chronic fibrotic response and chronic airflow obstruction of airways (Wiwanitkit, 2008). The national distribution of chronic respiratory diseases shows that Northern provinces have an occurrence of cases 2 to 3x higher than Northeast and Central regions and slightly higher than southern provinces (Chi Htwe et al., 2023).

Particulate matter is detrimental to the respiratory and cardiovascular systems and high levels of pollution are typically associated with increased hospitalization for various diseases (Wiwanitkit, 2008; Vichit-Vadakan & Vajanapoom, 2011; Liu et al., 2017b; Vajanapoom et al., 2020; Uttajug et al., 2021; 2022; Singkam et al., 2022; Rotjanabumrung et al., 2023). With an estimated number of haze days between 64 and 139 in the eight northern provinces, a 10 $\mu g/m^3$ increase is associated with increased hospital visits for children with respiratory diseases but not for conjunctivitis and dermatitis (Uttajug et al., 2021). The lag for respiratory diseases following high PM10 and hotspot numbers is 0 to 1 day with a correlation coefficient between 0.4 and 0.7. The lag is probably influenced by human behaviour on high pollution day such as staying indoor, affecting the expected direct effect (Uttajug et al., 2021). The fire ban in all provinces that has arguably reduced air pollution, has supposedly reduced hospital visits for respiratory diseases by 9.1% (º, Uttajug et al., 2022).

Other correlations with 10 $\mu g/m^3$ increase for PM10 and PM2.5 show a mortality increase of 1.31% and 1.92% respectively with a more significant effect for cardiovascular mortality increasing by 4.45 and 3.3% respectively while respiratory morbidity increase by 4.1 to 4.8% (Karanasiou et al., 2021; Ngamsang et al., 2023). It is important to note that most studies that have correlated health effects with various meteorological factors show the impact of particulate matter, but other meteorological parameters as well such as variations in temperature, humidity, rainfall, etc. (Pasukphun, 2018; Singkam et al., 2022). A specific study on the effect of temperature on mortality between 1998-2008 shows that extreme temperature (hot and cold) have an effect on cardiovascular and respiratory morbidity and mortality on the same level than air pollution, with cold being longer lasting (Guo et al., 2012).

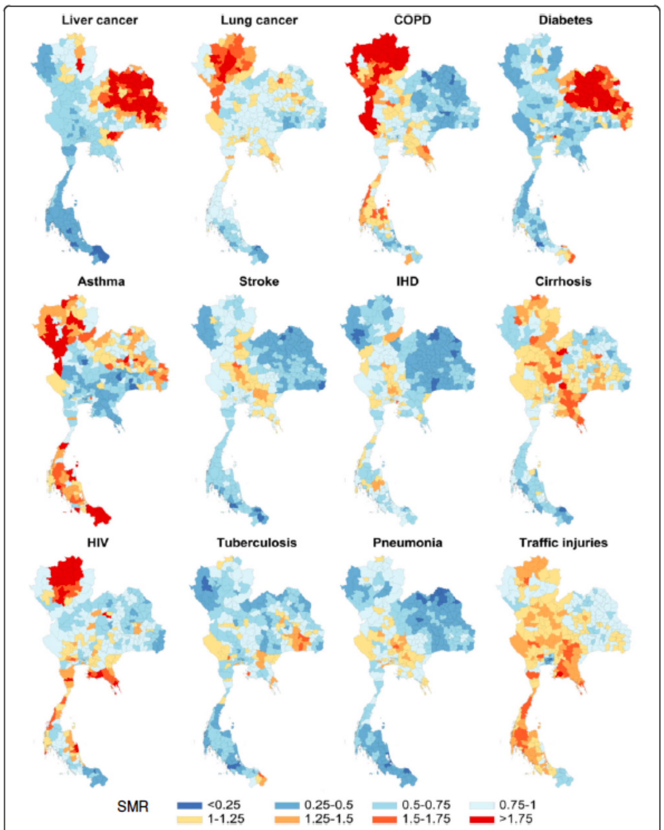

Fig. 6 Geographical distributions of super-district average annual cause-specific standardized mortality ratio, 2001-2014

Figure 7.2. District-based geographical distribution of average annual cause-specific standard mortality ratio between 2001 and 2014 (Aungkulanon et al., 2016).

7.3.1. Asthma

Asthma is a chronic inflammation of airways with reversible pulmonary obstruction and bronchospasms caused by a variety of factors, including air pollution. The prevalence of asthma in Northern Thailand in 2001-2002 was estimated to be 3.01% of adults (20-44 y.o.; Pothirat et al., 2016) and 5% for children with no significant differences between schools of the region (Sriyaraj et al., 2008).

The correlation between industrial & traffic PM2.5 (Lathaison & Tulrairatana, 2019) and biomass burning PM2.5 (Prapamontol et al., 2023) with asthma is known and a significant effect is already noticed for sensitive asthmatic children for particulate matter concentration as low as 12 µg/m^3 (Chankaew et al., 2022). For increased pollution, hospitalization rate is strongly correlated for children, weaker correlations are found for adult male and female (Lathaison & Tulrairatana, 2019). The aeroallergen and dust mites sensitization also contributes to asthmatic exacerbation when exposed to particulate matter (Sompornratthanaphan et al., 2020; Prapamontol et al., 2023).

For every 10 µg/m^3 of PM10, an increase of 10.35% in asthma cases is observed with a lag of 6 days, while a 10 µg/m^3 of PM2.5 brings an increase of 9.19% of cases (Pothirat et al., 2016; Karanasiou et al., 2021).

7.3.2. Chronic Obstructive Pulmonary Disease

Chronic Obstructive Pulmonary Disease (COPD) is an irreversible and progressive airflow limitation associated with chronic and aberrant pulmonary inflammation due to inhaled noxious particles and gases (Vestbo et al., 2013). The prevalence of COPD in Northern Thailand (2001-2002) is 5.4% of adults (20-44 y.o.; Pothirat et al., 2016) with 46% due to smoking, 20.7% ambient exposure to PM pollution and 15.6% due to occupational exposure to PM pollution (Hongthong et al., 2023). The study of specific markers to identify DNA damage and instability in COPD patient is significant for PM10 > 50 μg/m^3. COPD patients are 295x more at risk of developing DNA damage associated with cytokinetic effect than healthy individuals (Wunnapuk et al., 2019). The severity of COPD is correlated with PM10 levels, with a response up to 5.85x higher than unexposed groups during a heavy haze event, with tobacco a strong worsening factor in 88.4% of cases (Pramuansup et al., 2013).

Estimates of correlation between particulate matter and COPD cases show that a 10 μg/m^3 increase in PM2.5 leads to 3.1% (Li et al.. 2016) to 3.92% (Karanasiou et al., 2021) increase of COPD hospitalization while Singkam et al. (2022) have found a 1% increase in PM2.5 is followed by a COPD risk increase of 0.25%. An increase of 10 μg/m^3 of PM10 is associated with a 3.95% increase in COPD cases (Karanasiou et al., 2021) with a lag time of up to 7 days (Pothirat et al., 2016). COPD mortality increases by 2.5% (Li et al., 2016) to 3% (Chunram et al., 2007c) for each additional 10 μg/m^3 of PM2.5.

It is worth noting that a one percent increase in temperature, humidity or number of hot spots also increases COPD risk by a significant margin of 0.43% while an increase in the average lowest temperature produces a risk increase of 0.92% for COPD (Singkam et al., 2022). Finally, hospitalization and mortality trends for COPD are geographically dependent with the highest Disability-Adjusted Life Year (DALY) found in Nan (18%), Phayao (13%) and Chiang Mai (12%) while Lamphun (7%) has the lowest value based on PM10-AOD estimations (Samet et al., 2000; Hongthong et al., 2023).

7.3.3. Pneumonia

Pneumonia is mostly an infectious disease causing an inflammation of alveoli leading to difficulty breathing and a range of respiratory symptoms. A pathogen is often the cause, with increased risk for patients with asthma, COPD, blood and metabolic disorders, etc.

PM10 has a robust association with pneumonia cases and hospitalization in Chiang Mai, with no lag time linked to it (Ruchiraset et al., 2018; Ruchiraset & Tantrakarnapa, 2018) and a correlation factor of 0.61 was found for the disease (Pasukphun, 2018) as well as an increase risk of mortality by 4% for an increase of 10 μg/m^3 of PM2.5 (Chunram et al., 2007c).

The correlation factor with other meteorological variables is significant with 0.77 for rain; 0.76 for relative humidity and 0.97 for temperature (Pasukphun, 2018; Ruchiraset & Tantrakarnapa, 2018) which could explain the lack of strong correlation between air pollution and pneumonia cases in some studies (Karanasiou et al., 2021).

7.3.4. Other acute diseases

Like pneumonia, influenza has a correlation with the level of PM10 (0.82) but correlates higher with rain, relative humidity and temperature (0.88 to 0.94) (Pasukphun, 2018).

Pulmonary embolism has been correlated with increased air pollution in the North (Bumroongkit et al., 2022).

Lower birth weight and pre-term birth have been associated with long-term high level of particulate matter exposure (Muller et al., 2020; Karanasiou et al., 2021) and infant mortality also has a correlation with PM2.5, with a disproportionate impact of poorer population of northern Laos and Western Myanmar (Reddington et al., 2021).

An increase of 2% of Ischemic Heart Disease mortality has been observed for each 10 μg/m^3 of PM2.5 (Chunram et al., 2007c). However, although further studies have observed higher hospitalization rate for respiratory and cerebrovascular (stroke) diseases for PM10 with no lag time, no obvious relationship was seen for ischemic heart disease (Muller et al., 2020).

Evidence that exposure to particulate matter increase the risk of neurological and cognitive diseases (dementia, cognitive impairment, cognitive development) and metabolic (diabetes) is unclear as studies are done typically on urban pollution and conclusions cannot be transposed readily to biomass burning in Northern Thailand (*).

7.4. Long term diseases

The effects of long term exposure to biomass burning particulate matter are unclear. Chiang Mai province presents a lung cancer case anomaly that is recorded since 1983 (Srisukho & Sumitsawan, 2007). Lung cancer mortality has steadily increased in Northern Thailand for the past few decades, at a higher rate than the rest of the country (Aungkulanon et al., 2016; Rankantha et al., 2018; Pongnikorn et al., 2018; Nakharutai et al., 2022). Northern Thai women are the most at risk with one of the highest rate in Asia (Pongpiachan et al., 2013). However, the situation is not homogeneous in the North, and Chiang Mai has an even higher rate than other provinces (Vatanasapt et al., 1993; Vinitketkumnuen et al., 2002; 2007). The characterisation of lung cancer in Chiang Mai is 49.2% adenocarcinoma; 27.2% squamous cell; 10.3% small cell; 8.6% large cell carcinomas (Wiwatanadate, 2011).

Despite these alarming variations within Thailand, age standardised incidence rate of lung cancer in the North is 30.0 and 16.7 (male & female resp. for 100000 individuals); Chiang Mai, Lampang and Lamphun having the highest numbers (resp. Male: 36.8, 48.4, 38.5; Female: 24.6, 25.4, 24.9), significantly higher than Thailand average ASR but similar to Japan (38.7-13.3) and lower than the US (49.5-36.2) (Wiwatanadate, 2011).

The identification of a cause for the anomaly within Thailand remains elusive. Upper northern Thailand has among the lowest level of smokers in the country (11.3% compared to 15.2%; Somsunun et al., 2022) and has decreased considerably from 22.2% a decade earlier while it was in the national average (Wiwatanadate, 2011). The level of female smokers is quite high in the North, and could be associated with the increased anomaly for female lung cancer patients. However, adenocarcinoma, which form half of the lung cancer in the northern region is known to be more associated with environmental factors than tobacco smoking (Somsunun et al., 2022). Additionally, it has been suggested that a significant genetic factor might be at play due to the difference between blood lymphocytes in high incidence area compared to populations with low incidence of lung cancer (Heepchantree et al., 2005).

7.4.1. The role of air pollution

As long term exposure to high level of particulate matter has been culturally associated with lung cancer (º, Johnston et al., 2019; Muller et al 2020; Suriyawong et al., 2023), a first glance correlation with air pollution in northern Thailand seems plausible but the variability within districts of Chiang Mai province and even more with neighbouring provinces where air pollution conditions are mostly identical cast some doubt on the correlation (*). There is also some minor discrepancies between studies on which districts have the highest lung cancer anomalies. While Wiwatanadate (2011) show that Amphoe Mueang, Mae On, Hang Dong, San Pa Tong and San Kamphaeng top the list in Chiang Mai province; Rankantha et al. (2018) have found the highest lung cancer risk in Hang Dong, Doi Lo and San Pa Tong, and Thumvijit et al. (2020) claims that the highest lung cancer anomaly is found in Doi Saket.

Studies on long term effect of biomass burning particulate matter toxicology is not as advanced as effects due to traffic and urban pollution (Johnston et al., 2019). Some biomass burning fires such as peat, palm and rubber tree combustion are known to have some association with cancer (Jamhari et al., 2014; Urbancok et al., 2017; Adam et al., 2021) but there is no data for dry dipterocarp forest burning. The urban growth of Chiang Mai has been important in the past few decades, and is linked with declining air quality (Rankantha et al., 2018; Chi Htwe et al., 2023) but the variations in cancer risk during haze season have been shown to be higher in rural areas than urban zones while similar or slightly opposite outside the haze season (Insian et al., 2022). BaPeq in Northern Thailand has an annual mean dose around 20x higher than the WHO recommendation of

0.12 ng/m^3 but these values are not particularly different than what is found in Europe or China (Sirithian et al. 2017; Moran et al., 2019).

Compared to other urban and industrialized areas in South-East Asia, the carcinogenic risk in Northern Thailand is not particularly high, and depending on the conditions, several times lower than some large metropoles (Pongpiachan et al., 2015; Chi et al., 2022). Although the fact that some PAH pollution in Northern Thailand is non-dietary and remains a concerning aspect, the PAH exposure gives a low to medium cancer incidence for a lifetime of exposure (Wiriya et al., 2013; Pongpiachan et al., 2015). Finally, an observation has been made on the effect of particulate matter exposure to the survival rate of lung cancer patients, and the effects are significant after 3 years of remission (Nakharutai et al., 2022); however, no correlation has been observed in the mortality of child cancer patients (all types) (Sathitsamitphong et al., 2023).

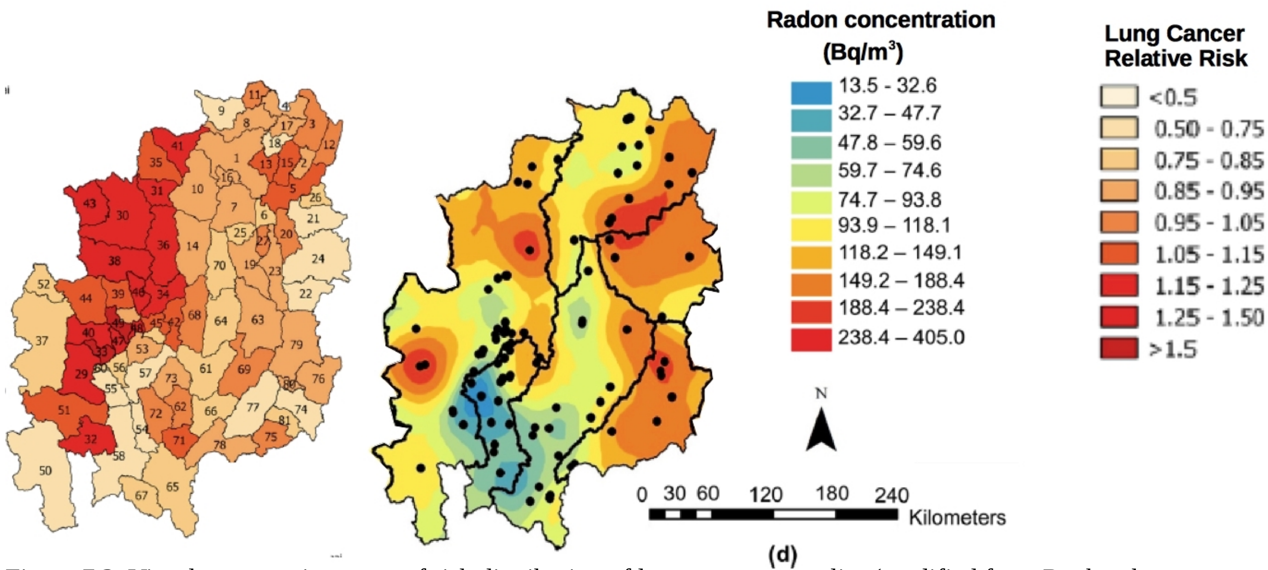

Figure 7.3. Visual comparative maps of risk distribution of lung cancer mortality (modified from Rankantha et al., 2018) and modelised distribution of indoor radon concentration (modified from Somsunun et al., 2022) in 6 provinces of Northern Thailand. Air pollution is unable to explain the heterogeneity of risk in Northern Thailand but indoor radon correlation is not particularly adequate either.

7.4.2. Alternative causes

Given the unclear relationship between particulate matter and lung cancer mortality in Northern Thailand, alternative causes have been sought such as the presence of high indoor radon. Radon is a heavy colourless, odorless radioactive gas of endogenic origin that can be accumulated in poorly ventilated areas and inhaled or ingested by the human body. Its relatively short half-life through alpha decay process causes DNA damage to respiratory epithelium cells and produce short-lived decay products (Po-218, Po-214) that further irradiate cells in the respiratory and digestive tract.

Indoor radon exposure is a common cause of lung cancer responsible for 10-20% of the disease worldwide (Somsunun et al., 2022). Most indoor radon is produced from direct ground emission while 10-15% could be produced from outgassing tap water. It is estimated that 1 to 7% of lung cancers are due directly to aqueous radon while another 11% of stomach cancer might find water-dissolved radon as a possible but not unique cause (Thumvijit et al., 2020). Some evidence of indoor radon effect has been directly observed in Chiang Mai province by studying the telomere length of chromosome in lung cancer patients and healthy patients subject to moderately high radon levels and low indoor radon, establishing that telomere length protects the chromosome from DNA degradation and dysfunction (Autsavapromporn et al., 2018).

Radon levels monitoring of South-East Asia shows that Northern Thailand is known to be the region with the highest levels of indoor radon (Wiwanatade, 2011). However, as a regional average, concentration are mostly within the acceptable range with 1.4±0.1 mSv/yr for Chiang Mai, not exceptionally different from the worldwide average of 1.15 mSv/yr. Radon concentration in Chiang Mai are variable between 46 and 105 Bq/m^3, a lot higher than Thailand (16 Bq/m^3) and global (39 Bq/m^3) averages but not that different from other places like western Europe (85 Bq/m^3). It theoretically put around one third of households in Chiang Mai above the WHO recommended levels of 100 Bq/m^3 but estimations vary considerably (2.2 to 41%) between authors (Autsavapromporn et al., 2018; 2022; Somsunun et al., 2022). There is however the possibility of higher value during the haze season due to the lack of atmospheric movement and voluntary poor house ventilation which could affect exposure (Autsavapromporn et al., 2018). The calculated effect gives an increase of excess lifetime carcinogenic risk from 0.5 to 0.67% between non-haze and haze episodes (Autsavapromporn et al., 2022).

The correlation between indoor radon and lung cancer risk has been poorly established in some studies (Rankantha et al., 2018) with the highest levels of indoor radon observed in Amphoe Mueang, Hang Dong, Saraphi and Sanpatong, the later having the highest levels (Autsavapromporn et al., 2022). Some attempts to correlate these values through aqueous radon emission have shown no significant increased risk (Thumvijit et al., 2020). At a regional level, the highest average indoor radon are in Phrae & Phayao, around 1.5x higher than Chiang Mai. Risk estimation due to radon exposure gives that 37% of lung cancer in Phrae & Phayao would be linked to radon, around 25% in Chiang Mai and only 19% in Lampang (Somsunun et al., 2022) based on the standard WHO exposure estimation which estimate that an increase of 100 Bq/m^3 of indoor radon will increase lung cancer risk by 8 to 33%. Regional distribution of lung cancer anomalies do not show a strong correlation with estimated radon exposure alone (*) but the high level of smokers among victims of lung cancer (96% male; 52% female) while the North hosts the lowest level of smokers in Thailand indicate that tobacco might have some synergistic effect in association with radon (Somsunun et al., 2022).

8. Environmental effects of fires and air pollution

8.1. Forest ecosystem

The regular fires in the forested areas of northern Thailand have affected the characteristics of dry dipterocarp and mixed forests. While some areas are subject to occasional wildfires, many forests see fires every year, which modify the tree population and some soil features. Dry dipterocarp forests are made of *Dipterocarpus tuberculatus*, *Shorea obtusa*, *Shorea siamensis*, *Lannea coromandelica* and *Dipterocarpus obtusfolius* with a tree density of 2350±354 tree/ha in sloped terrain and 1225±71 tree/ha in flat lands, giving 91.96 and 30.95 t/ha respectively (Junpen et al., 2013b; Chaiyo & Garivait, 2014). In mixed deciduous forests such as Doi Suthep, *Lagerstroemia duperreana*, *Terminalia mucronata*, *Tectona grandis*, *Xylia xylocarpa* and *Pterocarpus macrocarpus* are the main tree species with *Bambusa membranacea* and *nutans* also contributing to the forest cover (Junpen et al., 2013b). The tree density on Doi Suthep is 3353 tree/ha in dry deciduous forest and 1166 tree/ha in mixed deciduous forest (Junpen et al., 2013b).

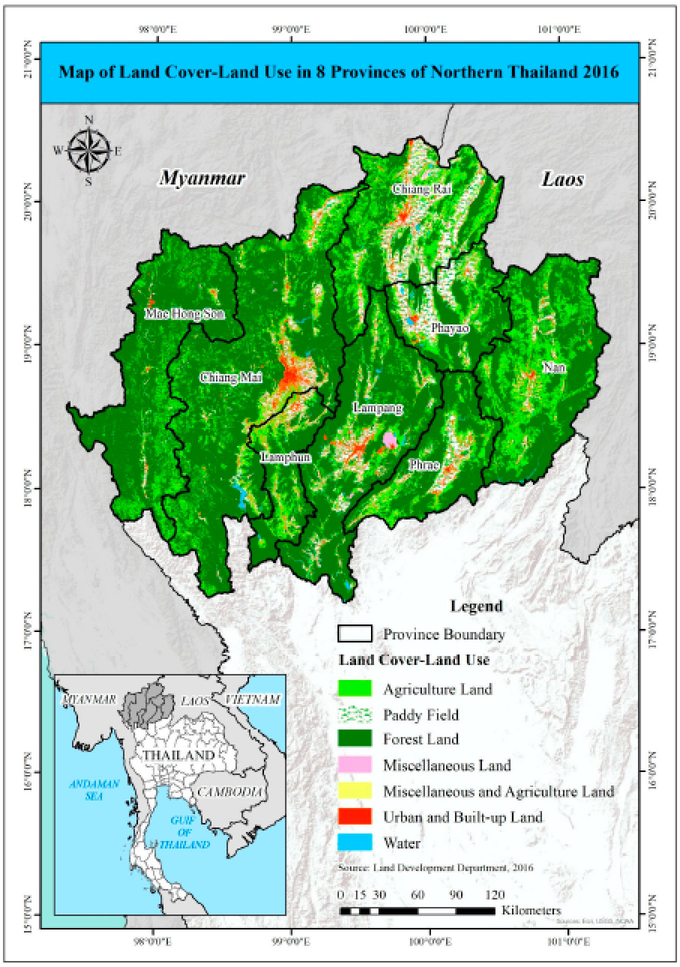

Figure 8.1. Land use map of Northern Thailand showing the large surface area that forests occupy in provinces such as Mae Hong Son, Chiang Mai while Chiang Rai and Nan have considerably more agricultural land (Nakharutai et al., 2022).

8.1.1. Effect of forest fires

Fires are typically described as surface fires and do not consume the overstory and canopy layer (Wanthongchai et al., 2011). Crown fires have never been reported since 2000 by the FFCD and the only type of forest fire indirectly linked to forest reduction are fires associated with illegal logging (Junpen et al., 2013b). However, surface fires have an effect on the upper layers of forests and in Miang Tea forests, yearly damage by fire reduces the canopy cover from 89.8% to 72.9% (Sysouphanthong et al., 2010).

Surface fires are fed by twigs, dead leaves and plants, grass and undergrowth (Junpen et al., 2013b). As a result, layers closer to the ground are heavily affected and generally, no yearly plants exceeding 1.3 m height survives fire (Chernkhunthod & Hioki, 2020) as well as any seedling with less than 1 cm basal diameter (Suthinavit et al., 1998). The yearly surface burn also has an effect on tree growth decreasing the annual diameter growth by 0.237 cm/yr and basal growth by 0.7 cm/y compared to forest that see fires every two to three years (Suthinavit et al., 1998).

As surface fires have low fuel density and are quickly moving, fires only affect the top soil layer but have limited direct effect on deeper layers. While the soil surface reaches 200 to 400ºC during a forest fire, the thermal gradient is very strong and at depth of 20mm, the temperature is only 30ºC (Chernkhunthod & Hioki, 2020) although other measurements have only reached such temperature at depth of >40 mm (Kennedy et al., 2012). However, regular fires consuming forest litter change the pedological properties and consequently, soil characteristics and nutrients dynamics (Wangthongchai et al., 2008). At the surface, forest burning has deleterious ecological consequences, increasing seedling and sapling mortality, a loss of biodiversity and of primary forest, while increasing grassy ground flora and decreasing overall soil nutrient (Kennedy et al., 2012).

8.1.2. Characteristics of forest fires

Anthropogenic fires exist for centuries (Makarabhirom et al., 2002) and are recurring events in most forests of Northern Thailand. Between 2008 and 2017, Doi Suthep/Pui alone has seen 16 fire incidents and another 12 in the decade before (Chernkhunthod & Hioki, 2020). The fires are typically surface fires fed by the whole understory vegetation, comprising litter (leaves, twigs, reproductive parts), grass and undergrowth (seedlings, various weeds, climbers (Junpen et al., 2013b). The main controlling parameters in forest combustion are the fuel characteristics (composition, load, arrangement, moisture, continuity, …), atmospheric conditions (temperature, relative humidity, wind,…) and topography (elevation, slope, angle, aspect, …).

The balance of fuel available rest on litterfall dynamics and decomposition process. The highest litter levels are reached in May as most leaves have fallen and decomposition is not very active yet due to low humidity. After a forest fire, the fuel recovery is around 2 years (Chernkhunthod & Hioki, 2020). This recovery should not be compared to the longer term recovery (~50 years) of degraded forests used for human activities (Fukushima et al., 2008; Trisurat et al., 2010). The biomass available for combustion is 2.74 to 4.69 tons/ha where 1.49-2.95 t/ha are fine biomass and 0.99-2.26 t/ha are coarse matter. Leaves form 41.1 to 67.2% of the available biomass (Junpen et al., 2013b). Overall fuel loads are 3.88 t/ha with 2.36 t/ha of dried leaves and grass and 1.52 t/ha of twigs and undergrowth (Junpen et al., 2013b). Other estimations provide similar numbers, with forest litter made of 3.42±1.9 t/ha of leaves, 1 t/ha of twigs, with 45.81±0.04% of carbon available (Chaiyo & Garivait, 2014) and 9.7 to 12.45% of moisture (Junpen et al., 2013b) or 4.52 to 17% (Junpen et al., 2013b). These laboratory based estimation are one order of magnitude inferior to a recent publication that put emission per hectare based on Aerosol Optical Depth in Mae Hong Son, Tak and Chiang Mai as ~30 t/ha and Chiang Rai, Phrae and Nan provinces at ~10 t/ha for PM10 alone (Hongthong et al., 2023). Such difference in numbers would require some clarification in the future as it is potentially in contradiction with the tree density and estimated mass per hectare of forest (*).

Forest fires have typically 0.2 to 0.9m of flame height (Chernkhunthod & Hioki, 2020) but can go up to 4m (FFCD), with a spreading rate of up to 2m/min (Chernkhunthod & Hioki, 2020). Other measured spreading rates are 0.53 to 2.25 m/min (Junpen et al., 2013b); 0.51 to 2.55 m/min (Junpen et al., 2013b) and 1.7 to 3.4 m/min (FFCD). The temperature of the fire is 300-500ºC (Chernkhunthod & Hioki, 2020) which release 110 to 250 kW/m of fireline intensity (FFCD).

Head fire is moving 2 to 15x faster than back fire and 1.6 to 3.8x faster than flank fire (Junpen et al., 2013b). Variations in fire spreading rate are function of topography (higher slope), moisture content of fuel, fuel load and proportion of dead leaves, wind speed.

The combustion consumes 60 to 70% of available fuel on average (Chernkhunthod & Hioki, 2020) and release 88.38±2.02% of available carbon (Chaiyo & Garivait, 2014). Combustion consumes 91 to 98% of small fuels (dead leaves & grasses, live grass), 48% of coarser fuel (stems, twigs) and 40-60% of coarse woody debris (Junpen et al., 2013a, b). Combustion efficiency in deciduous forest is 0.25 with a production of 10 g/kg of PM10 and PM2.5 while shrub combustion efficiency is 0.8 (Amnuaylojaroen 2009) (Fig.8.2.).

The average forest fire is 1.09 to 12.47 ha based on satellite data (Junpen et al., 2013a) while a more recent estimation gives 1.5 to 3 ha per fire (Janta et al., 2020). FFCD burning record from land survey gives several thousands of burning events per year with an average area of 1.6 to 3.2 ha per event and totaling tens of thousands of hectare but satellite imagery show that it is underestimated by a factor of 5 (Junpen et al., 2013a).

Figure 8.2. Effect of forest fires and dry season for an identical spot in Pa Daeng N.P.. The left picture is in mid-January while the right is early June, post burning when rains are not abundant yet (Kennedy et al., 2012)

8.2. Mushrooms

8.2.1. Earthstars Astraeus sp.

In Northern and North-East Thailand, one of the reasons to start fires in dry deciduous forests is to promote the production of false earthstars mushrooms: *Astraeus odoratus* (Het Thawp) (Phosri et al., 2004; Kennedy et al., 2012), *Astraeus hygrometricus* (Het Kra Bueang; Het Pho Fai; Het Fai) and *Astraeus thailandicus* and *asiaticus* (Hed Pho Hnang, Hed Hnang) (Petcharat, 2005; Phosri et al., 2007) and the more recently discovered *Astraeus sirindhorniae* found in forests of Chiang Mai and Chaiyaphum (Phosri et al., 2014).

All *Astraeus* sprorocarps are edible and found in dipterocarp forests (Petcharat, 2005) and the most common are *A. asiaticus* and *odoratus. A. sirindhorniae* is rarely found in markets and might often be considered as *A. odoratus (*Phosri et al., 2014). Market value for fresh basidiomes of *Astraeus* is 300-500 ฿/kg (Dell et al., 2006; Suwannasai et al. 2020) but prices can vary considerably depending on the May-June harvest, the quality of sporocarps and the species (*A. thailandicus* has a higher market value than *A. hygrometricus* (Petcharat, 2005)). Excess collection is preserved in a saline solution and exported to neighbouring countries (Suwannasai et al., 2020).

False earthstars occur in a wide range of dipterocarp forest conditions with intact or open canopies, thick ground or rocky soil. False earthstars are associated with specific tree species found in dipterocarp forests such as *Dipterocarpus tuberculatus* and *obtusfolius*, *Shorea obtusa*, *Gluta usitata*, *Tristaniopsis burmanica*, *Dalbergia cultrata*, *Lygodium flexuosum* and *Polytoca digita* (tree, vine, grass) and grasses *Eulalia siamensis* and *Apluda mutica* which are abundant in some places (Kennedy et al., 2012) (Fig. 8.3.).

Figure 8.3. *Astraeus odoratus* harvesting with cut and mature sporocarps in Pa Daeng N.P. end of May 2010 (Kennedy et al., 2012).

In vitro experiments also show an association with *Dipterocarpus alatus*, *Eucalyptus camaldulensis* and *Pinus densiflora* (Kennedy et al., 2012) and ectomycorrhizal associations of *A. sirindohrniae* with *Shorea siamensis*, *Shorea roxburghii*, *Shorea farinosa*, *Dipterocarpus alatus*, *Dipterocarpus intricatus*, *Dipterocarpus obtusfolius* and *Hopea odorata*. These studies show that some commensalism might occur with *A. odoratus* helping doubling the growth of *Shorea roxburghii* and a milder effect with *Dipterocarpus tuberculatus* compared to non-inoculated seedlings (Kaewgrajang et al., 2019). Similar observations were made between *A. sirindhorniae* and *Dipterocarpus alatus* (Suwannasai et al., 2020).

No laboratory growth has yet achieved the production of *Astraeus* sporocarps. Extensive mycelium growth has been obtained on *Dipterocarpus alatus* with a soil of vermiculite and peat and *Astraeus odoratus* spores on malt agar but the conditions required for fruiting are not met (Chabthaisong & Kaewgrajang, 2021; Anh et al., 2023).

The role of fire in the production of sporocarps is still debated. Fires are lit during the dry season (February-April) and the burned soil is scraped and scourged by gatherers looking for immature submerged sporocarps produced at the very beginning of the rainy season (end of May, June) until July (Petcharat, 2005; Kennedy et al., 2012). During a forest fire, the surface reaches a temperature above 250ºC, down to 122.4ºC at 1cm deep, 66.3ºC at 2cm, 41.6ºC at 4cm and below 40ºC at 6cm, which means that the mycelium is killed in the upper 2 cm of soil and the abundance of fungus in soil is 4 times lower after a fire (Kennedy et al., 2012). In 2010, a particularly intense burning season, the production of sporocarps was ~100 g/ha in a burned area of Chiang Dao while only 40 g/ha were found in an unburned area. Doi Saket had 10-20 g/ha in burned area and very little in unburned area. In 2011, a very mild burning season with some rain and not many fires, no sporocarps were found (Kennedy et al., 2012) (Fig. 8.4). It is thought that fire is not an absolute requirement for *A. odoratus* sporocarp production although the fungus is likely adapted to produce fruiting bodies in dry soil conditions, which are enhanced by fire and the clearing of forest litter. The absence of leaves and grasses after a fire is also a factor that facilitate harvesting conditions (Kennedy et al., 2012).

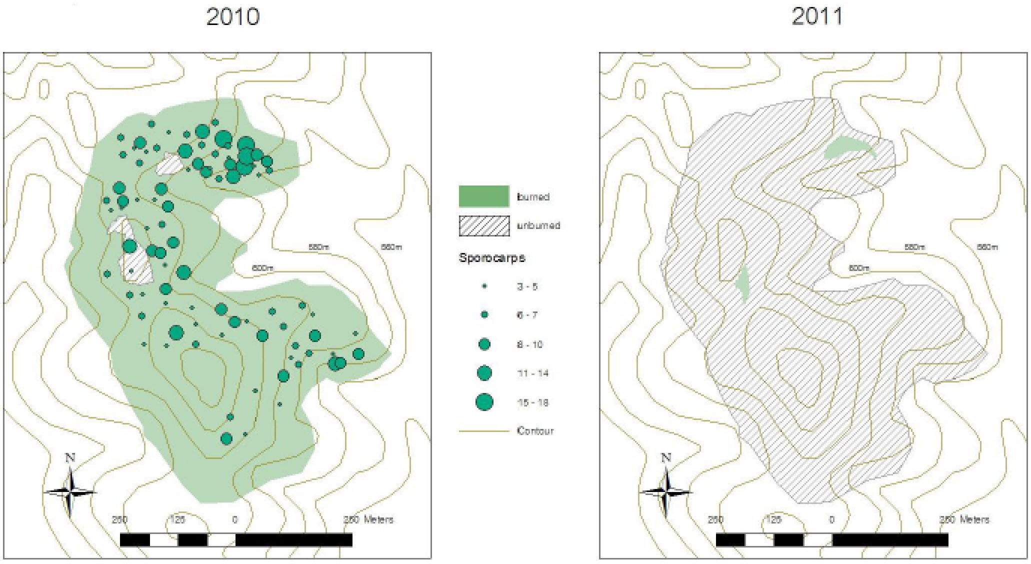

Figure 8.4. Comparison of yield for *Astraeus odoratus* in Pa Daeng N.P. between 2010, a dry year and 2011, a relatively humid burning season (Kennedy et al., 2012).

8.2.2. Other mushrooms

In dry dipterocarp forests, the fungi diversity covers 11 families, 21 genera and 52 species while a wet dipterocarp forest has only 8 families, 15 genera and 24 species. In dry dipterocarp forests, the dominant genera of ectomycorrhizas are *Russula*, *Boletus* and *Amanita* and 65% of the species found in these forests are not fruiting in other forest types (Dell et al., 2006). The impact of fire on these species is unknown but a study made in an abandoned miang tea forest shows 47 genera and 115 species of fungi while a similar forest damaged by yearly fires has a lower diversity of 25 genera and 48 species with a 35% reduction in collected sporocarp mass (Sysouphantong et al., 2010).

8.3. Others

The haze has an impact on agriculture as it decreases photosynthesis and lower yield for rice and wheat are recorded (Tie et al., 2016). This effect probably also applies to all plants but is unstudied. The haze can also increases fungal abundance (Sun et al., 2021) and induces microbial community changes (Sun et al., 2018).

The effect of haze on wild animals is unknown except for some studies show an impact on caterpillar to butterfly development (Tan et al., 2018).

9. <u>Prevention</u>

9.1. Personal prevention measures against air pollution

For the time being, there has been little change in the levels of air pollution reached in the last 3 decades. While some years (2003, 2011, 2022) have a very mild pollution with a small amount of forest fires associated with favorable meteorological conditions, most years have substantial haze with some years reaching hazardous levels for several days or even weeks (2007, 2010, 2023). It is therefore essential for the population and public services to provide some form of protection for individuals that limit the amount of particulate matter in the air or entering airways. Three approaches exist to reduce locally the amount of air pollution. At a personal level, the use of masks; at a room or building level, the use of large filtering devices and more speculatively, outdoor techniques to reduce air pollution.

Filters, as home devices or masks, are system designed to reduce particulate matter (and eventually other gaseous pollutants) from the air. The efficacy of such filters is often very high for a wide range of particulate range. Air filters are not just simple sieves and apply several physical processes where the sieving effect is only used for the largest particulates.

Five mechanisms exist in the filtering process of standard air filters:

- *Straining*: Coarse particulates (often 2-10 microns) are too large to pass through the mesh size of the filter.
- *Impaction*: Fine particulates (0.5-2 microns) hit the material of the filter and bounce or stop in the process.
- *Interception*: Ultrafine particulates (100-500 nm) flow through a random electrically charged mesh, deviating and eventually slowing down to never pass through the thickness of the filter.
- *Diffusion*: Nanoparticulates (50-300nm) are affected by considerable brownian motion, that in an electrically charged mesh, will eventually block it.
- *Adsorption*: (<50 nm) it is a process half-way between physical and chemical filtering where molecules or nanoparticulates are stuck in a porous and electrically charged material and will eventually stick to the surface of that material.

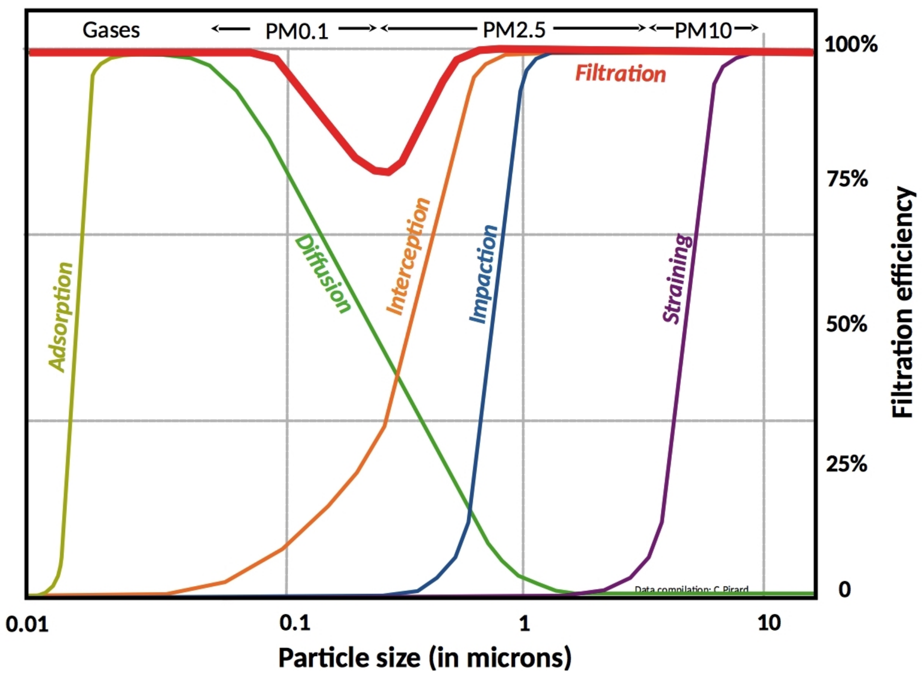

Figure 9.1. Distribution range of different filtering processes in an air filter with an 80% filtering capacity

Based on these physical processes, the filtering capability is the weakest at the transition between interception and diffusion at around 300 nm of aerodynamical diameter (Fig. 9.1). This particulate dimension is therefore used to estimate the filtering efficiency of a membrane. For very efficient filters, larger particulates are filtered at close to 100% and the same applies to some extent for smaller particulates.

Different scales exist to measure the efficiency of a filter. The Minimum Efficiency Reporting Value (MERV rating) characterises the filtering threshold of a membrane. It ranges from 1 to 20 and have 4 categories of particle size with strict requirements on their capacity for minimum particle size filtering.

EPA, HEPA and ULPA are three types of efficient filter categories with sub-categories that works on overall filtering efficiency and their retention for their most penetrating particle size which is most of the time around the 300 nm size (Fig. 9.2).

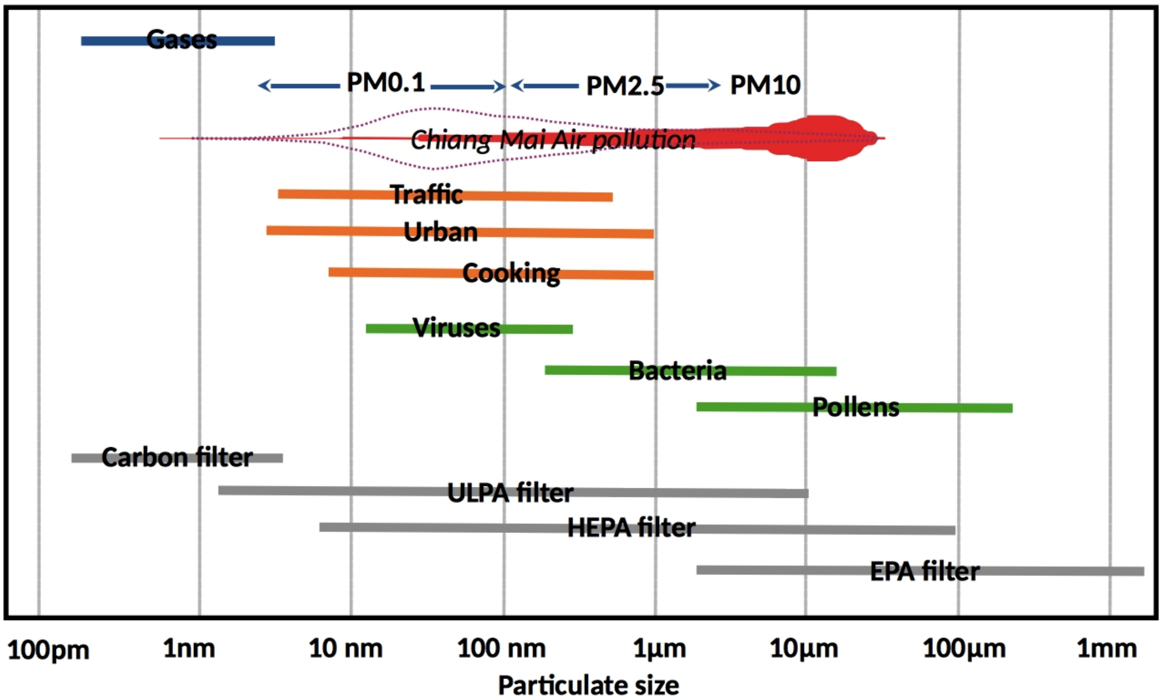

Figure 9.2. Distribution of the common application range of EPA, HEPA, ULPA and carbon filters compared to various aerosol sizes. Data for Chiang Mai air pollution is qualitatively given as mass proportion (red) or particulate number proportions (dotted line) .

9.1.1 Personal preventive equipment

This section covers filtering devices such as masks and respirators, worn on the users face, that capture air pollution to provide a cleaner air when entering airways.

Good quality masks with high filtering efficiency provide significant protection against high PM-based AQI. In most cases (and without medical counter-indications), the most suitable mask for Northern Thailand pollution is N95 or equivalents. The use of an outflow valve to such mask is also recommended as it prevents the accumulation of CO_2, reduces the risk of rash and bacterial infection from constant humidity and minimally improves the efficacy of the respirator by maintaining negative or neutral internal pressure.

The filtration efficiency of masks has mostly a typical inverted bell-shaped distribution where 250-400 nm range is often the minimum efficiency where filtering pass from aerodynamic behaviour to electrical mobility behaviour (Sankhyan et al., 2021). Filtration tests are done with polystyrene particles or NaCl aerosols between 10 and 10000 nm. For bacterial tests, *Staphylococcus aureus*, with a size of around 3±0.3 µm is used but no standard has been established yet for viral filtration performance (Krajnc et al., 2021). The filtering layers in masks are made of fibers with a diameter of 500 nm to 10 µm in supporting layers of 10 to 100 µm. Many high-efficiency masks contain a layer of polypropylene fibers manufactured in an electrical field. It creates permanently charged fibers known as electrets, which play a role in filtering small-size particles.

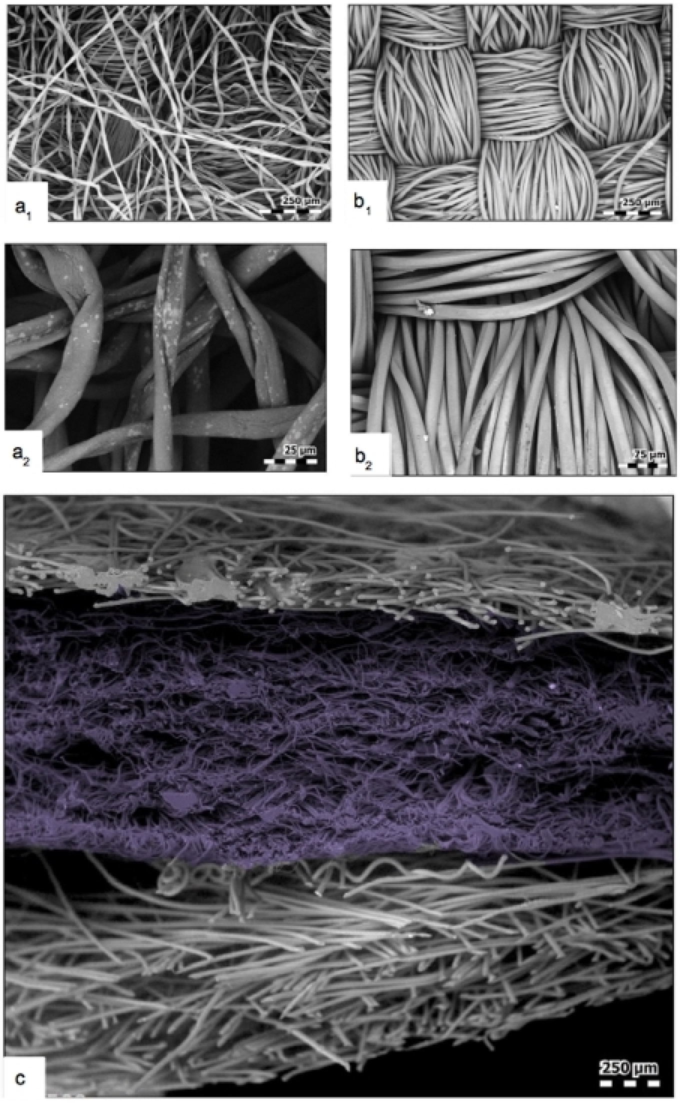

Figure 9.3. SEM imaging of fibers in a variety of filtering masks. (a) Cotton flannel mask with a disorganised layer. (b) Woven polyester mesh with very organised layer – studies show that randomness in fibers helps filtering particles. (c) Cross-section through a filtering layer of a N95 mask made of melt-blown polypropylene fibers (Press, 2021).

High efficiency respirators such as KN95, N95, FPP2, KF94, P2, DS2, PFF2 but also N99[(1)], N100[(2)] and FFP3[(1)] are masks made of random mesh of polypropylene fibers that filter 94-95% (99%[(1)] or 99.97%[(2)]) of particulates at 0.3 µm. The measured particulate removal efficiency is systematically higher than their rating. FPP2 (req. 94%) is measured at 98.6% and FPP3 (req. ~99%) is 99.9% in some studies (Langrish et al., 2009; Krajnc et al., 2021) (Fig.9.4). High efficiency at air filtering produces an inhalation resistance that is not negligible for respirators and can reach 150 to 200 Pa (Sankhyan et al., 2021). For the purpose of air filtering in Northern Thailand during haze episodes, respirators can be reused until damaged, soiled or causing increased breathing resistance. It is only in medium biosafety settings that respirators should be systematically discarded after use (NIOSH, 2018). R-rating and P-rating respirators have no specific use for northern Thailand air pollution as their main additional property is to be oil-resistant. High Efficiency (HE) respirators are similar to P100 rated masks but required a powered source and would only apply to persons medically disqualified from negative-pressure masks. Finally, non-mechanical respirators, using chemical cartridges such as activated carbon or resin to filter gaseous and volatile toxic components and nanoparticulates from the air are not suitable for typical particulate matter pollution from biomass burning as it would saturate relatively quickly.

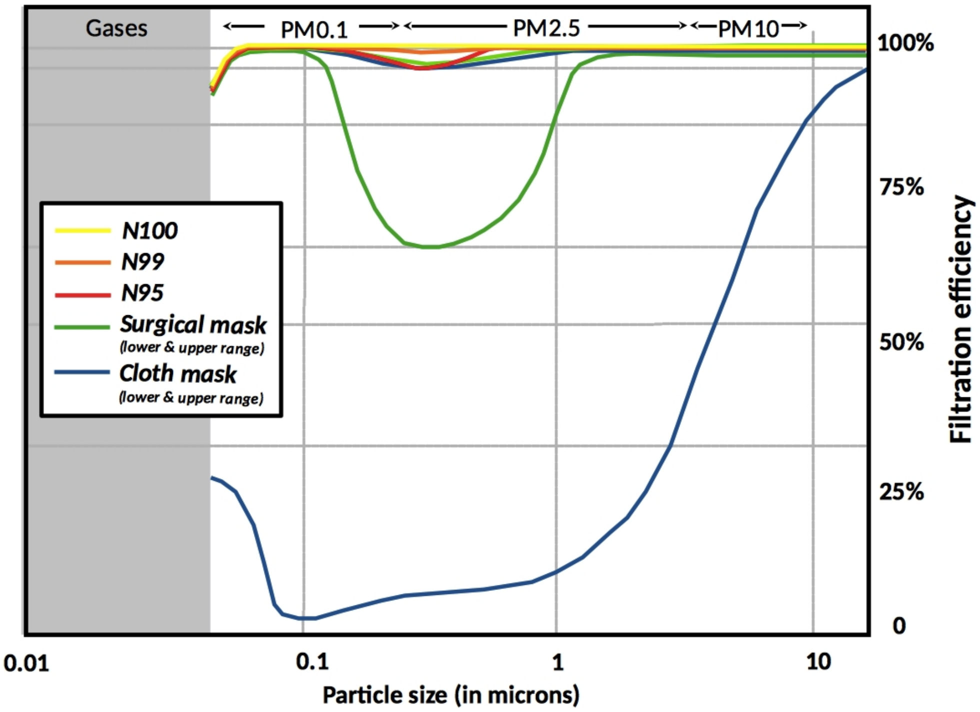

Figure 9.4. Maxima & minima of filtering efficiency in different masks type as a function of particle size. All masks & respirators have their minimum filtering ability in the 300 nm range and their ratings are based on that variable (modified from Sankhyan et al., 2021 and various commercial and audit data).

High quality surgical masks following standard EN14683, ASTMF2100 or YY0469 and traditionally used in the medical environment are made of a random mesh of polypropylene fibers similar to many respirators. They have a particle removal efficiency of 65 to 80% mostly due to the lack of good fit and negative pressure. However, the filtering ability of the mask itself is 94.6 to 99.5% with the minimum efficiency particle size between 200 and 500 nm. Such filtering capacity can be reached when tape-sealing the mask on the face of the user. Single use surgical-like masks can have a minimum efficiency at filtering as low as 40% as the applied standards are not as restrictive. The doubling of masks increases the filtering efficiency by 25%. The inhalation resistance of surgical masks is 50 to 100 Pa, the latter value for double masking (Langrish et al., 2009; Sankhyan et al., 2021; Krajnc et al., 2021).

Cloth masks are highly variable as they do not follow any filtration standard. Poplin-type cotton mask and other tightly woven cloth material have a particle removal efficiency of 70 to 80% but it can be as low as 10 to 30%. Testing on various commercial cloth masks have shown that some rare cases have filtering efficiencies similar to N99. Cyclists masks are often between 85 and 55% filtering. Inhalation resistance is variable but often around 50 Pa (Langrish et al., 2009; Sankhyan et al., 2021; Krajnc et al., 2021). The main issue with these commercial masks (and that would include unrated surgical-like masks) is the lack of reliability. Since there is no standard enforced, the only information available are consumers surveys and trusting reliable brands. However, it is also not that uncommon for standard rated masks from some companies to fail the filtering efficiency they are supposed to achieve.

The process of washing masks does not change the minimum efficiency value of filtering but it can marginally decrease the filtering ability of coarse particulates. It also increases the inhalation resistance by 20 Pa. After 20 washing cycles, masks fibers start to deconstruct themselves and damage become important above 50 washing cycles (Sankhyan et al., 2021) (Fig. 9.5).

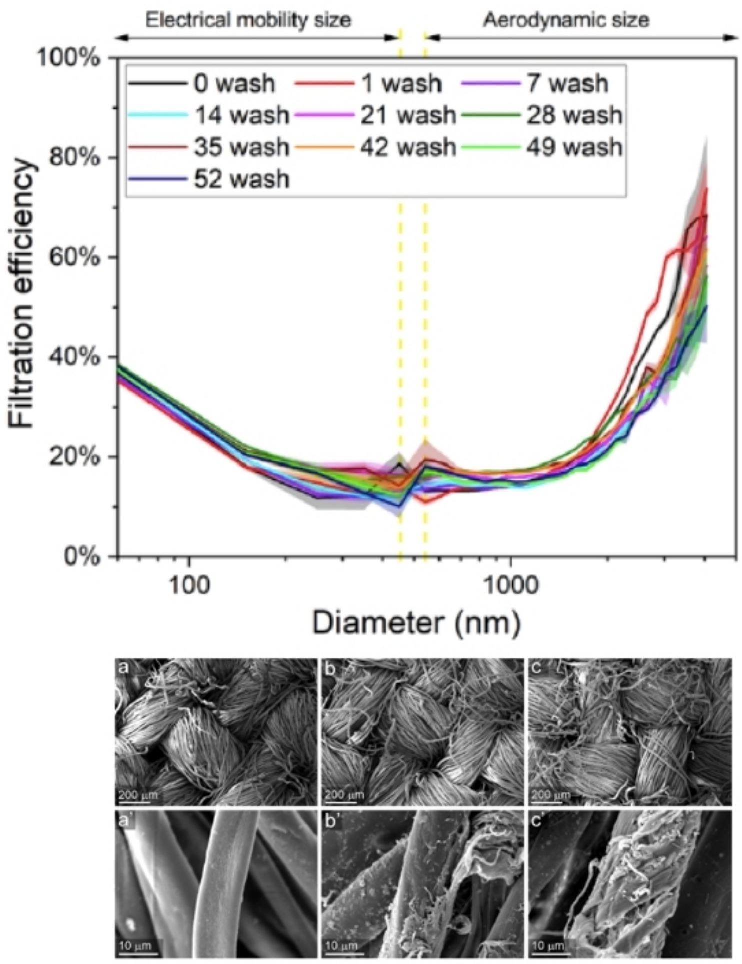

Figure 9.5. Effect of mask washing after 0 to 52 wash cycles does not fundamentally change the filtration efficiency of masks although the filtration curve might be modified. SEM pictures of successive washing cycles show a progressive deconstruction and damage to fibers (modified from Sankhyan et al., 2021).

Some negative aspects have been recorded for wearing a mask or a respirator but only a few conditions will have negatives weighting out the benefit of filtering heavy air pollution. Prolonged use of a high-efficiency mask or respirator can cause rashes and edema and a decrease in visibility due to lens fogging when humidity accumulates in the mask. Some minor but significant amount of heat is also released through breathing, which is limited when wearing a mask. Masks also impose limitations on blood glucose levels and muscle glycogen storage and limit the oxygen intake leading to increased exertion. The maximum oxygen uptake for different type of activities will make the individual reach its maximum oxygen debt quicker for intense exercise, counted in hours when walking but a few minutes if running uphill (Johnson, 2016). Heart rate for masks worn for short duration remains the same but the marginal decrease in systolic blood pressure will increase the average heart rate after a few hours (Langrish et al., 2009). All these limitations created by masks have minor repercussions on muscular abilities, cardiovascular efficiency and mental skills (Johnson, 2016). Some individuals are also psychologically affected by wearing masks with feeling of discomfort, anxiety and claustrophobia and the increase in humidity, temperature and lower oxygen intake that affect all mask-wearers (Johnson, 2016).

The physical consequences of wearing a mask are mostly without consequence except during intense physical activities and for individuals who have some type of respiratory or cardio-vascular issue. The increase in force required for inhalation can cause strain on the individual and in some cases, can bring more disadvantages than breathing polluted air. In such cases, a medical advice is required as less efficient masks with less inhalation resistance might be more suitable (*).

Finally, ill-fitted masks on children and people with facial hair can create leaks considerably decreasing the filtering efficiently of polluted air while making breathing more difficult (*).

9.1.2. Indoor filtering equipment

Particulate matter enters closed spaces through advection (open doors & windows) and infiltration (through gaps in structures). A variety of techniques exist to filter the air inside a closed space such as rooms, buildings, cars, etc. These includes DIY options installing additional filters on A/C units & homemade air purifiers but also commercial air purifiers and positive pressure systems. These systems are used in relatively insulated rooms and houses where the ambient air is sucked through various filters to produce clean air. It is a permanently running system since insulation, open doors and windows will bring fresh polluted air inside the room and can be alleviated by running continuously air purifiers or maintaining positive pressure.

Air purifiers are essentially simple fans pulling air through a HEPA filter with or without an associated low-cost sensor for air pollution. The homemade addition of an HEPA filter to standard A/C units is a cheap alternative to air purifiers but can be unsuitable depending on the maximum MERV rating accepted by the A/C system as it can bring considerable strain and damage to the unit. Positive pressure systems rely on pumping air from outside through HEPA filters to be released inside a bulding, resulting in an indoor pressure higher than the outside, preventing foul air to penetrate inside the building through advection and infiltration. Positive pressure systems have the advantage to replace indoor air with fresh clean air, reducing levels of CO_2, radon and other indoo pollutants but comes into direct competition with A/C system since they constantly bring hot (or cold) and humid (or dry) air inside the building. To partially solve this issue, some positive pressure systems are directly hooked on the HVAC house system but it still comes at an energy cost and HVAC systems remains relatively rare in Northern Thailand.

The most common filtering type on all these devices are meshes similar to masks, with a whole range of different filtering efficiency available. For a MERV13 filter installed on a powered unit, PM2.5 levels are reduced by ~80% (Cao et al., 2018a, b; Tham et al., 2018). MERV13 is the upper-range EPA filter factory installed on A/C units. However, it is largely insufficient on heavy haze days and more efficient mechanical filters or semi-chemical, chemical and electric filtering devices are also available for specific applications.

Efficiency Particulate Air (EPA) filters are a range of membranes that filter 80 to 99% of particulates (MERV11-16). These are often used in system that requires filtering but do not excessively restrict air flow. It is one filtering step higher than common filters on heating, ventilating and air conditioning systems that can have a lower MERV rating.

High Efficiency Particulate Air (HEPA) filters are made of a random mesh of polypropylene or borosilicate glass fibers electrets. These devices have a filtering efficiency of 99.97% at 300 nm (MERV17-18) and are particularly suitable for filtering standard air pollution to acceptable levels in a room or a building due to their high airflow capacity.

Ultra-Low Particulate Air (ULPA) filters have a similar design to HEPA filters but with increased porosity, which creates conditions where 99.999% of particulates at 120 nm are filtered (MERV19-20). These properties makes them suitable to clean air to an extremely high level of purity. However, higher filtering capability reduces the airflow, considerably limiting the volume to be treated, It also need regular replacement along with several pre-filters and cost a bit more than a standard HEPA for minimal gain since such filters are constantly filtering natural pollution brought or produced by residents. Although there is some marketing attempts to install such filters in homes in Northern Thailand, in practice, their use is mostly limited to clean rooms for medical, chemical or microelectronics applications where air locks, positive pressure, closed up dedicated suits and various preliminary processes are required before entering a room to ensure these filters are actually effective.

Adsorbing filters are made of activated carbon, silica gel or zeolites. The very high surface area of these porous forms of carbon, silica and silicate captures nanoparticulates and ultra fine particulate matter as well as some gaseous contaminants through adsorption. There are different types of filters in this category but are only suitable in Northern Thailand when used in combination with an HEPA filter otherwise they saturate quickly with fine and coarse particulate matter. Their filtering role is applied to some volatile organic components such as light-weight PAH, benzene-like compounds, ketones, etc. as well as burning odors associated with haze. At the end of the burning season, these filters can lose their efficiency as atmospheric humidity increases considerably.

Silver ion filters work with air passing through a porous surface coated with silver nitrate or other silver salts. Bacteria, fungi and viruses are supposedly rendered inactive in the process. This technique has been shown to work in water-based system where various bacteria are affected by a variety of silver-coated filtering support (Mpenyana-Monyatsi et al., 2012; Chien et al., 2021). However, the flow rate in these experiments is between 100 and 400 $l/m^2/h$ which is orders of magnitude inferior to the air flow usually met in housing at several thousands of m^3/h (equivalent to tonnes/h). It is likely largely insufficient for any effective action on micro-organisms passing through such filter.

Air ionization is a technique where a high voltage is applied ionising molecules in the air and traps contaminants through electrostatic attraction. These devices are often used in professional environments but the main issue is the lack of standard applicable for such equipments. Some are very efficient in their range of application and safe to use while other might not be so efficient and more importantly, might be harmful as they could produce ozone, nitrogen oxides, formaldehydes, etc. from an initially clean air. Regardless of their advantages and disadvantages, this method to filter air pollution in Northern Thailand is not well-suited at anything but the removal of the finest particulates (Cheng Qian, 2021).

Ultraviolet purifiers work by emitting a strong UV-C source through the air flow to disinfect air from bacteria, fungi and viruses by damaging their nucleic acids. Although the process works in some settings such as ultraviolet germicidal irradiation; in practice, the UV exposure for air passing through home devices is 10 to 100x too short to significantly kill microbes. The lack of construction standard for such air purifiers and the fact that UV-C is an ionising radiation that can produce a considerable amount of ozone (FDA, 2020) brings the same potentially harmful effect than air ionization devices. In Northern Thailand, these purifiers are unable to filter particulate matter pollution and the pollution carries very little to no biological components and are therefore of little use.

9.2. Outdoor filtering equipment

This last section covers techniques sought to reduce air pollution in an outdoor situation without direct action on particulate matter emission sources. It includes various use of water filtering and wet deposition, scaled up filtering devices, meteorological actions, etc.

Water spraying is a common practice in Chiang Mai and some other cities in Northern Thailand during the burning season and is heavily promoted by local governments. It consists of using large water canons, spraying droplets in the air to induce wet deposition of particulate matter. Although the technique is used and effective in mine sites and dust-producing factories, etc., the spraying of water in open spaces shows no effect in urban environment such as Chiang Mai (Asif et al., 2022).

Atomizers also rely on wet deposition to clean air in outdoor settings. The most common use is through the cooling effect created by the endothermic evaporation of countless small water droplets produced by these devices. As a protection against particulate matter pollution, a mist of water droplets would create a wet barrier precipitating pollutants (Pollock & Organiscak, 2007). Results have shown that this technique might actually make things worse when meteorological conditions are hot and dry, by dissolving and reprecipitating soluble particulate matter that can reach hundreds of milligram per liters. In heavily polluted areas, atomizers might collect more particulates than they produce but in mildly to low air pollution conditions, the misting process and its evaporation can create an air pollution ten times higher than initial environmental conditions (Knight et al., 2021).

Giant air filters is another government-advertised technique that has been seen in Chiang Mai. A large HEPA filter is attached to a very large fan and would filter the air in the process. The technique is an upscaled version of indoor filtering but the effect is insignificant and impractical in an outdoor setting. Assuming a hypothetical urban closed system where no polluted air would be introduced, it would require thousands of fans with the power of large jet engines to have a significant effect over Chiang Mai metropolitan area after a couple of weeks.

Cloud seeding is a yearly practice in Thailand as it has been part of the Royal Rainmaking project since the mid 50’s and routinely applied since the 60’s. In Thailand, planes are loaded with various powdered solids (NaCl, $CaCl_2$, CO_2, $CO(NH_2)_2$ and AgI) to be released at different altitudes in the enhancement layer containing clouds in the hope of initiating precipitation leading to rainfall. It is normally used in Thailand to help farmers in their struggle against drought. Studies in the North-East of Thailand and Tak Province have provided mitigated results. Statistical evidence of positive effect of cloud-seeding initiatives is either weak (Chumchean & Bunthai, 2011; Nakburee et al., 2021), or inconclusive due to the lack of proof-of-concept and identification of physical processes (Silverman, 2001; Woodley et al., 2003) but the Thailand Royal RainMaking Project claims a success rate of 93% (89-100%) (Rodruepid, 2020) which is a very significant anomaly even among the best experiments attempted elsewhere. In recent years, there has been attempts to initiate precipitation during Northern Thailand dry season in order to clean up pollution as it is experimented in China, India, Korea, etc. (Agrawal et al., 2023; Ku et al., 2023). Cloud seeding requires specific meteorological conditions such as a high relative humidity (>60%) over the whole lower atmosphere, mildly turbulent conditions in the mixing layer, a considerable cloud cover, etc. All these conditions are very rarely present during the burning season, making it very unlikely that a cloud-seeding campaign would be successful and efforts are more likely just for public relations reasons and very likely not economically viable.

Finally, a few other alternatives have been suggested, designed or built in various places to limit air pollution in urban environments. Among them are active adsorbing surfaces in Japan, the Netherlands and the United Kingdom to collect NO_2 from the air but results are inconclusive and NO_2 is not a problematic pollutant in Northern Thailand. Improvements in vehicle emissions, urban gardening, etc. are other minor to important improvements that have occurred over decades and will have to be considered in major cities such as Chiang Mai. Filtering towers installed in cities such as Rotterdam, Beijing, Tianjin, Krakow, Xi’an, Delhi, etc. have also appeared since 2016. They can be either mostly energetically passive through solar updraft or powered. Filtering system is either through ionization or physical filtering (Cao et al., 2018a, b). In all cases, the efficiency and practicality of such constructions is unclear (Asif et al., 2022) as the process is similar to giant air filters and would require thousands of such units to have any significant effect on a large city.

10. Future trends, policies and issues

10.1. Future trends

10.1.1. Forecasts

Some general forecasts on the severity of a haze season can often be made months ahead depending on the status and trend of the ENSO. La Niña years are typically relatively wet with specific wind patterns that limit the frequency and size of forest fires and meteorological conditions that will accumulate aerosol near the ground (*). Some models have been developed with a focus on long term PM trends with some success on their ability to predict seasonal trends (Thongrod et al., 2022).

Aside from these broad forecasts, early attempts to make daily predictions for air pollution using standard meteorological patterns and high emission intensities of biomass burning have shown that the regressive predictive power for 24h is 76% while a full biomass burning emission analysis increases the 24h haze warning accuracy of prediction to 81% (Kim Oanh & Leelasakultum, 2011). Logical regression analysis where additional parameters are included to determine haze occurrence has been described as a long and complex process of analysis (Pimpunchat et al., 2014).

A comparison between predictive models with high temporal resolution using various input data (AOD, meteorological conditions, land use, satellite imagery, …) through different logical pathways (generalized additive models, linear and non-linear fixed-effects models, geographically and/or temporally weighted regressions, artificial neural network, support vector regressions, random forest models, etc.) have shown to have a systematic better prediction value than a simple linear model. However, there is no clear model that surpass others through validation (Kamthonklat et al., 2021).

Statistical studies of variations of PM2.5 concentration are used and tested for future prediction (Intarapak & Supapakorn, 2021), as well as interpolative mapping using GIS for PM10 emissions (Mitmark & Jinsart, 2017). With the development of machine learning, additional weather models have been designed for 24h prediction of PM2.5 over the Chiang Mai area (Singhaworawong & Wiwatwattana, 2019). Some interpolative models have also been designed to provide a continuous PM2.5 map of Northern Thailand using random forest kriging approach with input from satellite data (hotspots & gaseous emissions) such as Sentinel-5P, but also ground measurement and topography (Han et al., 2022).

Finally, some models are designed for specific purposes to assess and forecast effects and actions to be taken. Network analysis of PM2.5 using spatial and temporal distribution characteristics show that air pollution is affected by a clustering pattern, which is an important feature to manage adverse effects of particulate matter and policymaking (Yan & Wu, 2016). Some forecasting models also use a preference based for asymmetric predictive balance, which theoretically provide a better forecasting advice to sensitive individuals by selecting a higher over-prediction ratio (Watakajaturaphon & Phetpradap, 2020). To better manage sources of air pollution, models have also been developed to study fire spreading rate using topography, moisture content, fuel load and fuel mass of dead leaves and grass and meteorological parameters (Junpen et al., 2013b). This ability to accurately predict fire behaviour is important to plan and decide when to conduct a prescribed fire or suppress an existing fire.

10.1.2. Future sources

At a local urban level, the increase of population and urbanisation is systematically associated with an increase in urban sources of air pollution. But the increase of population in Thailand also has an effect on the agriculture sector, automatically increasing the mass of crop residue (Kasem & Thapa, 2012). The use of private vehicles has also dramatically increase in the last couple of decades, contributing significantly to the urban pollution (Pongthanaisawan & Sorapipatana, 2010). Between 1999 and 2019, the number of cars in Thailand excluding Bangkok has grown from 15.93 to 30.03 millions (Marks & Miller, 2021)

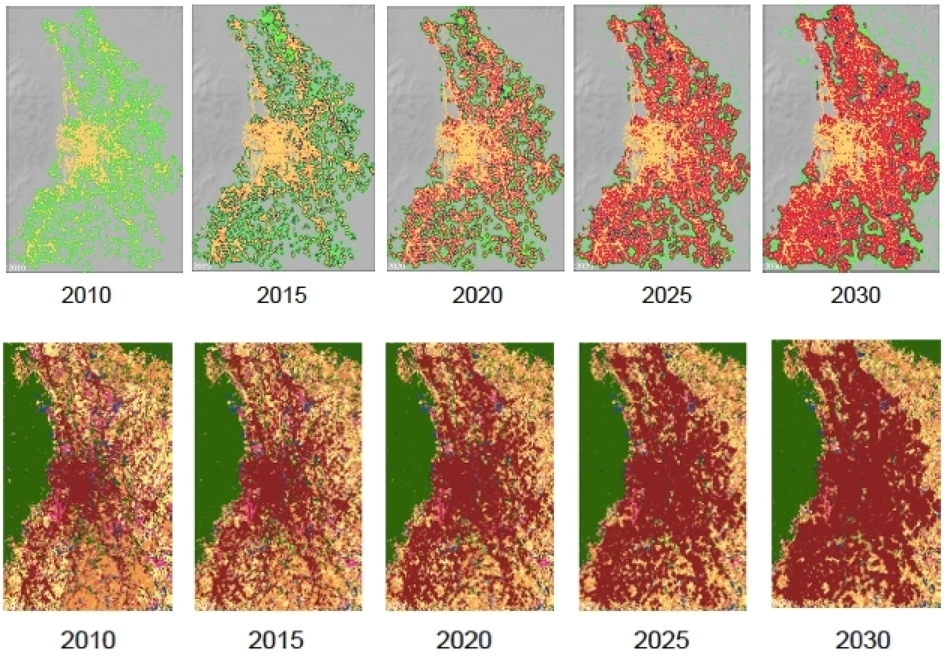

Figure 10.1. Prediction of urban growth (top) and simulated images of land usage (bottom) in Chiang Mai between 2010 and 2030 (modified from Sangawongse et al., 2011 in Kowsuvon & Sangawongse, 2016).

In parallel to the population and agriculture production growth, the type of crops change over time. In Northern Thailand and Isaan, sugarcane plantations had a significant growth in recent years due to the promotion of renewable energy such as bioethanol and gasohol. The produced mass of sugarcane is said to have doubled between 2005 and 2013 and the trend has continued in the following decade (Phairuang, 2021). An increasing surface use by sugarcane in Northern Thailand with unchanged practices, would lead to changes in the characteristics of air pollution (*).

Political decisions over agricultural output have also been identified as having an effect on emission sources. In 2012, the rice pledging scheme of the Yingluck Shinawatra government pushed farmers to boost their crop growing cycles with the indirect but predictable effect to increase rice field burning by 64%. This higher burning contribution was back to average values in 2016 (Junpen et al., 2018). It is not excluded that similar political ventures would occur in the future with a possible significant effect on air pollution.

In the past few decades, contract farming, which facilitate greatly market exchange, has been booming. It allows 2 to 3 crops per year mostly for the livestock feed industry (Sriboonchitta & Wiboonpoongse, 2008; Adeleke et al., 2017). The economic liberalism in ASEAN allowed the growth of Thai companies such as Charoen Pokphand Food Company and the Betagro group to expand corn production in the Mekong subregion. International agreements between ASEAN member states have increased land availability for crop production by hundreds of thousands of hectares. In Myanmar, the end of internal armed conflicts in 1990s has boosted the growth of crop production in Shan State and many other regions (Fongissara & Budharaksa, 2022). Despite the lack of strong academic evidence, many NGO activists group such as Greenpeace claim that corn is causing severe haze pollution and would be responsible of 30% of regional hotspots in Northern Thailand, Laos and Shan state (Fongissara & Budharaksa, 2022). The switch to large scale commercial farming is mostly associated with plains and valleys agriculture and it appears that the subject is rarely discussed among hilltribes (Adeleke et al., 2017) leaving some potential future development in that area. The local consequences of contract farming is the imperfect combustion of agricultural waste, producing gases, PAH, carbonaceous aerosols and other toxic compounds (Pongpiachan et al., 2009; 2013a, b; Pongpiachan & Paowa, 2015)).

10.1.3. Future atmospheric conditions

Over a few decades, atmospheric conditions are unlikely to change to be perceptible within the inter-annual variability. Trends could form from massive deforestation, large hydrological projects and urbanisation but the significance of the impact would have to be assessed (*).

However, in a context of climate change, some projections have been made to estimate the situation in an RCP8.5 model (IPCC, 2014). The results give an increase of 1 to 10 μg/m^3 of particulate matter in the dry season and a decrease of 10 to 20 μg/m^3 in the wet season, with an overall decrease for the yearly average. In such scenario, precipitation would decrease by 0.5 to 1 mm/day below local variation while temperature could increase of 1 to 9ºC with an average increase of 5-6ºC in the dry season and 2-3ºC in the wet season (Amnuaylojaroen et al., 2022b).

Since these models are solely atmospheric and do not take into account the obvious changes that would occur to agriculture and human activities in a RCP8.5 world, it remains very hypothetical as emission sources are likely to be modified. Other modeling from the same research group based on the extreme RCP8.5 scenario present some dreadful consequences with common 400 μg/m^3 values of PM2.5 for the next decade and projected health risks for young people (Amnuaylojaroen et al., 2022b, c; Amnuaylojaroen & Parasin, 2023). However, since the quality of validation of these models is very limited and important parameters and co-variables are left aside, it leaves considerable doubt on the accuracy of such modeling (*).

10.2. Public perception

10.2.1. Haze season severity

Historically, the haze season has been described more than a century ago in the diaries of foreigners working in Northern Siam (Eisenhofer, 1909; Weiler, 1913) and meteorological records in Chiang Mai (Kerr, 1910) with a systematic recording since 1972 (Suwanprasit et al., 2018). Until recently, most of the population has been indifferent to the issue but it eventually progressively shifted to vague annoyance and eventually fear & resentment in the urban population in recent years (*, Mostafanezhad & Evrard, 2021).

The source of haze and the cause of forest fires have been tracked back to local communities more than 40 years ago (Makarabhirom et al., 2002). Villagers themselves identify forest fires (60%) and waste burning (50%) as the main causes of haze while urban & industrial sources or climate change are rarely mentioned. Some hasty made social judgments on the causes of air pollution have fallen back on usual scapegoats such as the hilltribes population, which have been repeatedly targeted (communism, opium, deforestation, watershed management) to simplistically exclude ethnic Thai from these issues (Mostafanezhad & Evrard, 2021). Racially stereotyping hill tribes in their role for deforestation, fires and air pollution is an attitude that has been used in the past by the government as a state strategy to control natural resources (Beaulieu et al., 2023). As a result, the general perception among the population is that highland minorities are the major contributors to open burning and/or that smoke emission drift from Lao and Myanmar into Thailand (Adeleke et al., 2017). In recent years, local population (rural but also urban*) that regards their no-burning policy has enforced in their community feel they are no longer part of the cause of haze (Junlapeeya et al., 2023).

According to many publications and media archives, 2007 seems to be the year when people started to worried about haze in Northern Thailand (*, Pasukphun, 2018). This is mostly due to the extensive media coverage during March 2007, which is known to have been a particularly bad month in Northern Thailand air pollution records. From that point onwards, the rhetoric regarding the haze season has reached extremes with frequent claims such as ‘continuous haze since 2007’, ‘worst in the world’, ‘extremely toxic smog’, ‘constantly getting worse’, etc., all false or misinformed claims appearing periodically in various media and online social groups, but also in activists groups, official documents and even academic papers (see section 11.). The unbalanced and irrational media exposure of PM2.5 has been detrimental outside the region as national and international tourism suffers when compared with similar situation in other regions. Broad estimation of the impact of air pollution on tourism give a financial loss of half a billion baht per month for each 5% increase of PM2.5 monthly average in Chiang Mai (Namcome & Tansuchat, 2021).

From the mid-2000s onwards, social groups started to initiate a debate over air pollution with considerable bias initiated by the media and various organization excessively targeting hill-tribes, farmers or agro-industrial companies. However, these activists groups also attempted to make the government accountable in the 2010s onwards by requesting the application of WHO guidelines and a proper monitoring of particulate matter concentrations, etc. (Pardthaisong et al., 2018). It eventually resulted in pollution warning threshold to be lowered from 120 $\mu g/m^3$ (2010) to 50 $\mu g/m^3$ over a decade and another adjustment in 2023 to 37.5 $\mu g/m^3$ (*, Moran et al., 2019). It is worth noting that the updated WHO guidelines since 2021 have now become completely unrealistic in South-East Asia with an annual threshold of 15 $\mu g/m^3$ and 5 $\mu g/m^3$ for PM10 and PM2.5 respectively (*). The pressure from activist groups also helped in the monitoring of pollution by institutional groups and private contributors and has dramatically increased in northern Thailand and in neighbouring countries (Bach & Sirimongkalertkal, 2011).

Academically, there was some awareness among scholars of haze events in Northern Thailand in the 20th century. It is occasionally used as a comparison with other Asian cities due to the non-urban nature of the haze. In the early and mid-2000s, a handful of studies on particulate matter, PAH concentration, surveillance and modeling were available but by the end of the decade, the severity of the haze and its media exposure had initiated a plethora of health studies as well as an assessment of preventive measures. In the 2010s, more detailed studies on health impact of individuals and communities, effects of specific pollutants, causes of lung cancer, etc. have appeared and by the mid-2010s, air pollution sources were thoroughly examined (see references in appropriate sections).

The public perception of long term trends of air pollution in northern Thailand varies greatly for different groups. While the scientific evidence is unclear, all medium to long-term trends (increasing or decreasing) are not significant to be assessed by organoleptic means (Ma et al., 2019; Sukkhum et al., 2022). Among the urban population with higher socio-economic status, it is common to believe that haze events have considerably worsened in the last decade (*). The idea is supported by the media narrative and by a few academic papers that systematically lack any supporting scientific evidence or serious references to claim such trend (Nguitragool, 2011; Pimpunchat et al., 2014; Sereenonchai et al., 2020; Fongissara & Budharaksa, 2022).

Rural population (farmers & non-farmers) have a wider range of opinion with ~35 % who think it has decreased, 20 % that it is unchanged, 33 % who see it increasing and 10-20% who believe it fluctuates (Pardthaisong et al., 2018). Since studied medium and long-term trends (-0.8 to +0.3 $\mu g/m^3/yr$) are well below inter-annual variability (>50 $\mu g/m^3$ for maxima) (See section 3.1.2.), the last group holds the most correct answer as fluctuations are important and bad haze years are not particularly more abundant from one decade to another.

10.2.2. Health impact

The health impact of haze is acknowledged by all population groups. The urban population is overall more familiar and experience more effects from serious haze than rural population. It is partly due to topographic and weather features but also the level of education which has a direct correlation with the awareness of air pollution exposure (Sereenonchai et al., 2020). However, a significant proportion of the educated urban population in Northern Thailand has developed an unfounded or disproportionate fear of haze when compared to similar populations in other polluted environment. The majority of the urban population has however a relative understanding of the health effects and develop protection habits accordingly (*).

Among rural populations, 79% of villagers agree that haze affects the health of vulnerable people and of all weather phenomena (high heat, cold, high humidity, rainfall), smog is considered the worse (Junlapeeya et al., 2023). Despite that, only 66% would take action to limit emission (Pardthaisong et al., 2018) as the correlation with open-burning is not obviously clear for many (Adeleke et al., 2017). Despite the rural population having an unclear knowledge about how harmful is the haze, facial masks and staying indoor are common recommendations among this group (Adeleke et al., 2017). In highland areas (>1000m altitude), the rural population has less familiarity and lower exposure to air pollution. However, Thai, Akha and Lahu ethnic groups often mention that they have experienced worsening health symptoms in the past decade that they associate with forest fires. The specific impact on sensitive population (outdoor workers, elderly, sick, children) is unclear for this group (Adeleke et al., 2017).

On average, Thailand spend approximately 2 to 3 billion baht yearly on health care costs associated with air pollution, including masks and air purifiers (Chairattanawan & Patthirasinsiri, 2020; Singkam et al., 2022). Both urban and rural populations are willing to pay for protective masks, with the highest willingness in urban areas. On the other hand, rural populations are more willing to spend funds on haze management than self-protection (Sereenonchai et al., 2020). The willingness to pay for protective measures is directly linked to the demographic, socio-economic and educational levels of the different groups resulting in different risk perception towards severe haze event and the effect of protective personal equipment and devices. Financial abilities also have an effect. With an average monthly household income varying from 21000 THB in urban to 8000 THB in rural areas, the ability to pay for self-protection changes from 59-65% in low lands to 7-45% in highlands villagers for a mask (16-83 THB/piece). The economic and educational correlation is more visible for air purifiers (3700-12500 THB/piece) which is only an option for 10% of low lands villagers and not even considered for mountain populations. A similar trend is observed for A/C during high heat, considered as unaffordable for villagers (Junlapeeya et al., 2023). Oppositely, the funding support for local authorities (20 THB/year) is almost inexistent in the low lands (0-2%) while it’s up to 8-14% for high lands individuals (Sereenonchai et al., 2020). An alternative option among others that exist in villages is the presence of clean room shelters at community health centres of villages, funded by local authorities. Sensitive people can take some rest but the distance, the fear of communicable diseases (during COVID-19 pandemic) and a sort of enochlophobia limit its use when present (Junlapeeya et al., 2023).

10.2.3. Perception of actions

Activists were the first group to lead some actions against air pollution although it was initially indirectly through ecosystem conservation. In the 80s and early 90s, the social pressure limited the government plans for large-scale logging and public projects while forests were depopulated. In the 90s however, a schism appeared between eco-actors from the urban middle class for the protection of wild ecosystems that see local populations as ecological threats and would give little consideration for their livelihood while the other group is of rural origin, and while fighting for the protection of forests, they would also include interests and rights of people who live within and from forested areas. These two different views collide when the urban conservationists only see an approach where human influence must be removed while rural ‘forest guardians’ seek community participation in forest & land management with a possible redistribution to landless people (Beaulieu et al., 2023).

For two decades, the balance of power in the forest management debate gave no upper hand to these two approaches. In the last decade however, following the military coup of 2014, the government took the side of conservationist, leading to fire bans, large scale expropriation and reforestation, coinciding with an increasing public attention on air pollution (Beaulieu et al., 2023). The concept that was once just forest and land protection switched progressively to focus on seasonal haze and activists have now taken more decisive actions by supporting studies, taking legal steps and promoting education to prevent and manage air pollution although the overall misinformation by all kinds of media remains significant (*). Legal actions have peaked in 2023, when a group filed a partially successful lawsuit against the prime minister and the national environmental board for dereliction of duty towards the haze event.

State management of haze is seen by villagers as acceptable (23-27%) to good (48-56%) with only a minority of rural individuals realizing that government actions are not efficient and only applied to critical periods with no long-term management to deal with seasonal haze (Pardthaisong et al., 2018). This latter opinion is dominant among the urban population with higher socio-economic status (*).

In all populations (urban, low & high lands), the objective of preventive actions is to reduce or avoid crop residue burning with 40 to 60% of respondents seeing it as a primary objective. The second priority is to make information more available with urban population favouring the use of technology while high lands population prefers prescribed burning and a scientific approach to open burning (º, Sereenonchai et al., 2020).

In urban areas, information is mostly obtained through social media and internet in general; in rural areas, community announcement is the main source of information (63%), followed by television (51%) and radio (31%) (Chiramanee, 2016; Parthaisong et al., 2018; Junlapeeya et al., 2023). Despite the available information, villagers have an unclear knowledge of regulations and penalties. Even then, when policies such as burning ban or open-burning restrictions are acknowledged, these are often ignored. Open-burning is known to be illegal but often not reported by witnesses (Chiramanee, 2016; Adeleke et al., 2017; Parthaisong et al., 2018; Junlapeeya et al., 2023).

Strong restrictive government regulations are not supported by farmers (19%), at least when no alternative for non-burning is provided (42%) and overall, farmers prefer a gradual adjustment regarding haze control to protect their livelihood (Parthaisong et al., 2018). Government policies eventually discourage or forbid open burning at a local level, but alternatives such as the possibility to sell to a baler have to be provided (Junpen et al., 2018).

Non-farming rural individuals support strong government action regarding forest fires (32%) and waste-burning management (27%) with clear and regulative control (Pardthaisong et al., 2018). Urban populations are likely to support strong to very strong government action but they also have the lowest level of trust in local authority management (Sereenonchai et al., 2020).

10.3. Policies & Actions

10.3.1. Partially implemented and/or past & future actions

Traditional methods

Burning to clear and manage land is a regional traditional and cultural habit (Adeleke et al., 2017; Pasukphun, 2018). In the past (pre-90s), the village council would manage fire prevention with the setting up of a schedule of annual clearing of fire breaks done collectively 3 times per burning season (Makarabhirom et al., 2002). This process would reduce the scale of wildfires in the environment surrounding these communities. In some cases, cattle were brought to reduce forest fuel (Rakyutidharm, 2002) or perform prescribed burning where fire was used carefully to avoid spreading and damage to communal and private property. In those times, the reckless use of fire often led to identification of the culprit by the community, limiting such actions (Rakyutidharm, 2002).

In agricultural fields, burning would often require pruning and physical cleaning of fields a few weeks before burning. The decision to burn would depend on wind direction, slope, weather and would be partly controlled and limited by communal firebreaks, centripetal fire progression and downslope fire fronts (Rakyutidharm, 2002). In highlands, Swidden agriculture practiced by Karen and Lua tribes also had proper fire management and to some extent was used as a preventive measure against larger wildfires (Makarabhirom et al., 2002).

The issue of land rights

Changes in post-war Thailand land use and political trends have led to the rapid colonization of forest fringes and led to large degraded forest ecosystems in 1960-1980s. The development of villages in forested areas was tolerated and possibly encouraged by the government as a mean in their struggle against the communist insurgency (Beaulieu et al., 2023). With the end of the cold war in the mid-1980s, the decades of legal neglect from the government were reversed and large areas of forest were depopulated or confiscated with the aim of controlling land and groups of people and develop these areas for more important stakeholders. Estimation of population relocation since the 80s suggests a reduction from ~10 million to 2 million residents in the first decade and a continuing downslope trend to recent times (Kurashima & Jamroenprucksa, 2005; Leblond, 2010; Beaulieu et al., 2023).

Further changes in land rights in the 90s made all natural public resources owned by the state and it has therefore the responsibility to manage the forest and claim authority on most forested areas. At the government's insistence, the installation of weak local community leadership was required to limit the traditional management of forest using collective actions and root participation at village level (Tiyapairat, 2012). The administrative loss of forest resources by local communities happened at a time of significant economic and commercial farming development. It led to a quick loss of indigenous traditional knowledge and community responsibility in fire management (Makarabhirom et al., 2002).

As more intensive agriculture developed, so did individual farming at the depends of collective ownership, the abandonment of rotational shifting cultivation practices and altogether making fire management more difficult. Swidden agriculture has equally been discouraged and in both low lands and high lands farming areas, when a fire starts, there is no longer a community attempt to stop it as they have lost tenure and access to land (Makarabhirom et al., 2002). The development of these villages became unsustainable and government policies have in essence perpetuated the forest dependence of these small villages for non-timber products.

Fire prevention

Although fire breaks are used in the surrounding environments of communities and in frequented areas of national parks, fire breaks in most large forested areas of Northern Thailand are difficult to create and manage due to the topography, the tropical environment and the remoteness of some areas (*, Suriyawong et al., 2023).

Prescribed burning on the other hand, a normal practice in many countries, is possible due to the abundant leaf litter present in dry mixed dipterocarp forest of Northern and Western Thailand and thought to be manageable when incineration is done at the right time and place (Chernkhunthod & Hioki, 2020). The modelization of forest fire behaviour in Northern Thailand and the spatial recurrence of these fires will be an important tool for fire management (Kamthonklat et al., 2021). It will allow to plan prescribed fires and suppression of fires as well as the establishment of specific status for repeatable burning areas as emergency zones (Junpen et al., 2013b). So far, prescribed burning is a solution that has been applied in the colder months of the year. However, its application is still limited and can legally only be executed by the Department of Forestry. In practice, some prescribed burning surrounding villages is done with or without approved administrative oversight and are often mismanaged, leading to property damage and wildfires (*). There are organised by villages with voluntary participation of low-income farmers and labourers to create fire breaks and perform early burning and in some cases, extinguishing small scale wildfires threatening communal or religious properties (Parthaisong et al., 2018).

Burning bans are currently considered as the most efficient action to limit air pollution. In an urban environment such as Phayao, it has been shown that 85% of PM10 and 89% of PM2.5 originates from outside the city and modeling shows that for every percent of biomass burning that is avoided, the urban PM2.5 level would decrease by 0.7% (Pimonsree & Vongruang, 2018). With that idea in mind, the serious implementation of the burning ban occurred at the end of 2016. The plan consists of preventive actions from October to the ban itself, followed by coping measures during the burning ban and a 3rd phase, post-ban, when sustainable actions are taken, giving some permission to farmers to start agricultural fires.

Studies have shown a dramatic effect of the zero-burning policy on particulate matter concentration. The fire ban in affected provinces has produced a decrease in daily PM10 average of 5.3 to 34.3% and daily number of hotspots of 14.3 to 81.5% (º, Uttajug et al., 2022). A similar study comparing 2017-2018 PM2.5 levels with 2012-2015 shows a decrease down to 50% of PM2.5 and 50-80% of fire hotspots numbers compared to the 10 year average (º, Yabueng et al., 2020). Some data show however that the duration of the burning season is slightly extended (º, Thepnuan & Chantara, 2020; Yabueng et al., 2020). However, these studies ignore common confounders in air pollution and its inter-annual variability (i.e. La Niña vs El Niño & Neutral ENSO) that has a very important impact on the level of air pollution. By comparing a few years prior to 2016 (neutral or El Niño) atmospheric trends with post-burning ban years 2016-2018, which are La Niña, it creates a data bias that can only be managed using external standard of comparison (ex: Myanmar) or a proper reassessment using atmospheric models and historical data to compensate for the variability of meteorological data into years before and after 2016 (*). The data bias is exposed in post-2018 PM pollution where the 2016-2017 reduction is not observed and no obvious trend can be established (Beaulieu et al., 2023). For years such as 2019 and 2023, with considerable El Niño, it is clear that the effect of the zero-burning policy has to be properly assessed (*).

Regardless of the measures that could be taken to limit the amount of fires, there is some suggestions that in urban areas such as Chiang Mai, the air quality would remain bad if no biomass burning occur, due to traffic and general meteorological conditions (º, Moran et al., 2019). In 2020, an improvement was noticed in the air pollution in urban environment due to the COVID-19 lockdown, leading to a reduction in traffic, urban & industrial activities atmospheric emissions (Pongpiachan et al., 2021) and consequently, less hospital visits for cardiovascular and respiratory issues (Saengsawang & Phosri, 2023).

Fire management

According to the law, all natural public resources are owned and managed by the state but in practice, openly accessible to anyone. During the establishment of national parks and protected forests, some forest villages have been relocated outside of these areas. As the newly defined areas are accessible to outsiders, the fire risk remains unmodified and no local population is present to attempt to stop a wildfire in an early stage. It relies mostly on the FFCD which hasn't enough manpower to manage all fires starting at the beginning of the burning season as the land/human ratio exceed 100 km^2/official (Chiramanee, 2016).

Most forest fires of the past couple of decades are now often unwanted and out of control. Local people have become careless how they treat the environment, their communal and private properties as they have no feeling of ownership over those natural resources. It is now no longer possible to identify culprits of reckless burning, reinforced by increasing accessibility with starting fires occurring near frequented roads and tracks at the base of hills where it can progress rapidly upward and in intensity while being quickly unattended.

As the state is incapable of managing and maintaining all forested public areas and officially barred local people from managing it, it contributed to a resource degradation and unmanageable haze issues (Rakyutidharm, 2002). To cover for that deficiency, official attempts are made to impose a duty of care to local people as they are the most affected by mismanaged forest fire (loss of resources, drought, erosion, crop failure, etc.) while not giving them any right to manage forested areas. In this conflicting situation, the state rejects all local knowledge and traditional management techniques using fires for forested areas, leaving the responsibility solely on the FFCD which is seen in some cases as suspicious by local villagers who interpret prescribed fires and some wild fires as a form of corruption where the FFCD would benefit of fire activity, while the FFCD sees this blame as malicious actions from villagers (Rakyutidharm, 2002).

Unless strong actions can be taken and implemented from a centralized government down to the village level, no improvement is expected with the approach of fire prevention and management. The only successful implementation of forest fire control in the region is in Xishuangbanna (Chiang Hung) in southern Yunnan, China, where the tight control of the Chinese government on fire activities (Teng et al., 2016) eventually led to basically no local fires in natural reserves and a reduction of 50% of fires over the province. Most of the air pollution in the area is advected from the south-west (Ma et al., 2019).

Alternatives to burning

The zero-burning policy exists since 2013 but strict implementation and legal enforcement only started in 2016 with a control of open-burning for 60 days from February to April (Junpen et al., 2018; Yabueng et al., 2020). The extension of the burning ban to 90 days and 5000 THB rewards to identify culprits had limited success (Gebhart, 2013; Pasukphun, 2018) due partly to the lack of education among the rural population that affects their understanding of the implications for soil, human & animal health (Moran et al., 2019). Among rural people who abide by the rules of the burning ban, it is rarely done due to health & environmental knowledge but by fear of legal consequences. In practice, local people are more afraid and pay more respect to unwritten community laws set by community leaders in their area than official laws that are barely enforced (Chiramanee, 2016). From their point of view, zero-burning policies emanating from the government are seen more as a way to control rural people behaviour rather than reducing open-burning and haze problems (Adeleke et al., 2017).

The compliant side of a strict enforcement is also a cause to the limited success of these policies. Officials responsible for a rural area generally have strong connection with the community and can be reluctant to enforce the law due to closer relationships, empathy towards offenders, loss of popularity and fear of villagers protestations. Officials in remote and mountainous areas, like local people, have little understanding of the regional situation and consequences and have limited motivation due to a severe lack of manpower and intensive work during the burning season for minimal additional pay (Chiramanee, 2016).

Several authors admit that banning forest burning without appropriate management will not alleviate the risk of forest fires (Janta et al.,2020; Chankaew et al., 2022) and lack sustainability. Some drive for the extraction of non-timber forest products will still be present and it will be required to identify alternative solutions and source of income (Makarabhirom et al.
, 2002; Adam et al., 2021). Some growing alternatives seem possible (bamboos, some herbs, etc.) while other (mushrooms) have so far failed (Anh et al., 2023). These solutions will have to be accompanied with an improvement in public awareness about the adverse impact of biomass burning, an adequate man power to extinguish existing fires and the use of various remote technology to identify small scale fires (*, Adam et al., 2021)

Alternative to open-burning of crops and rice paddies has solutions that are already applied at a small scale or in other areas of Thailand. The valorization of biomass through biorefinery to produce energy products (bioethanol, biogas, biohydrogen, charcoal) is a suggested alternative to crop burning (Suriyawong et al., 2023) and can be a semi-direct agro-industrial energy source (Moran et al., 2019). These alternatives have to be economically profitable. In hilltribes and highlands Thai farmers, the average income per person is 3000 to 4000 THB/month with production costs of 6000-8000 THB/rai for rice, which essentially mean that alternatives to burning requires additional funds to employ laborers to pile and remove rice residues (Adeleke et al., 2017). Some mountainous areas also have cultivations in high, remote and steep terrain where burning probably will remain the only cost effective way to remove agricultural residues (Chiramanee, 2016).

Specific agricultural practices such as leaving straws in field to improve soil organic matter and texture (Sun et al., 2016), triple cropping system alternating two rice harvests with mung beans (Arunrat et al., 2018), expansion of cattle farming as a way to manage straw recycling as feed (Jomjunyong & Intaruccomporn, 2019) are all suggestions that have been made in academic papers and are occasionally applied by rural populations. Although some ethnic groups (i.e. Lahu, Karen) and Thai villages are more receptive to such changes and have a subsistence orientated approach of agriculture, other hilltribes (i.e. Akha, Hmong) are more commercially focused and conservative of their traditional agricultural methods. Approaches to alternative to burning will have to differ depending on the region and population (Adeleke et al., 2017; Beaulieu et al., 2023).

Deeper changes

The permanent reduction of the source of haze is thought to be in the management of forests integrating indigenous knowledge, conservation values and sustainable livelihood with the full involvement of the community in fire management. Such ideal solution has been identified more than two decades ago as likely the only way forward (Chamarik & Santasombut, 1994; Wasee, 1996; Sukwong, 1998; Ganz et al., 2001; Makarabhirom et al., 2002). Some optimistic views on this approach are still widely distributed by scholars, activists and foundations (Jainontee et al., 2022; Tanpipat et al., 2022), suggesting that fire management has to be integrated into the communities, providing them with a good understanding of ecology under strong village leadership, providing vague idealistic concepts that have been shown to be problematic in practice.

Some hilltribes communities have developed sustainable farming, water management and effective fire management, and under the auspices of a royal project, are able to fund their efforts against wildfires (tools, equipment, fire breaks, patrols, firefighter support) by selling forest products (bamboo shoots, honey, etc.) or through external funds. Some communities also make use of new technologies such as FIRMS, LCS and CCTV to manage wildfires (Tanpipat et al., 2022). Although some of these solutions might not be applicable on the long term or spread to other communities, there is evidence that the social pressure created from the problem-solving situation in specific villages has provided 80% of rural populations with a better understanding of forest protection that add to the 20% that always valued sustainable forest management (Beaulieu et al., 2023).

Mae Chaem district in SW Chiang Mai province, has been the subject of many studies as it has a high fire hotspot count, various agricultural lands and forested areas that can be used as comparison with other areas and several sub-district have been used for case study of law enforcement (Chiramanee, 2016), alternative agricultural practices (Arunrat et al., 2018; Jomjunyong & Intaruccomporn, 2019) and social studies on various communities (Sereenonchai et al., 2020; Mostafanezhad & Evrard, 2021; Beaulieu et al., 2023). The Mae Cham modeled is an ongoing 2002 experiment designed to be a participatory, multi-stakeholder forest landscape restoration initiative in order to limit wildfires and agricultural fires into a sustainable development (Beaulieu et al., 2023). Over the years, some adjustment have been made to the model but considerable disparity exists between the goals sought to be achieved and the strategies used in practice.

One of the core idea of the Mae Chaem project is to leave deforested areas based on 2002 air surveys as it is while more recently deforested zone (2011, 2016) would eventually lead to expropriation and reforestation and the existing forest left untouched. In theory, this seems to be a clear cut strategy but fallowed land, which is a traditional type of agriculture in the highlands, is considered as recently deforested leaving communities with an average 53.8% loss of cultivated land, reaching 88.2% in some villages (Beaulieu et al., 2023). An official consultation of highland farmers is made to prevent such mistakes but the reality is that land limits and their status are officially predetermined and the result of negotiations is irrelevant (Leblond, 2011). For authorities, many stakeholders and strictly conservationist activists groups, the resulting map appears to be robust and scientifically proven under the unfounded and unsupported claims that Forestry authorities use remote-sensing data, high-resolution satellite imagery and ground assessment in their decisions. Such lack of transparency and authoritative approach in a project supposed to be fully participatory with the local population leave some doubt towards its sustainability (Beaulieu et al., 2023). Without changes in land rights legislation, transparency in official decisions and a true participation of local population that is not just a cover for obedience, the current Mae Chaem model cannot be generalized as it would not bring any hope of a regionally sustainable, viable and credible solution for highland population and northern Thailand as a whole. True social responsibility of local populations towards their environment, with some type of genuine concertation on forest & fire management will be necessary (Makarabhirom et al., 2002; Pongpiachan & Paowa, 2015).

10.3.2. National administrative framework

Thailand has historically a very centralized approach to governance. The transition from the absolute Rattanakosin monarchy to constitutional Siam in 1932 has implemented no changes to the extreme centralization of power in Bangkok. This hierarchical structure remained broadly unchanged with the exception of the 1997 constitution that had some genuine attempts at decentralization but in practice, a very strong unitary state remained.

In 1992, the National Environmental Quality Act provided some legal framework to act on air pollution and a number of legislative instruments were issued to allow devolved environmental management functions to local provincial governments (Aghiros, 2001; Kritsanaphan & Sajor, 2011). However, despite the apparent decentralization, all policies were implemented directly from a national authority (Tiyapairat & Sajor, 2012).

Following the catastrophic 1997 Indonesian fires and the requirements of the newly established Thai constitution, a national action plan was put in place in Thailand to respond to hazardous levels of haze in Southern Thailand. Considering the transboundary nature of the pollution, policies were produced by the central government and no decentralization was necessary (*, Tiyapairat, 2012).

In the decade that followed, Thailand national policy towards haze management became an amalgam of existing policies in the US, EU and local actions plans done elsewhere in Thailand (Bangkok, Isaan, South). Three sources were identified by the 2006 Forest Fire Management as forest, farming and garbage burning with the hope to reach a resolution based on public relations, regulatory practices and local participation. The haze management that includes the prevention of forest fires and open burning and the implementation of a national emergency plan and risk monitoring was also established in the 2006-2010 period. The central government also included pre-haze burning controls and patrolling and extinguishing existing fires during serious haze episodes but budget allocation, technology for monitoring and forecasting, post-disaster participation and pre-haze burning reduction were never political and law enforcement priorities (Pardthaisong et al., 2018; Beaulieu et al., 2023).

In March 2007, the level of pollution in the North created sufficient social pressure on the central government for more action, resulting in a push for more policies with the same centralized approach that was used in the past. Some devolved governance was created at a provincial level but it did not allow any active role in tackling the haze problem. In practice, the situation was even more fruitless as these new set of policies were not known from lower administrative offices to be integrated into action (Tiyapairat, 2012). The action plan written in Bangkok, which consisted of controlling open burning, forest fires and public information, had no hold on the local population and administration and the one-size-fits-all attitude was a failure. The only local mandate at provincial level was applied to data collection and research on haze problems but not on preventive or fire fighting measures (Tiyapairat & Sajor, 2012).

In 2010, another particularly polluted year, the parliament passed an approval for urgent solving of haze events in Upper North Thailand, leading to urgent and long term strategies domestically and internationally to reduce the level of atmospheric pollution (Tiyapairat, 2012). A main outcome was the implementation of strict fire prevention measures (2011-2019) (Beaulieu et al., 2023) but the highly regulatory policy regime in Thailand regarding vegetation burning and haze pollution is set in a command-and-control type of philosophy. The authoritative approach spearheaded by the central government failed to take into account local conditions, the sources of haze and causes of burning, local people traditional practices and motivations and the traditional knowledge used to tackle this seasonal phenomenon (Scott, 1998). In the central government minds, their policies should cascade down unaltered to provincial, district, sub-district and village authorities and somehow applicable to local conditions (Tiyapairat & Sajor, 2012).

Eventually, adjustment in policies allowed some horizontal integration with cooperation between environmental, natural resources, forestry, agriculture, public health, transport, education and interior administrative structures and attempts at vertical integration with the application of central government policies into specific administration bodies (criminal code, disaster prevention, disaster management, etc.) (Tiyapairat, 2012). In practice however, despite various governmental approach, hierarchical integration and pseudo-holistic consideration have mostly failed (*). Since 2007, annual national meetings and regular provincial meetings are organised to tackle the haze problem but these meetings are at best, only attended by minor representative of each ministry, with no effective power to commit to anything and ministries remains ultimately too compartmentalised to have a coherent management of the haze problem. At provincial level, meetings are mostly regular sessions of information sharing between ministries where strictly pre-defined plan set up by ministries at higher level are presented but no collaborated action can form from these meetings. Even the provincial environmental management guidelines are set at a national level and the exercise of authority and political discretion of appointed provincial governors is equally under the direction of the Ministry of the Interior. Other sections of the provincial administration (forestry, disaster management, agriculture, land development) are subject to a similar national authority (Tiyapairat & Sajor, 2012).

In 2013, as part of the National Haze Action Plan originally set in 2004 to develop firebreaks, fire prevention and ‘villages free from burning’ campaigns, the burning ban was put in place but had basically no effect due to the lack of strict prohibitory measures and ultimately, when acted, it only change the time when residue burning occurred (either at other time of the day or the season)(Adeleke et al., 2017). In 2014, following the military coup, the junta requested a less single command approach for haze management from the Chiang Mai government to a top-down structure during haze events and a participatory strategy outside of it (Parthaisong et al., 2018; Beaulieu et al., 2023). This approach could possible create some converging point between eco-urban conservationist approaches and rural forest guardians management practices. The top-down legal structure led to the stricter implementation of the burning ban following the 2016 haze event with significant penalties for illegal burning (Uttajug et al., 2022) but a true participatory action outside the haze season remains elusive.

At the present time, all top-down government regulations on burning and haze management haven’t accomplished most of their objectives (Pardthaisong et al., 2018). The lack of spatial & temporal analysis (topography, human factors, meteorology,…), the absence of pre-critical management, an ineffective early warning system, a completely inappropriate budget allocation during the critical phase and a one-way communication between local wisdom and traditions, academic knowledge, private and civil society standpoints, all have contributed to the lack of significant progress in reducing the severity of the haze season (*). Overall, the governmental effort to solve air pollution in Northern Thailand is still considered very low (Sutthichamethee & Ariyasajjakorn, 2018) and prevention, control and information on health, economic and environmental impacts are only short lived and short term (Chairattanawan & Patthirasinsiri, 2020).

10.3.3. Limitations of the centralized and standard regulatory approach

With the central government emulating existing policies in western countries and comparisons with situations where the pollution is a different nature (Bangkok (urban), South (transboundary agro-industrial), Isaan (agricultural)), the direct application of unadapted methods to Northern Thailand is mostly futile (Tiyapairat & Sajor, 2012). Despite more than a decade of research on causes and sources of pollution in Northern Thailand, the Bangkok-urban centric attitude is still present in national and international reports where the northern issue is voluntary ignored and some nation-wide publications reflect this situation (Kiesewetter et al., 2023).

Chiang Mai province shows 35-50% of its revenue from manufacturing and retail and only 10% from agriculture, hunting and forestry as a result of standing as the most urbanised centre in Northern Thailand. However, a very large majority of people living in the province work in agriculture, with another 15% in tourism, giving a very different demographic landscape compared to fully rural provinces or central and southern regions of Thailand. In addition, the province also has a sizable (~15%) population of hilltribes (Karen, Hmong, Lahu, Meo, Lisu, Lua, Akha, Paong, Dai, Shan, etc.) often set as agriculturist societies in mountainous area. Penalization of pollution emitters in such situation cannot be comparable to a region where the main income would be agriculture or an urban region where traffic and industry are the main source of pollution.

The main source of fires, recorded by the ministry of forestry in Chiang Mai has been identified for a long time as mostly forest burning but this simple factual observation is routinely ignored when setting up actions towards the haze problem at the national level since actions directly against agricultural burning is more easily implemented. The identification of causes of forest burning have also been broadly identical for the past two decades, with 40-50% occurring for the collection of non-timber forests products, 20-25% for hunting, 10-20% for residue burning and a few percent for cattle grazing, conflicts, illegal logging, criminal intentions, etc. In some specific areas, Swidden cultivation is also an important cause and can contribute to 60% of local fires between February and April (Leelasakultum, 2009). Despite the evidence that agriculture residue burning is a significant but minor contributor in the north-western part of Thailand, a lot of political and media emphasis is aimed at the penalization of farmers while forest fires are ignored.

When forest causes are taken into account, since there is no province- or municipality-generated plans to deal with that source of haze and all actions are planned by the central government, the problem is solely seen as a regulatory issue solved by administrative task of control and penalizing perpetrators. This practice broadly failed as is does not take the ground reality and the vast heterogeneity and complexity of local conditions and drivers of forest burning behaviour into account (Tiyapairat & Sajor, 2012). Even the availability of funds allocated towards haze prevention are a symptom of this failure of understanding the situation. While Chiang Mai province is at the forefront in the application of policies through vertical integration, serious limitations are observed since allocated funds cannot be used outside the administrative jurisdiction and funds sourced from the national government are largely insufficient and often represent less than 5% of the requested amounts by provinces to effectively fight air pollution. Since locally generated funds for disaster management & prevention, crime, etc. are prioritised by local governing bodies to issues that strongly and directly affect their electorate, such as drought, flooding and poverty, the more abstractive action of haze prevention is secondary and local government rely on that minimal financial help from the central government (Tiyapairat, 2012).

10.3.4. International administrative framework

At the international level, ASEAN members have produced some initiatives since the early 80s when it was initially acknowledged that air pollution is an issue in South-East Asia and transboundary pollution has to be addressed. Eventually, in 1995, a cooperation plan for transboundary haze was published and actioned in Thailand in 1997.

The fundamental issue with ASEAN agreements is the lack of liability or compensation scheme to hold responsibility between member states (Tiyapairat, 2012). It is seen as part of the non-intervention aspect of the ASEAN treaty, resulting in simplistic policies focussing on negotiation rather than direct problem solving. The whole approach towards air pollution is diplomatic, based on consensus building, non-interference in domestic management and a major stumbling block preventing any intrusive in-country haze action plan which could have any significance (Fogissara & Budharaksa, 2022). As a result, the ASEAN solution is to respect each member state's framing of the haze problem and craft some international cooperation around it, while staying clear from policy debates and decisions that would be seen as interference within a member state (Tiyapairat & Sajor, 2012).

In that state of thoughts, Thailand has identified the haze problem through biomass burning which is seen as a manifestation of a deficit of regulatory regime and enforcement. The simplification of the haze problem as a mere administrative task of fire suppression, prevention and monitoring excluding to take local conditions into account in Malaysia, Indonesia and Southern Thailand has failed in these regions (Tiyapairat & Sajor, 2012) and in Northern Thailand (Murdyarso et al., 2004). Ultimately, ASEAN policies are hardly workable in some regions and applies at best, to the symptoms of haze pollution and biomass burning but never address the underlying causes (Tiyapairat & Sajor, 2012). As a result, the ASEAN agreement of 2002 on transboundary haze pollution was found to be ineffective (Tan, 2005; Adam et al., 2021). In 2011, the ASEAN meeting passed a resolution to reduce hotspots below 75000 in that year and 50000 by 2015 (Bach & Sirimongkalertkal, 2011), which is effectively only reached when weather conditions allow it (*). Eventually, additional management strategy for zero-burning practices were developed in the second half of 2010s with some partial success (Pasukphun, 2018).

Over the three decades of ASEAN agreements about haze events and transboundary pollution, the only improvement is towards monitoring (Bach & Sirimongkalertkal, 2011) as such action satisfies the non-interference clause of ASEAN (Fogissara & Budharaksa, 2022). PM10 is continuously monitored in Thailand for some time (Sirimonkonlertkun, 2018), followed by PM2.5 a few years later but it is the only country in the northern region with such monitoring system. Other systems in Myanmar and Laos are sponsored by Thailand or rely on satellite data.

Ultimately, for the haze season to be completely managed, a strong ASEAN agreement binding all member states will be necessary to achieve a significant outcome. It would require to modify the agreement charter to address the root causes of forest and agricultural burning, allow controlled burning, prevention and monitoring while being legally binding (Heilmann, 2015; Timwat, 2016; Fogissara & Budharaksa, 2022).

11. Metascientific discussion

This section is not a rigorous metascientific analysis of research and publications on air pollution in Northern Thailand but rather a summary of notes taken while reviewing publications on the topic that is estimated to have an impact on the overall quality of pollution-related research in this region. It only applies to the >200 papers that have Northern Thailand Air Pollution as a main topic and were used to write this review. It is mostly a personal take on the quality of the research published and communicated which has somewhat made this review a complicated task due to the poor ontological value of many claims.

Air pollution in Chiang Mai and Northern Thailand has become a hot discussion topic in the past decade and along with that, scientific publications have equally increased. While the subject is already mentioned in publications in the 90s and earlier (Matsushita et al., 1987, 1989; Vatanasapt et al., 1993; Koyano et al. 1998), it remained a relatively low interest research topic. In 2007, a particularly bad burning season initiated a strong academic interest and in the subsequent years, the number of publications has steadily increased. While only a handful of publications can be found in the decade before 2007, the 2007-2017 decade has around 60 publications dedicated to Northern Thailand pollution and more than a hundred since then.

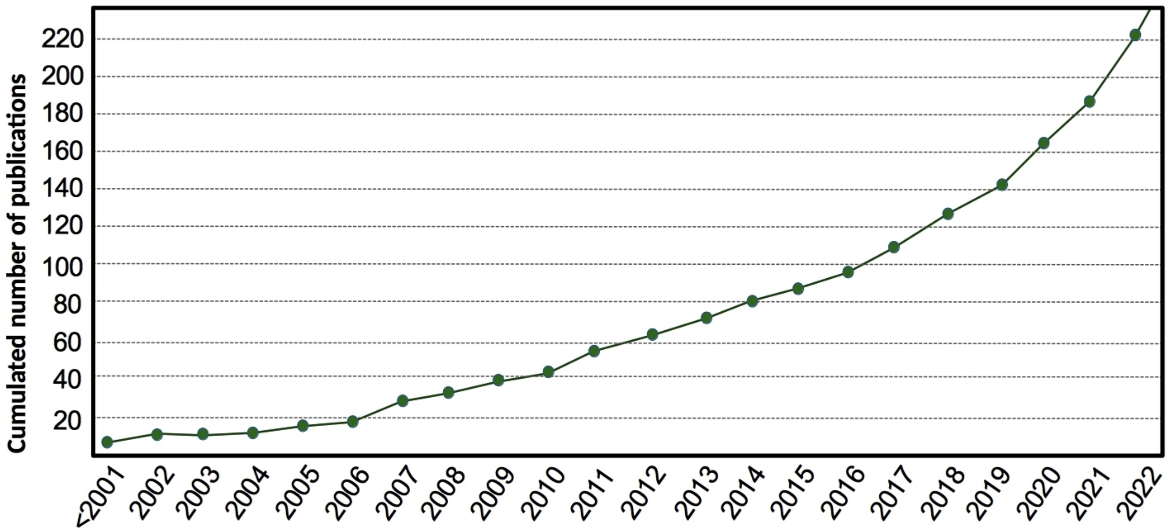

Figure 11.1. Cumulated number of peer-reviewed publications (1989-2023) on Northern Thailand air pollution used in this review

Around 50% of publications are produced by Northern Thailand universities and institutions (hospitals, NARIT, etc.) in Chiang Mai, Chiang Rai, Phayao, Lampang, Phitsanulok, Uttaradit, etc. on various subjects. In recent years, the number of publications produced by non-Thai universities has considerably increased and represent now almost a ¼ of all publications but a significant number of these publications are lead by Thai authors. Finally, Bangkok universities also represent a significant number of publications, often in the medical field (Fig. 11.2).

The topics of interest of these papers are mostly the characterization of particulate matter and air pollution (~40%), Health impact (~20%), Source identification (~20%) and around 20% of publications equally distributed between various models & forecasting, remote sensing, meteorology, policies and social studies. There is no obvious change in the proportion between different topics between 2007 and 2023 (Fig. 11.3).

In the past decade, a large amount of information and analysis has been made available to understand better this yearly atmospheric phenomenon. However, among this large number of research papers, reports and other documents, now reaching several dozens per year, the quality, even among academic research papers, is very variable. This variability requires a constant critical approach of many papers when considering relationships reached in discussions and conclusions but also in some cases the whole methodology and the dataset itself.

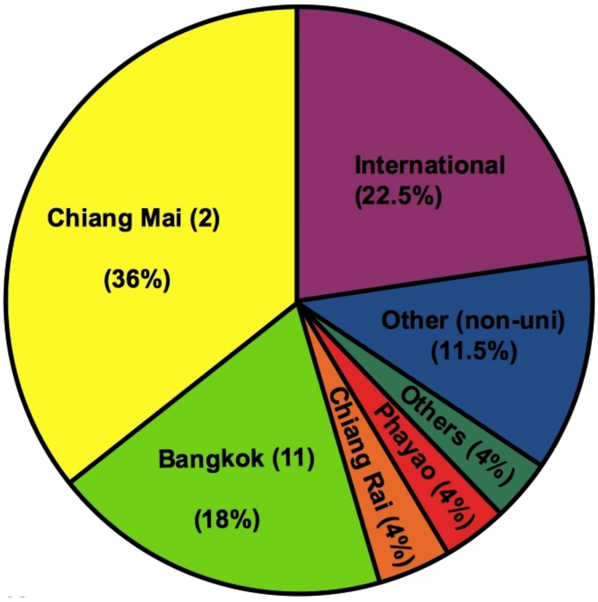

Figure 11.2. Proportion of origin of published research material on Northern Thailand air pollution between 1989 and 2023. Calculations are made based on equal contributions of each author affiliated to an institution. Chiang Mai includes 2 universities, Bangkok, 11 universities. Other (non-uni) category includes non university affiliated hospitals, government institutions and non-affiliated research centers publishing peer-reviewed material .Others include 1.5% from Hat Yai, 0.8% Nakhon Ratchasima, 0.5% Khon Kaen, 0.5% Phitsanulok, 0.4% Lampang, 0.2% Uttaradit and 0.1% Nakhon Phanom).

Most papers published in local journals (national & university publishers) are of medium to low quality but it is not uncommon to find similar material of poor scientific quality in international journals. The quality test fails on several points and varies from author to author (examples are taken from publications in this review). The following list are features found in at least 3 or 4 papers in the present review that would represent more than 1% of publications but it is not uncommon to have some criticism here below represented in up to 20% of publications on a specific subject.

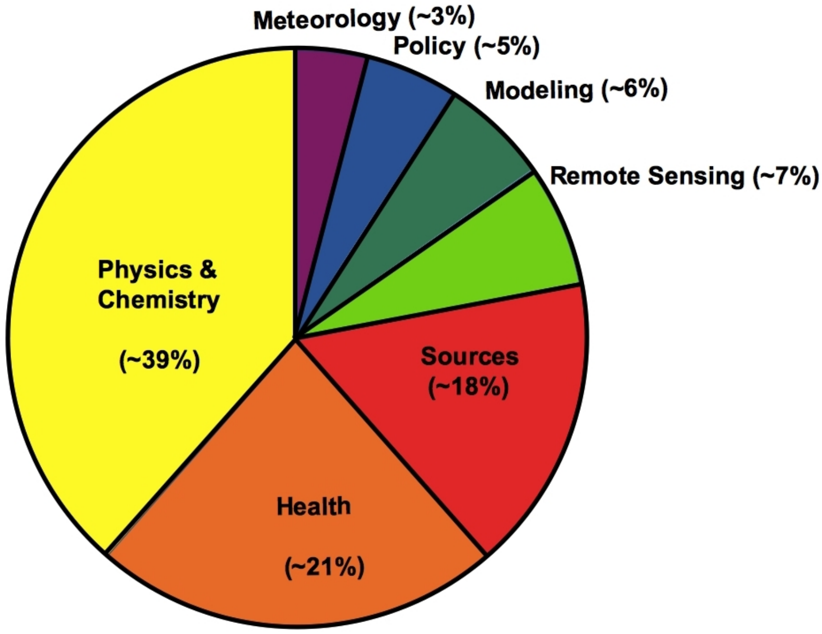

Figure 11.3. Proportion of topics covered in published research material on Northern Thailand air pollution between 1989 and 2023.

11.1. Statistical significance

In some fields, statistics and probabilities are an inclusive part of the dataset and some disciplines (i.e. health studies) generally provide dataset that are relatively sound statistically and in many cases, a discussion that relies on these numbers and their significance. However, many other papers covering physical and chemical properties of air pollution, some health impacts and some social studies have a few issues:

- ***Dataset with statistically insignificant variations*** that are used for extensive discussion and conclusions on an observed variation at least an order of magnitude lower than the natural variation, regardless of its origin. (i.e. a 1% variation when 2σ of the whole dataset is 20% with no explanation on how discriminative it is; the non-consideration of published or measured detection and quantification limits in discussion over chemical concentrations, etc.)

- ***Small dataset with significant observations*** discussed to reach strong conclusions on a limited dataset that lose all pertinence in a more extended dataset interpreted as a form of cherry-picking. (i.e. a trend of 5% in a selected dataset when the whole dataset has a variability of 250%; a long term trend established on 3 years of data with vastly different atmospheric setup that would require 2 decades of data to establish a statistically significant trend).

- ***Statistically unreliable surveys*** in social sciences where the amount of data is largely insufficient to proceed in identifying causes, comparison and conclusions (i.e. a handful of individuals in a single village would supposedly be representative of a whole province)

11.2. Sloppy scientific writing

This section covers mistakes directly linked to scientific writing and independent from the language used by the author. It is a type of mistake that leaves some doubt on the quality of the research and if any reviewing was ever performed on these manuscripts prior to publication. These issues notably cover:

- ***Basic spelling mistakes in scientific terms***. The English writing might be fine, but specific scientific words have a very unusual wording giving an unprofessional outlook or even a pseudoscientific feeling to the study (i.e. the “Latino phenomenon” for “El Niño phenomenon”; “reproductive combustion” or “cation power generation” for an energy source concept that could not be guessed by the author of the present review).

- ***Gross errors in the use of scientific units***, giving the impression that the author has no clue what he is actually researching (i.e. wrong units, confusion between mass, mass concentration, mass flux; unnecessary use of archaic non-SI unit or systematically wrong SI unit terminology).

- ***Choice of words*** that are not due to an inadequate level of English (or the native language of the author) (i.e. the use of ‘strong’ correlation for what most authors would consider a weak correlation coefficient, and then use the term to rhetorically strengthen the weak correlation in discussions and lead to strong conclusions).

11.3. Biases

A series of biases that might be involuntary in some cases, but are so basic that it leaves most of the study as a superficial or misleading approach of the subject. Some other biases are likely done consciously and cannot be considered as objective scientific research.

- ***Biases by omission***, more commonly through avoiding references to research that disprove the claim to strengthen discussions & conclusions (i.e. the effect of maize burning on air pollution by not citing papers that disprove (or prove for that matter) this source or show that other sources are more important).

- ***Biases by lack of scope & limitations*** where a conclusion is reached without including all obvious variables into consideration (i.e. effect of global warming avoiding to specify the strict meteorological nature of the study and not including any mention of dominant factors when assessing the future of air pollution).

- ***Bias in reference selection*** by orientating the study into a specific issue without mentioning the restrictiveness of the research (i.e. framing northern Thailand air pollution as the result of commercial agriculture and developing a methodology that exclude other (ex: wildfire, traffic) influences.

- ***Social studies with inadequate questionnaires*** leading to potentially misguided conclusions (i.e. rural population survey on the cause of fires, excluding any question where an open opinion could be provided on the source of haze).

- ***Ad hoc hypotheses*** to exclude data in a way that it won't affect the conclusion the author want to reach (i.e. fire ban is effective and the year that doesn't fit the trend is due to pollution from other countries).

- ***Directed studies*** where a selection of initial hypotheses with no objective approach is chosen, followed by a rhetorical style so that these initial hypotheses become facts (i.e. 450 $\mu g/m^3$ of PM10 is mostly due to maize burning). It is unfortunately a common practice in social science but rarer in natural sciences.

11.4. Methodological errors

It includes concept errors that makes a study poorly thought with fundamental scientific mistakes that void conclusions. It is quite common in all disciplines.

- ***Lack of identification of confounders*** and sometimes obvious co-variables which would affect observed correlations. Health sciences generally take these factors in good consideration but when natural science data is incorporated, some articles fail to perform a thorough analysis of variables. (i.e. gaseous aerosols causing health effects (despite being well below a health threshold) that are in fact caused by particulate matter strongly correlated with the studied gas; the particulate matter variation in concentration is caused by a change of wind pattern when in fact rainfall is the main factor with rain being associated with wind variations).

- ***Confusion between consequences and causation*** with sometimes confounding statements (i.e. It is because Thai government has set a lower AQI standard that a high level of the population live in polluted areas (*sic*)).

- ***Problematic model validation*** and application where lengthy discussions eventually hide the pitfalls of the model. (i.e. Long term predictive model validated on single year correlation (giving a trivial excellent fit) but very poor predictive values in a multi-year correlation).

- ***Lack of independent data*** serving as control sample when conditions changes (i.e. effect of zero-burning policy not compared with region with no policies for a same year).

- ***Unsuitable team of investigators*** where non-expert scientists provide a very basic interpretation of a field that should be properly investigated (i.e. element:element plotting of geochemical data with no specific thought, no multivariate analysis, picking up "good" correlations for the sake of the discussion; Elemental correlation supposedly confirming a specific chemical source but with vastly different stoechiometric values).

- ***Use of citations and cited claims*** without actually checking if it would make sense in the situation set in the study (i.e. metals associated with tyre & brake wears, welding, etc. would require extremely unrealistic amounts to explain even 1% of the measured haze concentration).

- ***Artificial limitation*** to spatial studies is not an issue in itself, but have no clear purpose in a strictly natural science study (i.e. many natural science papers use administrative boundaries of Thai provinces to describe and characterize a natural phenomenon extensively controlled by topographical features).

- ***Biased methodology*** where poorly defined terms are misused or research hypotheses are undefined, leading to conclusions based on the choice of hypotheses and where factual observations is causation.

11.5 Citations

Some citations used in some papers, particularly to support extraordinary claims, are problematic as they can obviously be ideologically or administratively biased. A number of important claims that turn out to be true also lack references.

- ***Use of non-scientific references*** to support preconceived ideas (i.e. corn is the main cause of pollution, with an unspecified GreenPeace report as reference).

- ***Use of non-scientific reference (if any) or misleading scientific references*** to provide an unnecessary relevance and importance to a paper (i.e. Chiang Mai has the highest level of pollution in the world (citing AirVisual, Bangkok Post); World's biggest serious environmental problem (no reference); Dramatic health effect (The Nation); Important economic impact (vague WHO report).

- ***Some reference scales have no published information*** on how the scale is set (i.e. the Thai AQI, as far as the authors of this review can tell, has no associated scientific publication to explain the characteristic of this index)

- ***Lack of references*** for claims used as essential part of the study or discussions (i.e. contribution of corn; source from Myanmar; Effect of radon; Role of hill tribes; Role of small businesses; correlation hotspot-Particulate Matter)

- ***The unsubstantiated claim that air pollution is worsening with time and started in 2007*** (or even 2014) is expressed in as many as papers 10% of the publications used in this review (around 30 papers). It systematically lacks references or provides a single data point to support this false claim. What air pollution did in 2007 is reaching a media threshold and become known to the public (and the average academic person it seems). Publications in social studies and long term trends are available to show that these two claims are plainly wrong.

11.6. Writing style

This section is not about the poor use of English (which could be an issue but is rarely the case) but about a voluntary choice of words that are not suitable for academic research writing.

- ***Missing items in the reference list*** should be a rare occurrence in publications that now have automatic detection of missing or incomplete references during final editing.

- ***Claims for research novelty*** is a very common feature in the introductory section that the research has never been done before or rarely studied in order to give relevance and importance to the study. It is most of the time wrong (i.e. 'PAH concentrations and health effects have never been studied in particulate matter of Chiang Mai' is false as there are up to 10 papers that have worked on this exact subject in 5 to 10 years prior to the publication of that claim). Some of these 'novelty' claims are amusingly contradicted in the same sentence by providing a reference to the 'subject never studied'.

- ***Claims for research novelty due to analytical constrains*** is presented in the introduction of some papers as the reason why the research is only possible at the time of publication when the actual techniques applied are routinely used for decades in other fields. (i.e. supposedly 'ground-breaking' articles using 40 years old techniques with current capabilities 2 or 3 orders of magnitudes higher than the data published).

- ***Claims of discoveries*** to give strong conclusions to a research article (i.e. Identification of biomass burning as the main source (instead of traffic-industry) in Northern Thailand in a 2023 paper when literally every paper on source identification since the early 2000s (tens of them) have identified biomass burning as the main emission source).

- ***Aimless reviews*** (as review papers or paragraphs) about Northern Thailand air pollution providing extensive data on the pollution in Southern Thailand, China, India or further away (US, Europe) with no critical thought on how it compares to Northern Thailand. In some papers, it remains unclear if the summarised data is actually applicable at all to Thailand.

- ***Unsupported review section*** is common practice. An introductory paragraph stating some broad but clear claims (i.e. worsening pollution) that fails to provide any reference to support it. In some cases, the support is done through a dataset that cannot be directly compared (i.e. monthly average vs daily or hourly averages). Finally, some papers provide references to claims that are either not covered in the cited literature or goes directly against it (i.e. Heavy metals is a major health issue in air pollution of Chiang Mai referenced with an article that do not show any impact from heavy metals).

- ***Unnecessary references*** that have no impact on the understanding of the manuscript. It isn't discussed, it isn't used in figures, it doesn't have an obvious usefulness and no meaningful comparison can be readily made (i.e. data from US, Europe with a systematic absence of comparative discussion). The sole purpose seems to fill some text and give some 'international' relevance to the research paper. Some citations also have an unclear purpose as they mention oddities, far from the studied topic (i.e. PAHs found in volcanoes… .is true but it was found very recently at ultratraces levels in a very limited number of publications).

- ***Misleading titles*** (i.e. nuclear analysis, when the technique is Energy Dispersive Spectrometry or X-ray Fluorescence spectrometry, so purely electronic analysis) or headers (i.e. Maize burning as the title section, to not mention maize a single time in the main text body)

- ***Extensive rambling and waffling*** (i.e. Entire paragraphs are sometimes repeated within the same paper, almost word for word; Some sections are just a mix of scientific-like writing but carry no meaning)

- ***Improper use of logical link words*** which do not have the expected logical consequence (i.e. A & B are very different situation. A variable is measured in A & B. Value A is different than Value B, therefore, A & B are not different)

- ***Use of childish display*** in figures (i.e. Hello Kitty-like cartoons to illustrate the toxicity level of AQI values in academic research paper and administrative reports).

- ***Low quality figures*** (i.e. low resolution, heavily pixelized, wrong captions, poor design/editing and graphical errors where values that should be the same aren't)

- ***Lack of graphical efficiency*** where figures carry a very limited amount of information or are not designed in a way to summarize a complex dataset (i.e. numerous plots with a couple of data points; extensive numerical comparison with world data that could be done in a single well-designed plot).

11.7. Academic practice

Problematic trends in published work in academia are not particularly different in the field of air pollution in Northern Thailand, but there is sufficient representation to be mentioned here.

- ***Redundancy in published papers*** has become common in all scientific fields. Among the publications used in this review, a few authors published several papers covering the same subject with a minimal amount of new data and almost no new interpretation. Such publications are solely there to boost an academic profile rather than advancing science.

- ***Lack of suitable skills in the authorship*** with papers covering disciplines where none of the authors are specialised in. It results in a manuscript with poor methodology, poor analytical skills and unsuitable interpretation of results (i.e. geochemistry papers with no earth scientist, leading to a processing and interpretation of data as it would have been done more than 50 years ago; Health papers with no author with a medical background or a history of publishing in that field).

- ***Unnecessary use of superlatives and anxiogenic terms*** to describe broad or specific observations about Thailand, often with no evidence, no quantification, no references (i.e. 'worst in the world' pollution; PM0.1 particles are significant carcinogenic emission) sometimes in research studies where the fear-inducing sentences are not related to the topic at all).

11.8 . Oral communication

This section is an incomplete view of how northern Thailand air pollution research is presented in conferences, seminars, symposium and public talks. As a general view, many issues are the same to what is observed in written communication.

- ***Lack of organisation*** around an oral presentation. While some aspects of Thai academia are very rigorous and strict with a respect of hierarchy and deference to authority, other aspects appear very relaxed from an international point of view. It is not unusual to start a 1h conference 30 minutes late, introduce a speaker in excessive superlative terms, sounding very unprofessional. The usual IT issues that could have been fixed an hour earlier are common and for attendees on a tight schedule, it might be better not to come.

- ***The cosmetic part of presentation*** is often poor to very poor quality, with slideshow loaded with poor resolution images, childish cartoons (with no humorous content), etc.

- ***Title of presentation*** might not reflect the content of the talk. Either the title is general but the reality is a tight focus on a tiny aspect of a specific issue and doesn't provide general conclusions or a technical title implying a relatively narrow topic that turns out to be a general public overview information.

- ***Poor presentation of data and delivery process.*** Some presentations look like an unchecked B.Sc level type of data presentation. It would be expected that senior scientists with 20-30 years of practice would know how to present data. This issue has also been observed in Thai health sciences and geosciences and is not exclusive to air pollution in Northern Thailand.

- ***Problematic knowledge of the field of study*** is not a major issue in public talks where the only expectation is objective correct information that doesn't fully require scientific scrutiny to be presented. However, when a presentation is aimed at fellow scientists, one would expect the speaker to be more rigorous and knowledgable. Coming from experts in the field, it appears unacceptable to display a very poor knowledge of the available literature (which is not that extensive) or make mistakes through basic ignorance (i.e. comparison of AQI from different world location without considering that AQI scales varies between places)

- ***Misleading claims by experts in the field*** to academic audiences where the author reinforces (unnecessarily) a point that goes against the scientific literature without providing evidence. It can be done using images from other institutions or research papers (often uncited), carrying an out-of-context information that has been clearly discredited by Thai and/or International research (i.e. a speaker claiming the indisputable role of air pollution in lung cancer in Northern Thailand when all recent papers failed to establish any strong relationship).

- ***Fallacious consideration of the audience*** when genuine questions by attendees (expert or not is unknown) are discarded under an argument of authority. This is particularly unacceptable when the answer to some of these questions are available in published material that an expert in air pollution in northern Thailand should be aware of.

11.9. Personal (C.P.) opinion on the literature

The data available in the 200+ papers used for this review are often usable information. However, the scientific methodology, analysis of information and discussion often fails in various way. As a reviewer in Earth Science and supervisor for student research, a non-negligible proportion of the published material remind me of the quality expected from B. Sc students reports: a disorganised methodology, unsubstantiated claims, poor referencing while not particularly bringing a lot of original ideas. Thai atmospheric scientific research gives a feeling of where Chinese science was a couple of decades ago, when the rigorousness of the scientific approach was often not considered. Unfortunately, Thai papers published in 2022 and 2023 do not show a particular improvement and one can hope that Thai research on this subject will eventually get to a point where most publications are free of these obvious issues.

Although this is an extensive and scalding critic of the published material on this subject, there are also good papers in the lot, where all the boxes of proper scientific methodology , analysis and writing are ticked, and provide very interesting studies. These papers are often seminal work on a particular approach of the problem and subsequent publications are not of the same quality. International research teams who apply some approach in Northern Thailand as they have done elsewhere in the world are also valuable source of information. Unfortunately, as of 2023, the ratio of good to low quality papers remains too low to make the screening of the available literature, as done in this review, an enjoyable task.

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