# UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Civil, Maritime and Environmental Engineering and Science Unit


**DEVELOPING AN INTEGRATED FRAMEWORK FOR THE POLICY DEVELOPMENT OF VEGETATION FIRES IN THE NORTH OF THAILAND**

by


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Thesis for the degree of Doctor of Philosophy

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# ABSTRACT

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## DEVELOPING AN INTEGRATED FRAMEWORK FOR THE POLICY DEVELOPMENT OF VEGETATION FIRES IN THE NORTH OF THAILAND

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Vegetation fires are an important source of particulate matter in the atmosphere. Every year in the fire season from February to April, the dry and stagnant weather in the north of Thailand allows the $PM_{10}$ (particulate matter with an aerodynamic diameter $\leq 10$ µm) from vegetation fires to accumulate in the atmosphere at concentrations higher than the national ambient standard of Thailand of 120 µg/$m^3$. This affects public health in terms of respiratory illnesses and premature deaths and necessitates fire management by the Government. This study has applied air quality models to investigate forest fire emissions in eight provinces in the north region of Thailand and neighbouring countries and cost-benefit analysis for calculating and comparing benefits and costs of the government policy. The integrated framework between the use of air quality models to reduce emissions to meet the air quality standard and the cost-benefit of the government intervention has created the framework of the policy.

Results from the model simulation show that $PM_{10}$ from nearby countries was less affected than the local $PM_{10}$. After simulating fire controls in agricultural areas and forest areas within a range of 1 km of agricultural areas scenario and fire controls in agricultural areas and forest areas within a range of 1 km and the neighbouring countries scenario, $PM_{10}$ concentrations results from both scenarios are the same condition with >120 µg/$m^3$ in many areas. For fires controlled agricultural areas and forest areas within a range of 4 km, $PM_{10}$ have decreased until below 120 µg/$m^3$ in every district area. In addition, meteorology is an important factor for the smoke problem in this study area. A few hot spots in the area can have high concentrations of $PM_{10}$ because the meteorology tends to be stagnant causing the fire smoke to be trapped near the ground surface. However, fire control agricultural areas and forest areas within a range of 1 and 4 km are possible actions that could solve this problem effectively in a term of the economical investment. Fires are needed for some vegetation ecosystems and used to decrease the severity of forest fires in Thailand. Therefore, the suggested policy framework is divided into two plans: zero burning during, and quota burning outside of, the fire season. This work provides a practical case study of effective integrated air quality management and socio-economic evaluation for the development of a multi-faceted environmental policy in a rapidly developing country.

Keywords: Air pollution, CALPUFF, Vegetation fire, $PM_{10}$, Air quality policy, North of Thailand

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# DECLARATION OF AUTHORSHIP

I, Sirirat Yensong declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

**Developing an Integrated Framework for the Policy Development of Vegetation Fires in the North of Thailand**

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
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Signed: ..............................................................................................................................

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# Definitions and Abbreviations

| | |
|---|---|
| $\mu g/m^3$ | Micrograms per cubic meter |
| AQI | Air Quality Index |
| CALPUFF | CALifornia PUFF model |
| CBA | Cost Benefit Analysis |
| CC | Combustion completeness or burning efficiency (%) |
| $CH_4$ | Methane |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| EF | Emission factor (g/kg Dry Matter). |
| ENSO | El Niño Southern Oscillation |
| FL | Fuel load (or biomass density kg Dry Matter $m^{-2}$) |
| FRI | Fire return interval |
| GDP | Gross domestic product |
| GIS | Geographic Information System |
| Ha | Hectare |
| hPa | Hectopascal (unit of pressure, = 100 pascal) |
| MM5 | Fifth-Generation Penn State/NCAR Mesoscale Model |
| MMIF | Mesoscale Model Interface program |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| NASA | National Aeronautics and Space Administration |
| NCAR | National Centre for Atmospheric Research |
| NO | Nitrogen monoxide |
| $NO_2$ | Nitrogen dioxide |
| PAHs | Polycyclic aromatic hydrocarbons |
| $PM_{10}$ | Particulate matter with aerodynamic diameter ≤10 micrograms per cubic meter |
| ppb | Parts per billion |
| PPP | Purchasing power parity |

| | |
|---|---|
| Tg | Tera grams (= $10^{12}$ grams) |
| US$ or $ or USD | United States dollar |
| VOCs | Volatile organic compounds |
| WTP | Willingness to Pay |
| WUI | Wildland-urban interface |
| NPV | Net Present Value |
| PES | Payments for ecosystem services or Payments for environmental services |
| VSL | Value of statistical life |

# Chapter 1

## Research Overview

### 1.1 Introduction

Vegetation fires occur regularly throughout the world. They release atmospheric pollutants, trace gases and aerosols, which adversely affect the environment and human health. Air pollution was estimated to cause of 7 million global premature deaths in 2012 (WHO and OECD, 2015). The largest premature deaths caused by air pollution in 2012 were occurred in low- and middle-income countries of the WHO South-East Asia and Western Pacific Regions with the number of 3.3 million deaths related to indoor air pollution and 2.6 million deaths related to outdoor air pollution (WHO, 2014). Fires also damage forests and ecosystem goods and services. This directly and indirectly impact humans in terms of food and timber provision, water regulation and carbon.

The occurrence of forest fires is an important issue and tends to be more frequent in summer periods when temperatures are high and air humidity and fuel moisture are low (Pinol et al., 1998). These types of conditions also occur in the north of Thailand in the fire season. This region faces an air pollution problem in terms of smoke caused by forest fires every year from February to April, the region's dry season with warm to hot weather. Besides forest fire events, in these months, the still, dry weather allows particulate matter (PM) to accumulate in the air, which increases the severity of an air pollution problem in this area. Temperature inversions are also an important factor of haze problems in the north of Thailand to raise $PM_{10}$ concentrations to a high level. They influence pollutants becoming trapped near to ground level (Pengchai et al., 2009, Amnauylawjarurn et al., 2010, Kim Oanh and Leelasakultum, 2011). Kim Oanh and Leelasakultum (2011) showed that >70% of weather conditions in Chiang Mai, Thailand during February and April could enhance the formation of ground-based radiative inversions.

In 2007, forest fire occurrences and weather conditions led to the accumulation of the 24-hour averaged $PM_{10}$ in the north of Thailand reaching up to 382.7 $\mu g/m^3$, which was three times higher than the 24-hour averaged national ambient standard of Thailand of 120 $\mu g/m^3$ (annual mean standard at 50 $\mu g/m^3$) (Pollution Control Department, 2010). The WHO guidelines state that this should not exceed 50 $\mu g/m^3$ for a 24-hour mean and 20 $\mu g/m^3$ for an annual mean. However, the WHO air quality guidelines are designed for worldwide protection of public health based on scientific evidence. Countries can develop national standards to fit their socio-economic context by balancing health risks, technological feasibility, economic considerations and various other political and social factors (WHO, 2006). Not only Thailand that adjusted national air-quality standard in order to achieve their objectives, but Europe and the United States also developed the standards to suit their socio-economic situations. The 24-hour and annual means $PM_{10}$ of the European standard state that they should not exceed 50 μg/m$^3$ and 40 μg/m$^3$, respectively (European Commission, 2016). For the 24-hour mean $PM_{10}$ standard of the United States, this should not exceed 150 μg/m$^3$ (Vahlsing and Smith, 2012). The level of standards of $PM_{10}$ in Thailand, the United Kingdom, the United States and European countries compared with WHO guidelines, are presented in Table 1.1. There are few countries, United Kingdom and European countries, that set 24-hour mean standard to meet air quality guideline by WHO at 50 μg/m$^3$. For annual mean standards, there is no country in Table 1.1 applying air quality guideline at 20 μg/m$^3$ as their national standard.

**Table 1.1** The $PM_{10}$ standards of Thailand, the United Kingdom, the United States, European countries compared to interim target values of WHO guidelines [adapted from WHO (2006), European Commission (2016), Kaiser et al. (2006), Pollution Control Department (2010), and Vahlsing and Smith (2012)]

| | 24-hour mean concentrations | | Annual mean concentrations | |
|---|---|---|---|---|
| | $PM_{10}$ (μg/m$^3$) | Basis for the selected level | $PM_{10}$ (μg/m$^3$) | Basis for the selected level |
| Interim target-1 (IT-1) | 150 | Based on published risk coefficients (about 5% increase of short- term mortality over the air quality guidelines value).<br>- United State standard is 150 μg/m$^3$ (IT-1)<br>- Thailand standard is 120 μg/m$^3$ (between IT-1 and 2) | 70 | These levels are associated with about a 15% higher long-term mortality risk relative to the air quality guidelines level. |
| Interim target-2 (IT-2) | 100 | Based on published risk coefficients (about 2.5% increase of short- term mortality over the air quality guidelines value). | 50 | In addition to other health benefits, these levels lower the risk of premature mortality by approximately 6% (2–11%) relative to the IT-1 level.<br>- Thailand standard is 50 μg/m$^3$ (IT-2)<br>- United Kingdom and European countries standards are 40 μg/m$^3$ (between IT-2 and 3) |
| Interim target-3 (IT-3) | 75 | Based on published risk coefficients (about 1.2% increase in short-term mortality over the air quality guidelines value). | 30 | In addition to other health benefits, these levels reduce the mortality risk by approximately 6% (2-11%) relative to the IT-2 level. |
| Air quality guideline | 50 | Based on relationship between 24-hour and annual PM levels.<br>- United Kingdom and European countries standards are 50 μg/m$^3$ | 20 | These are the lowest levels at which total, cardiopulmonary and lung cancer mortality have been shown to increase with more than 95% confidence in response to long-term exposure to $PM_{2.5}$. |

In the case of health impacts, data from the Ministry of Public Health showed that during 15–23 March 2007, there were 61,000 reported outpatient visits stimulated by haze-related illnesses such as respiratory, ophthalmological, cardiovascular, and dermatological diseases in eight provinces of the upper northern region of Thailand. However, it is unclear to what extent these illnesses are attributable to the air pollution (Wiwatanadate and Trakultivakorn, 2010). In 2002, the Pollution Control Department of Thailand (PCD) identified major sources of PM in Chiang Mai province, the largest city in the northern region. It was found that 89% of PM was from forest fires and 2.3% from agricultural residue burning whereas industrial sources contributed only 0.08%, transportation sources 2.6% and other sources 0.56% (Kim Oanh and Leelasakultum, 2011). Forest fires are one of the significant sources of PM that concern the government. The Pollution Control Department of Thailand showed that 64% of fire events occurred in forest areas, whereas 36% were in the agricultural areas (Pollution Control Department, 2011). The main causes of forest fires were communities breaking a law by using fires to clear forest ground for collecting natural products such as mushrooms and honey (Department of National Parks Wildlife and Plant Conservation, 2012), and illegal forest plantations. Amnuaylojaroen and Kreasuwun (2012) reported that forest fire emission sources contributed 54-71 % of total PM emissions in Chiang Mai province.

In addition to local burning, another contributory factor to smoke haze comes from outside of the country. Satellite imagery shows that there are hotspots because of biomass burning activities in Thailand as well as in the neighbouring regions of Laos, Cambodia, and Myanmar. These activities generally peak in March, April and May (Reid et al., 2013). Transboundary haze pollution from other countries clearly affects air quality in the southern part of Thailand. Severe vegetation fires in 1997 in Indonesia led to air pollution problems in Singapore, Malaysia, Brunei and the southern part of Thailand (Sahani et al., 2014). Haze problems continuously occurred via a series of serious regional haze episodes until recent years (Miriam et al., 2015) and this has become a shared concern within the region. In 2002, member countries in the Association of Southeast Asian Nations (ASEAN) started to sign the Agreement on Transboundary Haze Pollution (Forsyth, 2014). The objective of the agreement is to prevent and monitor transboundary haze pollution caused by land and/or forest fires. In 2010, the Association of Southeast Asian Nations (ASEAN) have provided funding for activities under the Technical Working Group on Transboundary Haze Pollution in the Mekong Sub-Region (TWG Mekong). Member countries collectively agreed to closely monitor the fire occurrence in their own countries (Pollution Control Department, 2012).

To mitigate these problems, an investigation of the processes that spread air pollution from forest fires by using suitable tools to classify the significant cause and their effects is important. Subsequently, both the potential economic costs of forest fires and the benefits of prevention/mitigation measures should be considered and integrated into public policies in order to control fires.

## 1.2 Aims and Objectives

### 1.2.1 Aims

The aim of this study is to investigate an air pollution problem caused by forest fires in the northern region of Thailand and develop a framework to enhance policy development to solve this problem. The framework to enhance policy development will be based on the both the air quality meeting standards and the budget of the government intervention being appropriate. This will be a practical case study of effective integrated air quality management in a rapidly developing country.

### 1.2.2 Research Questions

Vegetation fire is the main cause of air pollution problems in many parts of the world. There are a number of studies of forest fire emissions and their impacts and the impact of policies such as the dispersion of particulate matter ($PM_{10}$) from forest fires in Chiang Mai province (Amnauylawjarurn et al., 2010). Fire effects the entire forest landscape of continental Southeast Asia (Baker and Bunyavejchewin, 2009). Policy responses from transboundary haze caused by vegetation fires in Southeast Asia (Murdiyarso et al., 2004) have not addressed the north of Thailand including: Chiang Mai, Lampang, Lamphun, Chiang Rai, Phayao, Mae Hong Son, Phrae and Nan provinces. Many studies of forest fire policies are developed by approaches such as public sector responses to haze management in the north of Thailand (Tiyapairat, 2012). However, there is no study using an integrated framework involving the use of air quality models to reduce emissions to meet the air quality standard and cost-benefit analysis of potential government interventions. To develop a policy to deal with the air pollution caused by vegetation fires in the north of Thailand based on an integrated framework, several questions need to be answered:

1. What are the main causes and effects of forest fires? How do forest fires affect people's health, environment and ecology?
2. What are the processes that influence fires emissions impact on the ambient air quality of the north of Thailand? How can we control forest fire emissions in the north of Thailand to meet air quality standards? What are the main sources and emissions to be controlled?
3. Before applying any government intervention, who are the main groups affected and in what ways are they affected? How much will government interventions cost?

4. After applying government interventions by controlling the main causes of fires by following the air-quality model scenarios, who are the main groups affected and in what ways are they affected? How much are the costs and benefits? Which government intervention is the most worthwhile?
5. Which government interventions should be developed as public policies? Can the policies be used to relieve problems both in the short-term and long-term? Do they yield a significant net gain to society?

### 1.2.3 Research Aims and Objectives

The Thai government has tried to mitigate annual air pollution problems caused by vegetation fires in the north of Thailand, but problems still occur. The relatively large size of vegetation areas and the wide range of impacted stakeholders were important factors when compared to the limited amount of government officers and budgets available to address the issues. Therefore, this study aims to solve these air pollution problems efficiently in terms of facilitating air quality to meet the Thai standard within the available budget. To achieve the research aims, an air quality model is applied for investigating the control of main source pollutions, while cost-benefit analysis is applied for comparing between costs and benefits from each source controls. It is anticipated that a suitable fire-management option will be generated via the integration of air quality model and cost-benefit analysis. The processes that are necessary to achieve the research aims are outlined as follows.

- An investigation of the causes of forest fires, their emissions, and their impacts including health, environmental, social and ecological impacts, from a global view. This was shown in Chapter 2.
- An investigation of the air quality in the north of Thailand caused by the forest fires from the different type of vegetation, the surrounding area and neighbouring countries. (Chapter 3). The processes are shown below.
    - To estimate emissions from each source.
    - To determine the processes that influence fire emissions affecting ambient air quality in the north of Thailand and cause them to exceed the Thai air quality standards.
    - To simulate scenarios for potential fire controls to find the optimal pollution reduction targets from selected areas.
    - To indicate the main pollutant sources and the numbers of areas needed to control atmospheric emissions from fires in order to meet the air quality standards.

- An evaluation of the impacts of forest fires by assessing damage costs to the parties affected, including the government, people's health, and ecosystem goods and services (see Chapter 4).
    - To identify the main parties affected and the effects of forest fires.
    - To value the losses of each party affected.
- An evaluation of the Thai government's interventions after controlling the main causes of fires following the air-quality model scenarios (see Chapter 4).
    - To evaluate costs and benefits to the main parties affected by interventions after controlling the different main causes of fires.
    - To compare costs and benefits of the interventions before and after controlling the different main causes of fire emissions, and select the interventions that are the worthwhile for the government, society and ecosystems.
    - To assess costs and benefits of the selected interventions for short- and long-term periods.
- To develop a policy for forest fire management from the selected government interventions (see Chapter 5).

## 1.3 Study area

The north of Thailand borders Myanmar to the north and west, and Laos to the north and east (see Figure 1.1). Its geography is generally mountainous with north-south-aligned hill ridges parallel from west to east. This geography leads to agricultural activity on the hillside area. Farmers on the hillside area of northern Thailand not only cultivate rice for subsistence but are also engaged in cash crop production. The planted cash crops in this area changed dramatically after the 1970s (Michaud, 1997). These changes in cash crops contributed to changes not only in agricultural techniques but also to socioeconomic activities (Jian, 2001).

According to Office of the National Economic and Social Development Board (2011), in 2009, poverty in the upper north of Thailand area was a significant problem with 16.84% of the population regarded as "poor" with income less than 1,586 Baht/ capita/ month ( 48 USD/capita/month). People who were under the poverty line almost all lived in rural areas.

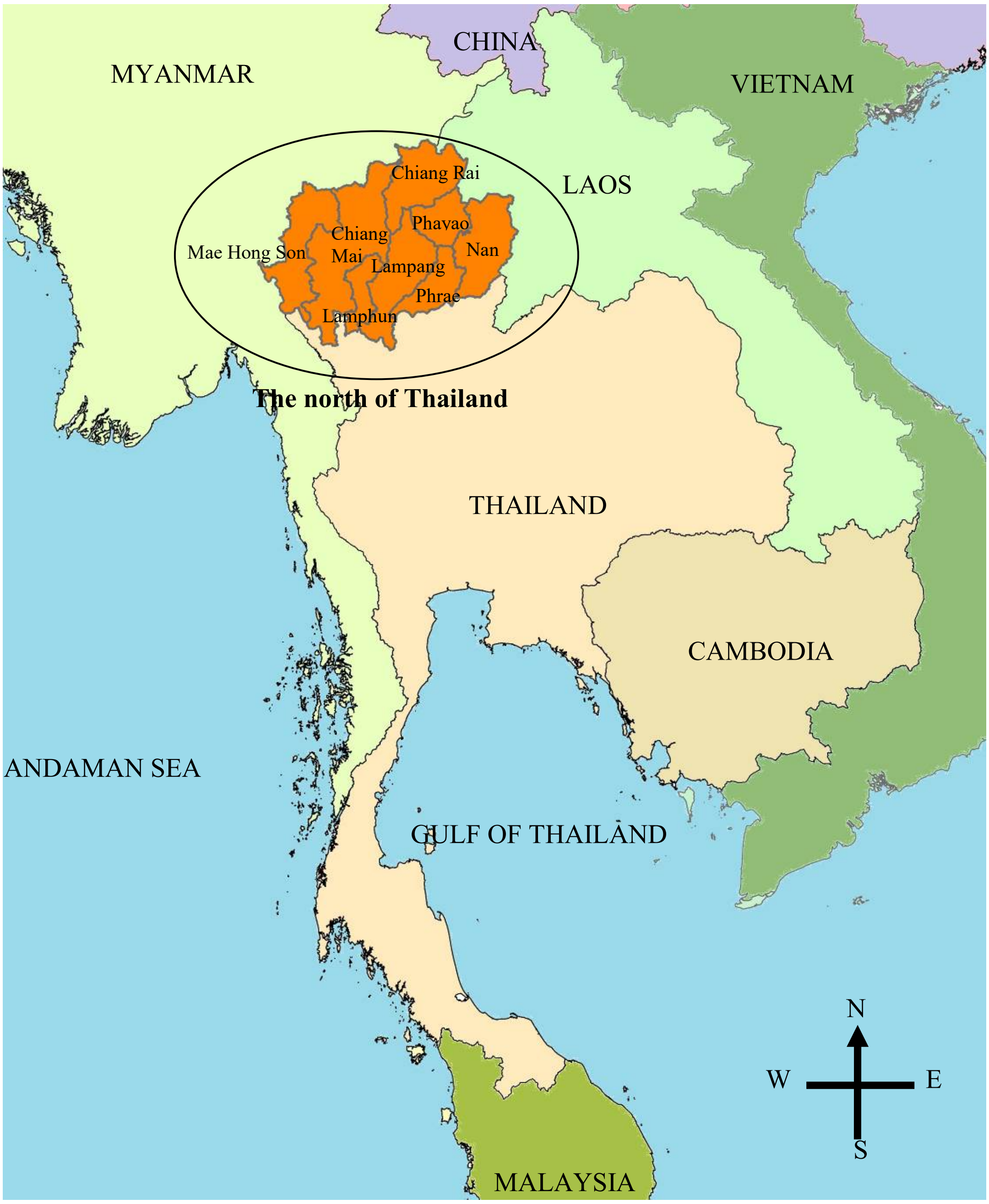



**Figure 1.1** The location and the name of provinces in the upper north of Thailand**.**

### 1.3.1 Forest fires in the north of Thailand

The total area of Thailand's forests was estimated by the Royal Forest Department of Thailand in 2008 as 17,158,600 ha, around 9,507,500 ha (55%) of which was in the northern region. There are two main forest types: evergreen and seasonal forest. The types of vegetation in the evergreen forest are tropical rainforest, hill evergreen forest, dry evergreen forest, pine forest, mangrove forest and peat forest, while seasonal forests are mixed deciduous forest and dry deciduous dipterocarp forest (Wiriya, 2010). The Royal Forest Department (2008) stated that the forest area of Thailand rapidly decreased between 1961 and 1981 by 5.47% per year mainly due to the conversion of forest areas to agriculture and logging activities. After 1982 until 1998, the forest areas only declined by around 0.75% per year. The slower decline in forest area was a result of the logging ban Act. In 1989, the Thai government declared a logging ban after which all logging contracts and concessions were cancelled, and applications for new concessions were dismissed. However, logging can be operated by the government and wood via the private sector can be produced from forest plantations. Between 1998 and 2008, the forest area increased by around 1.16% per year.

Generally, there are three types of forest fires: crown fire, surface fires and ground fires. The forest fire that burns and spreads through the tops of trees or shrubs is a crown fire. A surface fire is a fire that burns loose debris on the surface including dead branches, leaves and low vegetation. A ground fire consumes organic material beneath the surface litter level (National Wildfire Coordinating Group, 2012). Forest fires in Thailand are predominantly surface fires that consumed surface fuel including litter and small vegetation. Fires occur annually in the dry season, between December and April in the dry dipterocarp and mixed deciduous forests (Wiriya, 2010). The intensities of fires in Thailand are low to moderate levels with fire-line intensity 35-865 $kWm^{-1}$ and a rate spread of 0.5-9 $m.m^{-1}$. However, high intensity fires seldom occur in grass land and the canopy in mixed deciduous forest with bamboo or pine plantations (Tanpipat et al., 2009, Wiriya, 2010). The Thai Department of National Parks Wildlife and Plant Conservation estimated the area burned during 2002 to 2012 by using satellite images, as shown in Figure 1.2. The annual area burned in the northern region of Thailand has significantly decreased since 2004 from about 18,000 ha to <5,000, while the frequency of fires has declined by about 50% (~6,000 to 3,000).

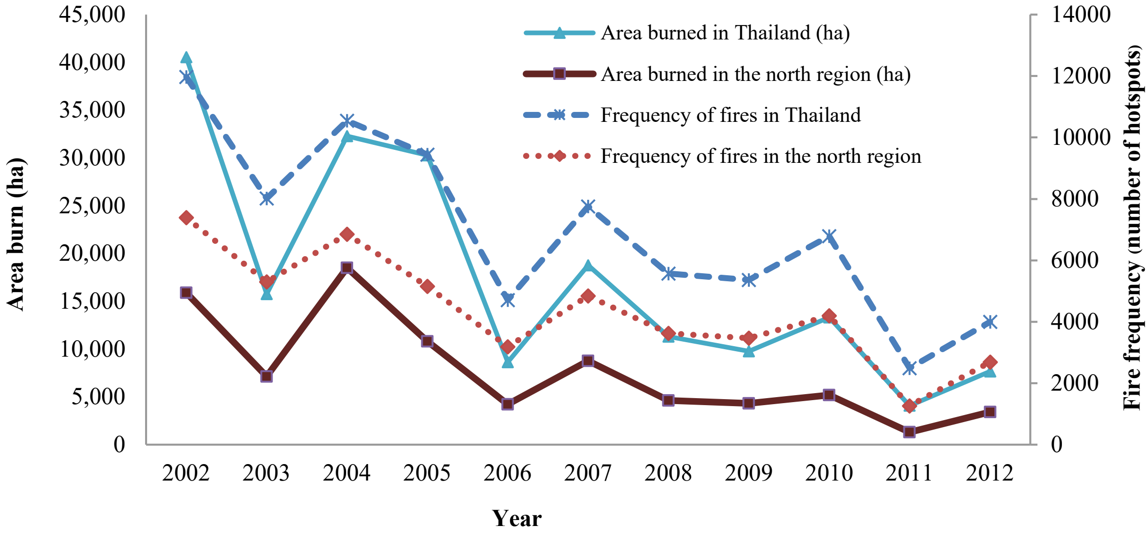



**Figure 1.2** Forest fire occurrence and area burned in the north of Thailand [adapted from Department of National Parks Wildlife and Plant Conservation (2012)]

Furthermore, the Department of National Parks Wildlife and Plant Conservation (2012) revealed that a major cause of forest fires - about 88% in Thailand - were human activities, with around 12% unidentified causes. Gathering forest products was a major cause of fire (37%), followed by hunting, burning agricultural residue, pasture, tourists' activities, conflicts between people and government, and neglect (see Figure 1.3).

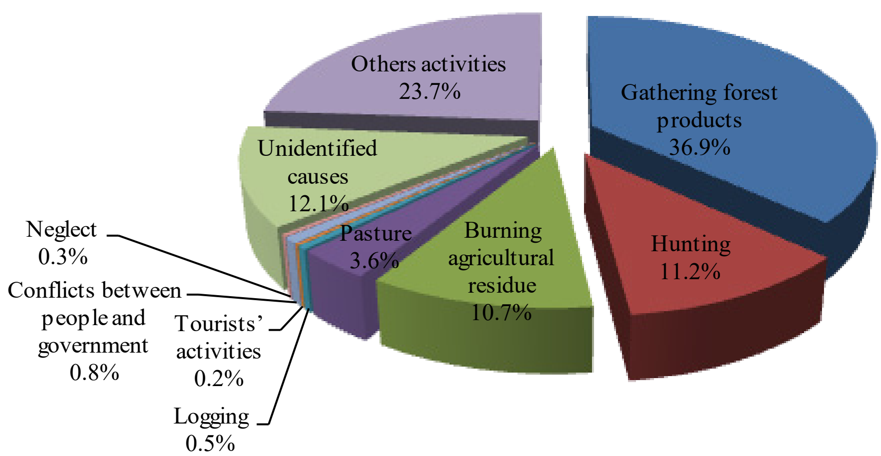



**Figure 1.3** Relative causes of forest fires in Thailand, which include gathering forest products, hunting, burning agricultural residue, pasture, logging, tourists' activities, conflicts between people and government, and neglect.

Approximately 500,000 families in Thailand heavily depend on a variety of forest products and services for their subsistence and livelihoods (Salam et al., 2006). In the dry season, forest products such as fuel wood, bamboo, honey and mushrooms, are collected by rural people. Fires are used to clear out litter, grasses and undergrowth on the forest floor in order to help collecting products easier. In the agricultural sector, farmers use fires to clear agricultural residue for preparing their land. A fire is used as a tool by rural people due to it being the most cost-effective and time-effective way to clear land. Uncontrolled fires from these activities have become a major source of fires.

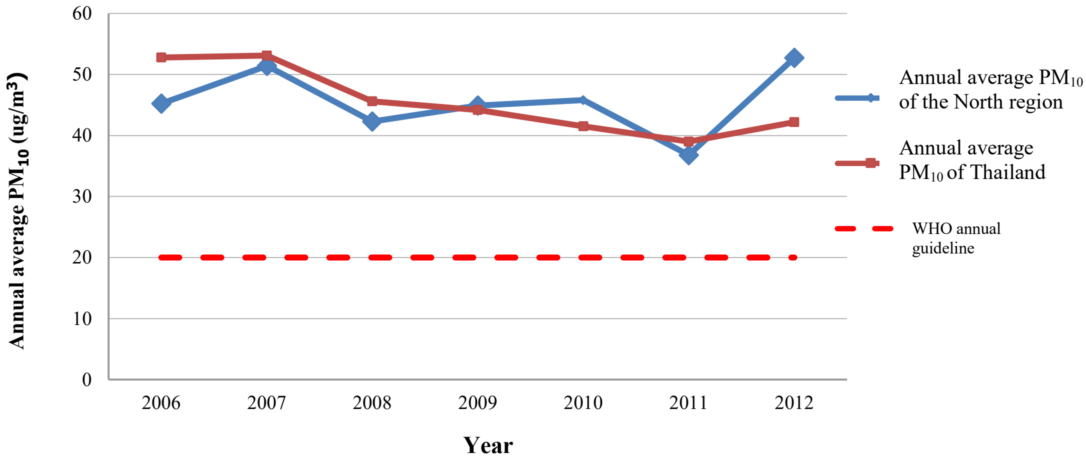



**Figure 1.4** Annual average $PM_{10}$ of Thailand and the north region monitored by Pollution Control Department, Thailand**.**

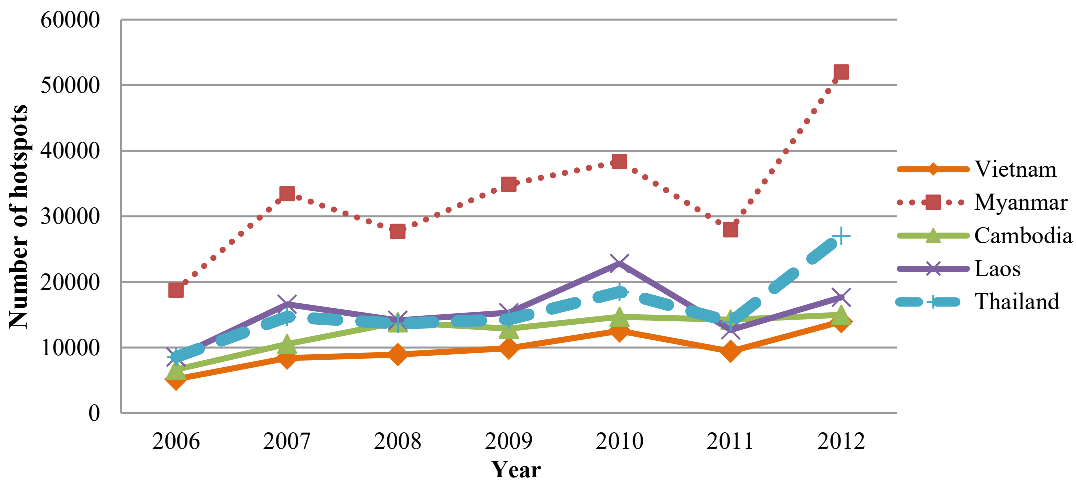



**Figure 1.5** The number of hotspots in Thailand and neighbouring countries including Vietnam, Myanmar, Cambodia and Laos**.**

Forest fires emit large amounts of gases and PM in the north of Thailand. $PM_{10}$ in this area reached up to 382.7 μg/$m^3$ and 279.9 μg/$m^3$ at Province of Chiang Mai Government Centre in March 2007 and March 2010, respectively (Pollution Control Department, 2009, 2012). The government made an effort to mitigate air quality problems in domestic areas and this problem can be solved by taking action to decrease the annual average $PM_{10}$. However, annual average $PM_{10}$ in the north region has fluctuated depending on the area burned in both the north of Thailand (see Figure 1.4) and potentially in the neighbouring countries (see Figure 1.5). The graphs of Thailand, Myanmar and Laos during 2006 to 2012 show the same direction of hotspot numbers and $PM_{10}$ concentrations in the north of Thailand. The highest values of hotspot numbers and $PM_{10}$ concentrations appeared in 2012.

### 1.3.2 Laws in Thailand

The Thai government has legislated relevant laws and regulations for preventing and mitigating forest fires and air pollution. In a forested area, the conserved area classified by laws may be divided into 3 types of forests: 1) national park, 2) wildlife conservation and protection and 3) national reserved forest. The related legislation is as follows.

1) The National Reserved Forest Act, B.E.2507 (1964) - Chapter 2, in the National Reserved Forest, these activities: occupying or possessing land, burning forest, collecting forest products, or doing any matter with purport to decay a condition of forest are not permitted accept with a license from a competent officer or by time period permission of a competent officer of each National Reserved Forest.
2) The National Park Act, B.E.2504 (1961) – Chapter 3, in the National Park, these activities: occupying or possessing land, burning forest, collecting some forest products or doing any matters with purport to decay a condition of forest are not permitted.
3) The Wildlife Conservation and Protection Act, B.E.2535 (1992) - Chapter 6, in a wildlife sanctuary, no person shall possess or occupy the land or build up, or any other means whatsoever construct, or cut, fell, clear, burn, or destroy trees.

The relevant regulations for the use of fires also appeared in the Public Health Act, B.E.2535 – Chapter 5. Local officials have powers to forbid any person who makes a source of nuisance that includes foul odour, toxic particles or any matter that may be harmful to health.

Moreover, there are indirect laws that may be applied to control forest fires in the Enhancement and Conservation of National Environmental Quality Act (B.E. 2535). In Section 6, for the purposes of public participation in the enhancement and conservation of national environmental quality, individual persons have rights to petition or lodge a complaint against the offender in case of being a witness to any act committed in violation or infringement of the laws relating to pollution control or conservation of natural resources, and to cooperate and assist government officials in the performance of duty relating to the enhancement and conservation of environmental quality.

In Section 9, in case there is an emergency or public danger arising from a natural disaster or pollution caused by contamination and spread of pollutants, the Prime Minister shall have the power to order, as deemed appropriate, government agencies, state enterprises or any persons, including the persons who are or may be the victims of such danger or damage, to take prompt action, individually or jointly, in order to be able to control, extinguish or mitigate the adverse effects of such danger or damage.

### 1.3.3 Policy in Thailand

#### 1.3.3.1 The functions of each government organization

According to the Thai Government's cabinet resolution (on Tuesday 8th January 2013), eleven ministries were assigned to solve problems from haze, including the Ministries of: Natural Resources and Environment, Agriculture and Cooperatives, Interior, Transportation, Education, Public Health, Defence, Foreign Affairs, Office of the Permanent Secretary, Science and Technology, and Tourism and Sports. Measures for mitigating the problem consist of: 1) the control of burning from February to April; 2) preparing officers for prevention and control forest fire events; 3) the promotion of zero burning to communities; 4) cooperating with private organisation, state enterprises and contracting parties to manage the haze problem; 5) giving knowledge about the prevention and control of open burning (refuse and vegetation burned) to the target party such as local communities and farmers; 6) monitoring and warning about haze pollution; 7) international cooperation on transboundary haze pollution control; and 8) establishing centres for management of pollution from haze and forest fires in every province in the upper north region. However, the main ministries that clearly involve the management of forest fires in their missions are summarised in Table 1.1.

**Table 1.2** The name of Thai Ministries and their roles to tackle forest fire problems (Tiyapairat, 2012**).**

| Thai Government Ministry | Role |
|---|---|
| Natural Resources and Environment | - Prevention and control of forest fires.<br>- Development of monitoring and warning systems for forest fires and haze.<br>- Cooperating with neighbouring countries to solve transboundary haze pollution |
| Agriculture and Cooperatives | - Promotion and dissemination of organic agriculture without burning.<br>- Management and control plan for burning in post-harvest periods. |
| Interior | - Prevention and control of forest fires by local administrative offices. |
| Transportation | - Controlling and preventing burning of weed and waste along roads. |
| Office of the Prime Minister | - Promotion of education on haze pollution and forest fires at a community level. |
| Public Health | - Development of health monitoring and health service systems |

### 1.3.3.2 Measures to solve haze problem

Various agencies in Thailand take measures to mitigate haze problems from biomass burning in the upper north region. Many measures have been employed as outlined in the following sections.

#### 1.3.3.2.1 Preparation for forest fires

At the beginning of the so-called "forest fire season", every province in the upper north of Thailand will set an action plan to control forest fires in conservation and national reserve forest areas. There is also a preparation of teams via training and provision of equipment to help extinguish forest fires in relevant areas and permission for people to enter a forest area is stricter than during other periods. Fire breaks are set up in the areas connecting villages and between agricultural and forest areas (Pollution Control Department, 2012).

There are different plans for the rest of the year than at the start of the forest fire season. These general plans require the provinces to establish provincial administration and cooperation centres to tackle haze and forest fire problems. Provincial announcements are typically issued to set measures on controlling and preventing haze and forest fires. Villages' forest fire control areas are announced. Arrangements for the cooperation have been agreed between central and local administration organizations on preventing and fighting forest fires. In addition, training for volunteer forest fire fighters is provided. The sub-district rescue teams are tasked to extinguish forest fires. Campaigns to prevent and eradicate haze and drought problems are organised and delivered. Information about management of haze and forest fires is disseminated (Pollution Control Department, 2012, The Secretariat of the Senate, 2009).

#### 1.3.3.2.2 The action plan on tackling haze and forest fire problems in 2010 and the management plan for haze and forest fire problems 2012 - 2016

The National Forest Fire and Haze Management Committee, in its report No. 1/2553 (2010), approved an action plan intended to solve haze and forest fire problems in 2010 and assigned agencies to execute the plan. The Upper North forest fire and haze management subcommittee was appointed. The haze and forest fire management plan for 8 provinces in the Upper North was established. A practical solution plan was put in place by cooperation between 8 provinces and related organizations to prevent and suppress all vegetation fires. Restricting the using of forest goods, prohibiting the burning of agricultural residues, volunteers training for fire fighters, building firebreaks are the focus of this plan.

#### 1.3.3.2.3 The international cooperation on transboundary haze pollution control

Every year, there are two international meetings, Meeting of the Technical Working Group on Transboundary Haze Pollution in the Mekong Sub-Region (TWG-Mekong) and the Sub-Regional Ministerial Steering Committee (MSC), which aim to mitigate transboundary haze problems (Pollution Control Department, 2012). The TWG-Mekong was established in 2007 to provide methodology and technology in fire management to the member countries, including Thailand, Laos, Myanmar, Cambodia, and Vietnam. Member countries agreed to prepare a project proposal in order to obtain financial support from international organizations and other financial sources under the Association of Southeast Asian Nations (ASEAN) framework (ASEAN Haze online, 2012). In 2011, the MSC on Transboundary Haze Pollution in the Mekong Sub-Region was established. The meeting was set to oversee the implementation of measures to control and solve the open burning problems as well as transboundary haze pollution in the Mekong Sub-Region (Pollution Control Department, 2012).

### 1.3.4 Studies for future forest fire policy in Thailand

According to Tiyapairat (2012), a study showed that the state policy responses have been via a centralized political structure. There is an effort to decentralize to provincial and district levels, but the result has not been satisfactory to date. There is an on-going need to build the capacity of government officers especially at provincial and district levels. Moreover, the management of forest areas lacked the appropriate involvement and participation of the local communities. Generally, community members of forested areas are highly interested in methods to protect trees, especially rural people who have a long relationship with natural systems and processes. Non-timber forest products (NTFPs) play a crucial role in local livelihoods for subsistence and necessitate protection of the forest watershed, which is vital to support their occupations (Salam et al., 2006). Individuals are viewed as a key resource for the development of effective solutions to environmental problems. Accordingly, there is a continual need for prevention campaigns to enhance local people's understanding, awareness, and participation as well as local communities' networking in the quest for sustainable solutions to the haze problem. As transboundary haze pollution from a regional point of view is a problem too large for one agency to manage alone, it requires concrete actions collaboratively undertaken by various agencies and stakeholders, together with a considerable amount of resources in terms of time, finance and technical inputs (Tiyapairat, 2012).

Zero burning is not a practical land management method for farmers with many limitations, such as insufficient budgets for buying machinery to manage agricultural residues and a limited time to prepare the next cycle of products (Murdiyarso et al., 2004, Thai Environment Foundation, 2010). The Thai Environment Foundation (2010) tried via engagement with farmers and concerned agencies in the north of Thailand to assess feasible ideas and suggestions to regulate the use of fire in agricultural areas. A requirement to obtain permission for burning is an acceptable approach for such farmers. For this approach, an air quality model was used to assess the maximum loading of pollutants released from a field burning without affecting people's health. A quota for burning areas can then be set by local government. The farmers have to ask for permission and process the use of fire by following the legislation. However, the box model could not effectively investigate air pollution problems in the study area. The results were rough and less accurate since some meteorological data are needed for running this model.

Various methodologies have been developed for managing fire problems in many countries. Integrating various approaches to synthesize a practical and effective solution for Thailand is an important and prudent process and different cultural, economic, social, climate and ecological issues should be considered. Air pollution problems in the north of Thailand are the results of three main sources: burning agricultural residues, transboundary haze pollution and forest fires. Air quality models will be applied to find the proportion of each source's emissions to decrease. Then the optimum policy will be evaluated using an appropriate socio-economic approach.

## 1.4 Research design

### 1.4.1 Concept for the study

Air quality models and cost-benefit analysis (CBA) will be used as the main tools for this study. Carefully selected air quality models will give the results of the approaches to control fires to meet air quality standards in terms of locations, the amount of areas burned, emissions and sources of pollutants. Costs and benefits associated with different mitigating strategies will be used to develop policies. A comparison of the benefits of a given action with the economic costs of taking action in a policy was undertaken by evaluating the positive and negative changes associated with policy changes. CBA will be calculated based on air quality impacts (i.e., people's health) from the change of pollutants' concentrations after fire events, ecological impacts (i.e., watershed protection and carbon sequestration) from the changes of amount of area burned and forests damaged, social impacts classified by selected social indicators (i.e., farmer and employee of fire company). The details of costs and benefits are shown in sections 4.1 and 4.2 of Chapter 4. For this study, people's health is the first priority because it is the most serious problem in the north of Thailand every year. Then fire emissions will be controlled to meet the air quality standard. Then ecosystem services values will be added to evaluate the whole costs and benefits for developing the national policy. The approach needs results from air quality models, which show the location, type of fire area and the amounts of area, burned before and after the fires control. The methods used in this study can be categorized into four:

1) The analysis and evaluation of emissions that affect health, air quality and ecosystem caused by vegetation fires in the study area

Information on topography, meteorology and social background of the study area will be collected to analyse how they influence forest fire emissions. Previous studies will be used alongside new data to summarise and evaluate study results. In addition, data on vegetation types and their potential emissions will be evaluated for estimating emissions in a study area.

2) Assessment of emissions control scenarios to find the optimal pollution reduction strategies from forest fires by simulating scenarios that reduce biomass burning emissions from each type of vegetation and land use (also see Figure 1.6)

3) Evaluation of physical, social and economic impacts from forest fires by assessing damage costs of the parties affected

Previous studies and statistical data collected by reliable organizations will be used to assist in the evaluation of costs to stakeholders.

3.1) Estimation of damage costs to people who are affected from fires by accounting for health impacts, lost life and loss of income.

3.2) Estimation of damage costs to ecological systems caused by fires such as wildlife, water regulations, and soil erosion.

4) Investigation of suitable policies to mitigate problems and associated costs.

Case studies from various countries and previous research on forest fire management will be evaluated in order to devise optimum policies for the northern region of Thailand. The steps in evaluating policies consist of the following:

4.1) Evaluating costs of various policies for short-term and long-term periods.

4.2) Weighting costs and benefits of potential government interventions to mitigate problems.

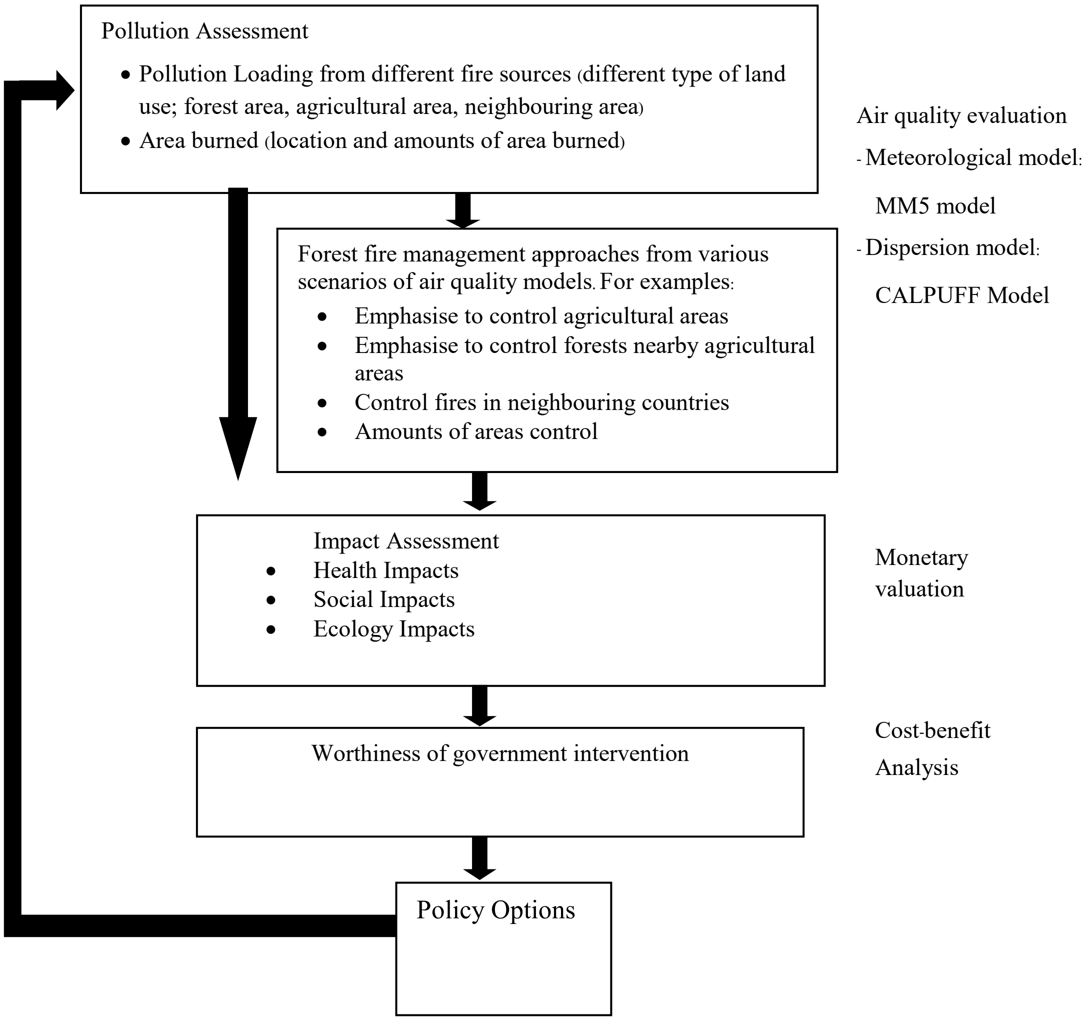



**Figure 1.6** Conceptual flow diagrams for the study of **"**Developing an Integrated Framework for the Policy Development of Vegetation Fires in the North of Thailand**"**

### 1.4.2 Air quality models

An air quality model is an important tool for an action plan especially when air quality is below the legal standards. It can be used for investigating source apportionment, transboundary and natural contributions, and its results can cover areas where there are no monitoring stations installed (Denby et al., 2010). In this study, the north of Thailand faces an air pollution problem in a term of smoke caused by forest fires every year. The source apportionment of forest fires, transboundary haze from neighbouring countries and pollution dispersion processes needs to be investigated. However, the study areas of the fire emissions locations are large, with a diameter of about 735 km (~ 425,000 km$^2$) covering the north of Thailand and some parts of neighbouring countries. The limitation of each model was considered when applying the models in the study. The size of the study area is an important condition for selecting the model.

Generally, regional and long-range models are used when the areas are larger than 300 km (Denby et al., 2010). Examples of these models are the CALifornia PUFF (CALPUFF), CAMx (Comprehensive Air Quality Model with extensions), WRF-Chem (Weather Research & Forecasting Model with Chemistry), HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) and Community Multi-scale Air Quality (CMAQ) models. For regional and long-range models, the CALPUFF model is the non-commercial software that runs on the Windows operating system. This study used the CALPUFF modelling system for evaluation the air quality from vegetation fires. The CALPUFF model has been approved by the U.S. Environmental Protection Agency and is suitable for regulatory use for long-range transport and on a case-by-case basis for short-range applications involving complex and non-steady-state flows such as in complex terrain, coastal situations, and where flow stagnation and flow reversals are important (Environmental Protection Agency (US EPA), 2003).

There are many studies using CALPUFF for evaluating air quality impacts. For example, Henderson et al. (2008) used CALMET/CALPUFF package to assess smoke exposure for an area of 325,000 $km^2$ with complex terrain. The study concluded that the CALPUFF model could provide a simple and globally applicable approach to understand the relationship between health risks and forest fire smoke. Choi and Fernando (2007) applied the CALPUFF modelling system coupled with the MM5 prognostic model to simulate $PM_{10}$ dispersion from agricultural fires in the Yuma/SanLuis area along the U.S./Mexico border, with the aim of investigating local and regional air quality impacts of fires.

To evaluate the amount of pollutant loading reduction for an optimum air-quality value in this study, CALPUFF was used to simulate various scenarios (see Figure 1.6). Most previous studies have highlighted that fire events are caused by humans (Cardille et al., 2001, San-Miguel-Ayanz and Ravail, 2005, Food and Agriculture Organization (FAO) of the United Nations, 2007, Department of National Parks Wildlife and Plant Conservation, 2012, Soto et al., 2013). Each scenario was set to find the optimum reduction of pollutant loading from each fire source, including agricultural areas and various types of forests near villages or agricultural areas. Dontee et al. (2011) showed that the locations of hotspots in Chiang Mai province, Thailand, at around 89% were in forests areas ranging1-4 km from villages and 30-40% occurred in the range of 1 km. Therefore, the fire controls in agricultural area and forest areas ranging 4 km from agricultural areas will be focused as the main source of fire emissions in this study. The transboundary haze from neighbouring countries, which may relate with the change of pollutants concentrations in the north of Thailand, is also considered for the air quality models scenario.

The objective of each scenario is that the air quality value should not exceed the daily Thai ambient air quality standard at 120 $\mu g/m^3$. The expected results from the air quality model are the land-use types and size of target areas to be controlled and pollutant concentrations before and after fires controlled in target areas. These results will be fed to the economic evaluation part for estimation damages and costs from vegetation fires including people's health and ecosystem goods and services impacts. The costs and benefits of fires before and after government interventions will be compared for indicating the suitable policy options.

### 1.4.3 Economic evaluation

Forest fires affect people's health and ecosystems. To control fires, a large amount of money is spent every year. Socio-economic tools play an important role for forest fire management. Cost-Benefit Analysis (CBA) (Peachey et al., 2006) is a socio-economic tool that compares the gains with the losses for specific policy decisions. There are many approaches to estimate the value of costs and benefits, including the production function, revealed preference and stated preference, economic welfare and risk approaches. This study will use the benefit transfer approach to evaluate the impact/ value of the parties affected. CBA was used to evaluate the gains and the losses from government interventions both before and after fire-controls scenarios.

# Chapter 2

## Review of the Scale, Health, Environmental and Socio-Economic impacts of Vegetation Fires

### 2.1 Introduction

A forest fire (or wildfire) may be defined as "an unplanned, unwanted wildland fire including unauthorized human-caused fires, escaped wildland fire use events, escaped prescribed fire projects, and all other wildland fires where the objective is to put the fire out" (National Wildfire Coordinating Group, 2012). The occurrence of forest fires has become an important issue at local, regional and international scales. Fire events release trace gases and aerosol particles into the atmosphere, causing environmental hazards in terms of air pollution and climate effects (Langmann et al., 2009). Aerosol particles may be the cause of global cooling in the short-term (Ramanathan et al., 2001, Lohmann and Feichter, 2005) whereas other trace gases such as carbon dioxide ($CO_2$) may cause global warming after several decades (Jacobson, 2004). More recently, Methane with an atmospheric life time of 10 years, is described as a short-lived climate pollutant (SLCP) (Shindell et al., 2012). In addition, forest fires can lead to significant socio-economic costs such as medical and property damage. It is estimated that forest fires cause the deaths of about 339,000 people annually (Johnston et al., 2012). In the United States, fire suppression costs are around $1 billion annually and economic losses are estimated around $1.6 billion annually in South America (González-Cabán, 2008).

This review presents and critically analyses the scale, health, environmental and socio-economic impacts of forest fires in various countries and regions of the world by identifying, discussing and evaluating the:

- Causes of forest fires
- Global trends and distribution
- Emissions and methods of estimating emissions
- Pollutants and impacts
- Socio-economic impacts.

### 2.2 Causes of forest fires

Forest fires start via a combination of fuel, particular weather conditions and ignition agents (Stolle et al., 2003). Ignition can be caused naturally by lightning or via anthropogenic initiation such as using fire for hunting and clearing areas for plantation. Globally, fires are mainly caused by human pressure on the environment (San-Miguel-Ayanz and Ravail, 2005). The Food and Agriculture Organization of the United Nations (2007) has shown that >79% of the causes of fire in the Mediterranean, South Asia, South America and Northeast Asia were from humans. In Chile, a study of risk variables from forest fires showed that approximately 99% of fires are caused by humans (Soto et al., 2013). In another study, Cardille et al. (2001) revealed that human settlement and land use clearly correlated with fire patterns in and near Lake States forests in the Upper Midwest, United States.

Climate and weather significantly affect the occurrence of fires. Forest fires tend to be more frequent when temperatures are high and air humidity and fuel moisture are low (Pinol et al., 1998, Daniau et al., 2012). Vasilakos et al. (2009) showed that rain is the most influential meteorological variable followed by temperature, wind speed and relative humidity, respectively. Moreover, this study indicated that temperature and relative humidity are positive influences while wind speed and rain are negative effects on fire ignition.

Fuels are an important factor in the occurrence of forest fires. Fuels include downed trees, forest litter, mosses/lichens, forbs/dwarf shrubs, flammable trees and other combustible matter. The capacity for fire ignition tends to decrease when moisture values of the fuel increase (Vasilakos et al., 2009). The first stage for fire development is from fine fuels (e.g. grass, heather, leaves/needles, moss, surface litter etc.) because these fuels are easy to ignite and burn rapidly. The light, medium and coarse fuels (e.g. small trees, sticks, branch wood, shrubs, Mature trees, standing and fallen deadwood, logs etc.) are more difficult to ignite because of fuel moisture but generate higher temperatures and longer periods of burning (Department of Agriculture and Rural Development, 2014). According to the US EPA (2002), fuel consumption for burning depends on the pre-burn fuel loading, fuel types, fuel conditions, meteorological factors, and fire intensity. Fuel consumption will vary for different types of fuel or vegetation. To estimate fuel consumption, various models have been developed based on values of pre-burn fuel loadings for different types of vegetation.

## 2.3 Distribution of forest fires and global trends

### 2.3.1 Global area burned

Forest fires occur on every vegetated area of the world. They tend to concentrate in the warmer parts of the world: Africa, Australia, South America, Asia and North America (Giglio et al., 2009, Ito and Penner, 2004). Many studies (see Table 2.1) show that Africa has the largest area of burning - >50% of the global burning - followed by Australia, America, Asia and Europe, respectively.

**Table 2.1** Summary of the vegetated areas burned in the African, Australian, American, Asian and European regions.

| Study Period | Method | Global Area Burned (x $10^6$ ha) [a] | | | | | | References |
|---|---|---|---|---|---|---|---|---|
| | | Africa | Australia | America | Asia | Europe | Global | |
| 1997-2008 | Satellite dataset from 4 sensors; Moderate Resolution Imaging Spectroradiometer (MODIS) during 2001-2009), Calibrated data of Tropical Rainfall Measuring Mission (TRMM), Visible and Infrared Scanner (VIRS) and the Along-Track Scanning Radiometer (ATSR) during 1997-2008 | 231.7-301.8 | 24.9-88.3 | 19.3-50.5 | 23.7-44.2 | 0.4-1.2 | 329.7-431.2 | Giglio et al. (2009) |
| 1960-2000 | Use of literature reviews, different satellite products and numerical models | 269 | 57 | 32.8 | 23.9 | 0.5 | 383.2 | Schultz et al. (2008) |
| 2000 | Use of dataset from Global Burnt Scar satellite product (GLOBSCAR) and Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM) | 118.1 | 17.8 | 13.2 | 21.6 | 1.3 | 172.0 | (Hoelzemann et al., 2004) |
| 1998-2001 | Using satellite dataset from Tropical Rainfall Measuring Mission (TRMM), Visible and Infrared Scanner (VIRS) | 282 | 118 | 104 | 39 | n/a | 543 | van der Werf et al. (2003) |

[a] Burning areas of each study were classified with different criteria

Grassland fires were the highest proportion of area burned in Africa and America and they were the most burned areas (>71%) of the global area burned (Ito and Penner, 2004, Giglio et al., 2013). Beside grassland fires, cropland fires were the most prevalent in Europe and the Middle East whereas forest fires were dominant in Equatorial Asia (Indonesia, Philippines, Malaysia and Brunei) (Giglio et al., 2013). The Food and Agriculture Organization of the United Nations (2007) has stated that the large number of areas burned in Africa occur because the climate, wet and dry seasons in Africa are suited to vegetation fires. The plants grow well in the wet season and then the dry season provides good conditions for fires. Moreover, the human use of fire for slash-and-burn practices and forest maintenance are significant causes of fires.

### 2.3.2 Trends in forest fires

Schultz et al.'s (2008a) study of burning emissions from 1960 to 2000 indicated that there was an increase in vegetative burning during the 1960s to 1990s, as shown in Figure 2.1. After that, from 2000 to 2012, Giglio et al. (2013) showed that global area burned tends to decrease by around 1.2% per year. The decreases in areas burned occurred in South America, Europe, North Africa, North/Central/Equatorial Asia and Australia while the areas burned in North/Central America, Middle East, South Africa and Southeast Asia increased.

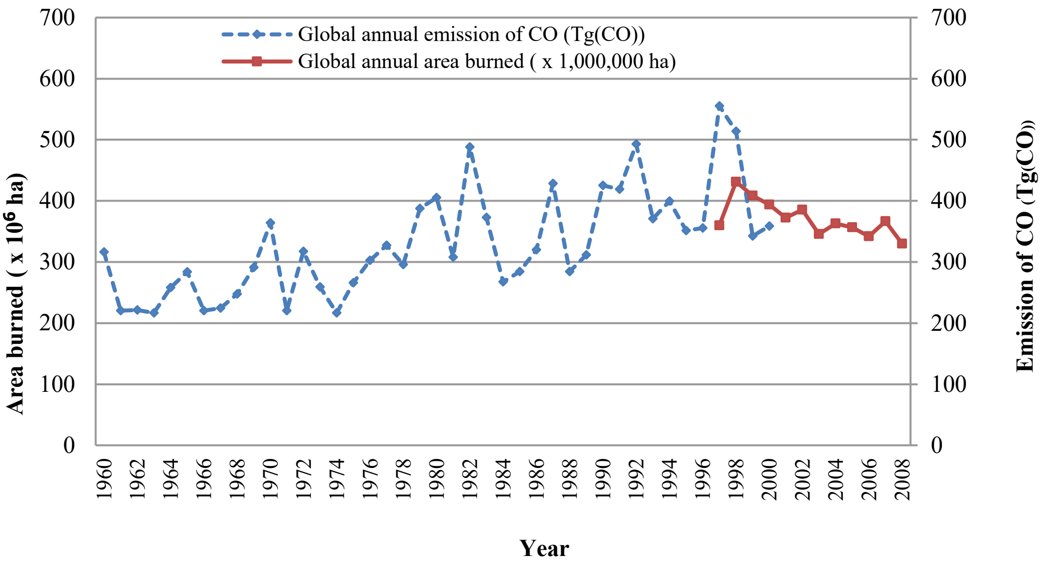



**Figure 2.1** Global annual emission of CO (Tg (CO)) from forest fires using data from a study of Schultz et al. (2008a) and global annual area burned from forest fires using data from a study of Giglio et al. (2009)

In the years 1997 and 1998, the El Niño Southern Oscillation (ENSO) event started and it affected the trends of fires. Giglio et al. (2009) reported that the ENSO event affected continental Southeast Asia to have greater burning. Duncan et al. (2003) showed that the extreme ENSO event during 1997-1998induced forest fires in Indonesia and Malaysia to have an increased frequency and intensity. This was a result of ENSO-induced droughts. The ENSO event during 1997–1998 was the most extreme of the century and the event of 1982–1983 was the second largest one. El Niño events also influenced weather conditions in South America and Africa to become severe droughts and to be causes of widespread forest fires in 1992, 1993, 1997 and 1998 (Food and Agriculture Organization of the United Nations, 2007)

## 2.4 Estimating emissions from forest fires

### 2.4.1 Emission equations

Forest fires generate greenhouse gases and hazardous pollutants such as carbon dioxide ($CO_2$), carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs), aldehydes, volatile organic compounds (VOCs), mercury and particulate matter (PM) (Sapkota et al., 2005, Sigler et al., 2003, Wang et al., 2010). The types and composition of pollutants generated depend on many factors, including meteorological conditions, vegetative types and their characteristics.

Generally, burning emissions (E) for each vegetative type can be estimated using the equation from Seiler and Crutzen (1980).

$$E = A \times FL \times CC \times EF \qquad (2.1)$$

Where A denotes the burned area ($m^2$), FL is the fuel load or biomass density (kg Dry Matter $m^{-2}$), CC is combustion completeness or burning efficiency (%) and EF is the specific emission factor (g/kg Dry Matter).

### 2.4.2 Areas burned

Images from various satellites are used to estimate the areas burned by forest fires. Fire products can be divided into 2 main groups: burned area and active fire products. Burned area products are characterized by changes in the reflectance of the surface which results from charcoal and ash, the vegetation removed, and the change of the vegetation structure (Roy, 1999). Active fire products are based on the apparent temperature of the fire pixel and the difference between the fire pixel and its background temperature that are burning at the time of overpass under relatively cloud-free conditions (Giglio et al., 2003). An advantage of the burned area products over active fire detection is that observational gaps due to cloud cover and satellite revisit time can be filled by the burn scar of the next overpass (Roy, 1999). However, data from the burned area products are not real-time information because the forest has already burnt. Active fire products can detect a fire in near-real-time and have been used in forecasting of air pollution e.g. the Realtime Air Quality Modelling System (RAQMS) for supporting flight planning and data analysis during March-May and August-October 2006 NOAA (Al-Saadi et al., 2008). A study by Zhang et al. (2008) used active fire products to develop the near-real-time monitoring of biomass burning particulate emissions in the United States. The National Aeronautics and Space Administration (NASA) have generated digital maps of global fires by using the MODIS, Terra and Aqua MODIS systems to support emission models (Justice et al., 2011). An overview of fire products from satellites is shown in Table 2.2.

**Table 2.2** Area and time scales of satellite fire products both active fire and burned area products **[**adapted from Manyangadze **(**2009**)** and Kaiser et al**. (**2006**)]**

| SENSOR(S) of SATELLITE | Owner | COVERAGE Spatial | Status | RESOLUTION Spatial | Temporal | Expenditure |
|---|---|---|---|---|---|---|
| **Active Fire Products (no quantitative information)** | | | | | | |
| MODIS | NASA | global | 2001 – present | 1 km | 1 day<br><br>4 times in 24 hrs (2-day and 2-night) | Free (There are additional prices for higher-level product) |
| ERS2-ATSR2, Envisat-AATSR | European Space Agency (ESA) | global | 1995 - present | 1 km | 1 day | Not free |
| AVHRR | NOAA | global | 1978-present | 1.1 km | 1 day ( 2 times in 24 hrs) | Free for raw L1B data |
| TRMM-VIRS | NASA | 40˚N - 40˚S | 1988-2002 | 2 km | 1 month | |
| **Active Fire Products with quantitative information** | | | | | | |
| GOES-E/W | NOAA | N/S-America | 1995-present | 1 km<br>4 km | 15,30 min and 3 hrs | |
| MODIS | NASA | global | 2001-present | 1 km | 1 day | Free (there are additional prices for higher-level product) |
| Met SEVIRI | European satellite (operated by EUMETSAT) | Africa & Europe | 1981-present | 1.6 km<br>4.8 km | 15 min | |
| MTSAT-2,1R | Japanese (operated by JMA) | Asia & Australi a | 2005-present | 1 km<br>4 km | 1 hr | |
| **Burned Area Products** | | | | | | |
| AVHRR | NOAA | global | 1978-present | 1.1 km | 1 day | Free for raw L1B data |
| SPOT 4,5 | France (Space Imaging) | global | 1998-present | 2.5-20 m | 3 days | Not free |
| MODIS | NASA | global | 2001-present | 500 m | 1 day | Free (there are additional prices for higher-level product) |
| ERS2-ATSR2, Envisat-AATSR, Envisat-MERIS, SPOT-VGT | European Space Agency (ESA) | global | 1998-2007 | 8 km | 1 month | |

The detection of active fire products depends on a number of factors including the fire temperature and satellite viewing angle. MODIS active fires can detect flaming fires (~1,000 Kelvin, K) as small as~100 m2 under ideal conditions with a 50% detection probability, or 1,000–2,000 $m^2$ for a smouldering fire (~600K) (Hawbaker et al., 2008, Giglio et al., 2003). The detected area with fire temperature is plotted to produce a 'hotspot', which means an area of smouldering or flaming fires. Estimating the hotspot area burned is different for each vegetation type. Tansey et al. (2008) showed that tropical peat swamp forest burnt area was around 15–16 ha for each hotspot detected. Wotawa et al. (2006) used a value of 180 ha for boreal forests. However, the studies of Ballhorn et al. (2009), Wiedinmyer et al. (2006) and Henderson et al. (2008) have assumed that each hotspot was equivalent to 1 $km^2$ (100 ha) of the area burned.

### 2.4.3 Fuel load

Generally, not all biomass is burned in a fire event. To calculate fire emissions, the fuel load or the amount of biomass available that can be burned in each fire will be required in order to estimate emissions. The fuel load depends on factors such as vegetation type, weather, soil type and other disturbance. Fuel loads can be estimated by using biome-averaged values (Langmann et al., 2009) and numerical biogeochemical models can be used to simulate fuel loads (van der Werf et al., 2006, Hoelzemann et al., 2004, Ito and Penner, 2004). The Intergovernmental Panel on Climate Change (IPCC) (2006), Michel et al. (2005) and Wiedinmyer et al. (2011) have collected fuel load parameters from other studies, as shown as Table 2.3. Most of values reported in Wiedinmyer's study came from Hoelzemann et al., (2004)'s study. Studies by IPCC (2006) and Wiedinmyer et al. (2011) can be applied for a global study due to data collected from all region and whileMichel et al. (2005) is suitable for Asia area.

**Table 2.3** Fuel loads (g/m$^2$) classified by vegetation types and the global regions**.**

| Vegetation Type | Michel et al. (2005) Asia | Wiedinmyer et al. (2011) America | Africa | Europe | Asia | IPCC (2006) |
|---|---|---|---|---|---|---|
| Evergreen needleleaf forest | 36,700 | | | | | |
| Evergreen broadleaf forest | 23,350 | | | | | |
| Deciduous needleleaf forest | 18,900 | | | | | |
| Deciduous broadleaf forest | 20,000 | | | | | |
| Mixed forest | 22,250 | | | | | |
| Tropical Forest | | 20,260-28,076 | 25,295-25,366 | 28,076 | 6,181-27,969 | 4,220-11,960 |
| Temperate Forest | | 7,400-11,000 | 3,497-6,100 | 7,120-11,386 | 7,865-20,807 | 5,040 |
| Boreal Forest | | 25,000 | | 6,228-8,146 | 25,000 | 4,100 |
| Eucalypt Forest | | | | | | 6,940 |
| Woodland | 10,000 | 2,224-5,705 | 2,483-2,501 | 4,523-7,752 | 2,946-11,009 | 260-460 |
| Wooded grassland | 3,300 | 2,224-5,705 | 2,483-2,501 | 4,523-7,752 | 2,946-11,009 | 210-1,000 |
| Closed shrubland | 7,200 | 2,224-5,705 | 2,483-2,501 | 4,523-7,752 | 2,946-11,009 | 1,430 |
| Open shrubland | 1,600 | 2,224-5,705 | 2,483-2,501 | 4,523-7,752 | 2,946-11,009 | 1,430 |
| Grassland | 1,250 | 552-976 | 318-360 | 1,321-1,612 | 655-2,170 | |
| Cropland | 5,100 | | | | | |

### 2.4.4 Combustion completeness

The combustion completeness (CC) or the combustion factor (CF) is defined as the ratio of fuel consumption to total available fuels. Fuel type, fuel moisture content and fuel spatial arrangement influence the CC value (Ito and Penner, 2004). The CC for complete combustion of fuels such as dry surface litter could be near one whereas coarse fuels such as large piece of woods burn less completely. The values of the combustion factor classified by coarse sizes and vegetation types are shown in Table 2. 4 and Table 2. 5. The percentages of combustion completeness by IPCC (2003) cover all main type of global forests then it can be used for the global views while Michel et al. (2005) and Heil (2007) focused on forests in Asia.

**Table 2.4** The percentage of combustion completeness for fine and coarse fuels in forests from different studies**.**

| Study | Fine Fuels (Litter and leaves) | Coarse Fuels (Wood : branches and trunks) | Average Fuels |
|---|---|---|---|
| Fearnside et al. (2001) | 0.68 | 0.26 | 0.30 |
| Carvalho et al. (2001) | 0.92 | 0.26 | 0.33 |
| Araújo et al. (1999) | 0.83 | 0.13 | 0.20 |
| Guild et al. (1998) | 0.95 | 0.47 | 0.51 |

**Table 2.5** The percentage of combustion completeness for different vegetation types**.**

| Vegetation Type | Michel et al. (2005) | IPCC (2003) | Heil (2007) |
|---|---|---|---|
| Evergreen needleleaf forest | 0.25 | | 0.39 |
| Evergreen broadleaf forest | 0.25 | | 0.39 |
| Deciduous needleleaf forest | 0.25 | | 0.39 |
| Deciduous broadleaf forest | 0.25 | | 0.39 |
| Mixed forest | 0.25 | | |
| Primary tropical Forest | | 0.36 | |
| Temperate Forest | | 0.45 | |
| Secondary tropical Forest | | 0.55 | |
| Boreal Forest | | 0.34 | |
| Eucalyptus Forest | | 0.63 | |
| Woodland | 0.35 | 0.40-0.74 | |
| Wooded grassland | 0.40 | 0.74-0.77 | |
| Closed shrubland | 0.50 | 0.72 | |
| Open shrubland | 0.85 | 0.72 | |
| Grassland | 0.95 | | 0.93 |
| Cropland | 0.60 | | 0.93 |

### 2.4.5 Emission factors

Emission factors are usually defined as grams of emitted gas per kilogram of dry matter (DM) during the burning process (Schwarze et al., 2007). There are studies that have provided new measurements of EF, but in most studies, estimation of emission burning such as studies of Hoelzemann et al. (2004) and Ito and Penner (2004), relied in some parts on emission factors reported by Andreae and Merlet (2001) which consist of vegetation types including tropical forest, extra-tropical forest, savannah and grassland. However, Akagi et al. (2011) have collected emission factors from various studies between 2001 to 2010 on different types of vegetation, including boreal forest, temperate forest and peat lands. A summary of emission factors derived from Andreae and Merlet (2001) and Akagi et al. (2011) is shown in Table 2.6. Emission factors were estimated from various references, their values are shown as means and standard deviations ($x \pm s$).

**Table 2.6** Emission factors[c] **(g kg$^{-1}$)** for species emitted from various types of vegetation burning**.**

| Parameters | Savanna and Grassland[a] | Savanna [b] | Tropical Forest[a] | Tropical Forest[b] | Extratropical Forest[a] | Extratropical Forest[b] | Crop Residue[a] | Crop Residue[b] | Boreal Forest[b] | Temperate Forest[b] | Peatland[b] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Carbon Dioxide ($CO_2$) | 1613 ± 95 | 1686 ± 38 | 1580 ± 90 | 1643 ± 58 | 1569 ± 131 | 1509 ± 98 | 1515 ± 177 | 1585 ± 100 | 1489 ± 121 | 1637 ± 71 | 1563 ± 65 |
| Carbon Monoxide (CO) | 65 ± 20 | 63 ± 17 | 104 ± 20 | 93 ± 27 | 107 ± 37 | 122 ± 44 | 92 ± 84 | 102 ± 33 | 127 ± 45 | 89 ± 32 | 182 ± 60 |
| Methane ($CH_4$) | 2.3 ± 0.9 | 1.94 ± 0.85 | 2.3 ± 0.9 | 5.07 ± 1.98 | 4.7 ± 109 | 5.68 ± 3.24 | 2.7 | 5.82 ± 3.56 | 5.96 ± 3.14 | 3.92 ± 2.39 | 11.8 ± 7.8 |
| Hydrogen ($H_2$) | 0.97 ± 0.38 | 1.70 ± 0.64 | 3.6 - 4.0 | 3.36 ± 1.3 | 1.8 ± 0.5 | n/a | 2.4 | 2.59 ± 1.78 | n/a | n/a | n/a |
| Nitrogen Oxides ($NO_x$ as NO) | 3.9 ± 2.4 | 3.9 ± 0.80 | 1.6 ± 0.7 | 2.55 ± 1.4 | 3.0 ± 1.4 | 1.12 ± 0.69 | 2.5 ± 1.0 | 3.11 ± 1.57 | 0.90 ± 0.69 | 0.16 ± 0.21 | 0.8 ± 0.57 |
| Nitrous Oxide ($N_2O$) | 0.21 ± 0.10 | n/a | 0.2 | n/a | 0.26 ± 0.07 | 0.38 ± 0.35 | 0.07 | n/a | n/a | 11.9 ± 7.6 | n/a |
| Sulphur Dioxide ($SO_2$) | 0.35 ± 0.16 | 0.48 ± 0.27 | 0.57 ± 0.23 | 0.40 ± 0.19 | 1.0 | n/a | 0.4 | 0.32 ± 0.14 | 0.52 ± 0.15 | 0.52 ± 0.15 | n/a |
| Total Suspended Particulate (TSP) | 8.3 ± 3.2 | n/a | 6.5 - 10.5 | 13 | 17.6 ± 6.4 | n/a | 13 | n/a | n/a | n/a | n/a |
| Total Particulate Carbon | 3.7 ± 1.3 | 3.00 ± 1.43 | 6.6 ± 1.5 | 5.24 ± 2.91 | 6.1 - 10.4 | n/a | 4 | n/a | n/a | n/a | n/a |
| Particulate matter <2.5 µm diameter ($PM_{2.5}$) | 5.4 ± 1.5 | 7.17 ± 3.42 | 9.1 ± 1.5 | 9.1 ± 3.5 | 13.0 ± 7.0 | 15 ± 7.5 | 3.9 | 6.26 ± 2.36 | 15.3 ± 5.9 | n/a | n/a |
| Black Carbon (BC) | 0.48 ± 0.18 | 0.37 ± 0.20 | 0.66 ± 0.31 | 0.52 ± 0.28 | 0.56 ± 0.19 | 0.56 ± 0.19 | 0.69 ± 0.13 | 0.75 | n/a | n/a | 0.2 ± 0.11 |
| Organic Carbon (OC) | 3.4 ± 1.4 | 2.62 ± 1.24 | 5.2 ± 1.5 | 4.71 ± 2.73 | 8.6 - 9.7 | 8.6 - 9.7 | 3.3 | 2.3 | n/a | n/a | 6.23 ± 3.6 |

a Source is Andreae and Merlet (2001)

b Source is Akagi et al. (2011)

c Emission factors are given in gram species per kilogram dry matter burned.

## 2.5 Pollutants from forest fires

### 2.5.1 Global forest fires emissions

Forest fires release various gaseous substances and particles to the atmosphere. Studies by Kaiser et al. (2012), Hoelzemann et al. (2004), Streets et al. (2003), and Schultz et al. (2008) show that forest fires emit large amounts of gases and PM (Table 2.7), of which carbon dioxide ($CO_2$) is the main gas followed by carbon monoxide (CO) and PM. Africa emits the most pollutants from fires whereas Europe releases the least, which is consistent with total areas burned. In addition, these studies used different estimation methods and satellite products, which is a cause of the various values reported for emissions, although the emission factors for all studies were based on the work of Andreae and Merlet (2001).

**Table 2.7** Average annual emission **[**Tg**]** of selected pollutants for Africa, Australia, America, Asia and Europe regions[a]

| Emissions | Africa | America | Asia | Australia | Europe | global | References |
|---|---|---|---|---|---|---|---|
| $CO_2$ | 3,204.7 | 1,706.2 | 1,455.0 | 444.0 | 110.6 | 6,906.7 | Kaiser et al. (2012) |
| | | | | | | 5,716.0 | Hoelzemann et al. (2004)[b] |
| | | | 1,100.0 | | | | Streets et al. (2003) |
| C | 939.9 | 513.8 | 456.0 | 130.1 | 33.1 | 2,068.8 | Kaiser et al. (2012) |
| | 993.0 | 644.2 | 270.1 | 169.0 | 2.6 | 2,078.9 | Schultz et al. (2008) |
| | | | | | | 1,741.0 | Hoelzemann et al. (2004) |
| CO | 127.3 | 91.9 | 110.5 | 17.4 | 5.6 | 351.5 | Kaiser et al. (2012) |
| | 128.0 | 62.7 | 70.6 | 6.7 | 2.3 | 270.3 | Hoelzemann et al. (2004) |
| | | | 67.0 | | | | Streets et al. (2003) |
| TPM | 17.3 | 12.2 | 12.0 | 2.4 | 0.74 | 44.6 | Kaiser et al. (2012) |
| $PM_{2.5}$ | 10.5 | 8.6 | 8.8 | 1.5 | 0.47 | 29.7 | Kaiser et al. (2012) |
| | | | | | | 24.3 | Hoelzemann et al. (2004) |
| NMHC | 7.3 | 5.8 | 6.7 | 0.98 | 0.41 | 21.1 | Kaiser et al. (2012) |
| TC | 7.7 | 5.8 | 5.8 | 1.1 | 0.29 | 20.6 | Kaiser et al. (2012) |
| $CH_4$ | 5.2 | 5.0 | 8.0 | 0.67 | 0.34 | 19.0 | Kaiser et al. (2012) |
| | | | | | | 12.5 | Hoelzemann et al. (2004) |
| | | | 3.1 | | | | Streets et al. (2003) |
| OC | 6.5 | 5.0 | 5.5 | 0.96 | 0.28 | 18.2 | Kaiser et al. (2012) |
| | | | | | | 15.8 | Hoelzemann et al. (2004) |
| | | | 3.3 | | | | Streets et al. (2003) |
| $NO_x$ | 4.2 | 2.5 | 2.1 | 0.59 | 0.16 | 9.5 | Kaiser et al. (2012) |
| | 3.9 | 1.8 | 2.1 | 0.24 | 0.08 | 8.1 | Hoelzemann et al. (2004) |
| | | | 2.8 | | | | Streets et al. (2003) |

[a] Burning areas of each study was classified in different criteria
[b] Emission from GWEM-1.21 results

### 2.5.2 Forest fires emissions of Asia

According to Streets et al. (2003), forests are the most significant source of burning in Southeast Asia at 330 Tg (dry matter burned) annually, whilst in East Asia and South Asia, crop residue burning is the main source of fire emissions at 114.9 and 107.2 Tg annually, respectively. Streets et al. (2003) also studied individual emissions from biomass burning, including $SO_2$, $NO_x$, $CO_2$, CO, $CH_4$, non-methane volatile organic compounds (NMVOC), black carbon (BC), organic carbon (OC), and $NH_3$. Similarly to global emissions, $CO_2$ and CO are the most significant pollutants (Table 2.8).

**Table 2.8** Total national emissions from biomass burning in Asia **(Gg)**

| Country | $SO_2$ | $NO_x$ | $CO_2$ | CO | $CH_4$ | NMVOC | BC | OC | $NH_3$ |
|---|---|---|---|---|---|---|---|---|---|
| China | 83 | 820 | 280,000 | 16,000 | 540 | 2,700 | 110 | 730 | 230 |
| Mongolia | 17 | 180 | 52,000 | 2,500 | 97 | 430 | 16 | 160 | 38 |
| Korea, DPR | 1.3 | 7.8 | 2,800 | 180 | 6.9 | 35 | 1.1 | 12 | 2.5 |
| Japan | 1.3 | 9.7 | 3,700 | 230 | 7.6 | 41 | 1.6 | 11 | 3.2 |
| Korea, Rep. of | 0.8 | 7 | 2,800 | 170 | 5.1 | 29 | 1.2 | 6.4 | 2.4 |
| Taiwan, China | 0.2 | 1.9 | 840 | 52 | 2 | 9.1 | 0.4 | 2.1 | 0.7 |
| **Total East Asia** | **103.6** | **1,026.4** | **342,140** | **19,132** | **658.6** | **3244.1** | **130.3** | **921.5** | **276.8** |
| Indonesia | 48 | 310 | 150,000 | 9,000 | 530 | 1,600 | 59 | 440 | 120 |
| Myanmar | 34 | 160 | 97,000 | 6,300 | 390 | 1,200 | 40 | 310 | 79 |
| Thailand | 28 | 190 | 88,000 | 5,200 | 290 | 930 | 35 | 250 | 69 |
| Vietnam | 15 | 130 | 53,000 | 2,900 | 150 | 500 | 20 | 140 | 40 |
| Laos | 13 | 78 | 39,000 | 2,400 | 140 | 420 | 15 | 120 | 31 |
| Malaysia | 13 | 57 | 36,000 | 2,400 | 150 | 440 | 15 | 120 | 30 |
| Philippines | 12 | 69 | 37,000 | 2,400 | 130 | 440 | 16 | 110 | 31 |
| Cambodia | 6.1 | 62 | 22,000 | 1,100 | 57 | 190 | 7.8 | 57 | 16 |
| Brunei | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| Singapore | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| **Total Southeast Asia** | **169.1** | **1,056** | **522,000** | **31,700** | **1,837** | **5,720** | **207.8** | **1547** | **416** |
| India | 74 | 540 | 200,000 | 12,000 | 420 | 2,200 | 83 | 650 | 170 |
| Bangladesh | 9.3 | 63 | 30,000 | 1,900 | 88 | 340 | 13 | 81 | 25 |
| Nepal | 5.8 | 31 | 11,000 | 710 | 29 | 140 | 4.2 | 52 | 10 |
| Pakistan | 6 | 61 | 22,000 | 1,200 | 39 | 210 | 9 | 52 | 18 |
| Sri Lanka | 2.3 | 10 | 6,500 | 430 | 27 | 79 | 2.7 | 21 | 5.4 |
| Bhutan | 0.7 | 3.2 | 1,100 | 75 | 3.3 | 15 | 0.4 | 6.3 | 1 |
| **Total South Asia** | **98.1** | **708.2** | **270,600** | **16,315** | **606.3** | **2984** | **112.3** | **862.3** | **229.4** |
| **Asia Total** | **370** | **2,800** | **1,100,000** | **67,000** | **3100** | **12,000** | **450** | **3300** | **920** |

## 2.6 Health Impacts

According to Ammann et al. (2008), PM is the principal pollutant of concern from forest fires' smoke because of the relatively short-term exposure periods (hours to weeks). The sizes of particles relate to different health impacts and can be classified into three groups: 1) particles larger than 10 micrometres, 2) particle with diameters from 2.5 to 10 micrometres ($PM_{10-2.5}$), and 3) particle with diameters 2.5 micrometres and smaller ($PM_{2.5}$). Particles larger than 10 micrometres do not usually reach the lungs, but can irritate the eyes, nose, and throat while $PM_{10-2.5}$ can get deep into lungs and $PM_{2.5}$ can affect the lungs and heart. The results of many studies provided information of associations between short-term $PM_{2.5}$ exposure and mortality, medication use, cardiovascular and respiratory symptoms but only little evidence showed the relation between $PM_{10-2.5}$ and mortality, cardiovascular and respiratory health effects (US EPA, 2009). At present, most air quality monitoring systems generate data based on the measurement of $PM_{10}$. $PM_{10}$ is a particle with diameters less than or equal to 10 micrometres and it includes both $PM_{2.5}$ and $PM_{10-2.5}$. The ratio of 0.5 between $PM_{2.5}$ and $PM_{10}$ is found in developing country urban areas and the range ratio of 0.5–0.8 in developed country urban areas (WHO, 2006). $PM_{10}$ impacts people's health, causing respiratory symptoms, transient reductions in lung function, and pulmonary inflammation (Ammann et al., 2008) and mortality (US EPA, 2009).

Since 1997 there also have been serious regional episodes of forest fires in the ASEAN region in 2002, 2006, 2009, 2013, 2014 and 2015 (Page and Hooijer, 2016). The forest fire occurrence in Indonesia year 2013 was widely reported by the global news media from fires adversely affected people's health and the air quality of neighbouring countries, including Malaysia and Singapore (BBC, 2013). This event led to the Pollutant Standards Index (PSI, pollution levels for the major air pollutants) of Singapore reaching 401 (a PSI reading above 300 is defined as "hazardous"). In southern Malaysia, around 300 schools were closed. Severe forest fires in Indonesia also happened in 1997. Relevant studies of health impacts from forest fires of Indonesia and other countries are summarized in Table 2.9.

**Table 2.9** Key studies of health impacts caused by forest fires

| Reference | Study description | Health outcome |
|---|---|---|
| Kunii et al. (2002). | In the 1997 forest fire disaster in Indonesia, concentrations of carbon monoxide and $PM_{10}$ reached "very unhealthy" and "hazardous" levels as defined by the Pollution Standards Index. | More than 90% of the respondents had respiratory symptoms, and elderly individuals suffered a serious deterioration of overall health (respiratory system) |
| Emmanuel (2000) | In Indonesia, $PM_{10}$ levels caused by forest fires had increased from 50 µg/m$^3$ to 150 µg/m$^3$. | There were increases of 12% of upper respiratory tract illness, 19% asthma and 26% rhinitis. (upper respiratory system) |
| Lee et al. (2009) | In California, forest fires released $PM_{10}$, reaching hazardous level. This study used stratified multivariate logistic regression models to find the relationship between patients seeking care and $PM_{10}$ exposure. | $PM_{10}$ concentrations were significant predictors for patients seeking care for circulatory illness among residents of nearby communities and new patients, and for respiratory illness. (circulatory system) |
| Chen et al. (2006) | $PM_{10}$ ranged 4.90-60.60 µg/m$^3$ appeared during forest fire event in Brisbane, Australia. | $PM_{10}$ was statistically significantly associated with an increased risk of respiratory hospital admissions (respiratory system) |
| Johnston et al. (2006) | In Australia, $PM_{10}$ generated by forest fire event ranged 2.6-43.3 µg/m$^3$. | The lower level of $PM_{10}$ (2.6-43.3 µg/m$^3$) also was significantly associated with onset of asthma symptoms, commencing oral steroid medication but no associations were found with the more severe outcomes of asthma attacks, increased health care attendances or missed school/ work days (asthma) |
| Wiwatanadate and Liwsrisakun (2011) | A study ran from August 2005 to June 2006 in Chiang Mai, Thailand. $PM_{10}$ concentrations were 16-237 µg/m$^3$. | No pollutants were related to asthma symptoms in Chiang Mai, Thailand. More studies are needed, particularly at low dose in adult asthmatics, to validate findings (asthma) |

## 2.7 Environmental Impacts

### 2.7.1 Effects of fires on the ambient air quality

Emissions from forest fires affect the environment both directly and indirectly. Greenhouse gases and aerosols emitted directly elevate the concentration of pollutants in ambient air, and indirectly they are causes of secondary effects on atmospheric chemistry such as ozone formation. In 2001, the 7-day Chisholm (Canada) fire burned 116,000 ha of land and increased the PM concentration of Edmonton city located 160 km away from a daily average concentration of 12 $\mu g/m^3$ to an hourly high of 261 $\mu g/m^3$ (Rittmaster et al., 2006). Some pollutants not only affect the local area, but also affect the regional area. For example, PM released can be transported for thousands of kilometres in the atmosphere (Sapkota et al., 2005) and impact other regions. Vegetation fires in Indonesia year 2015 have released the emissions loading (in Gg) of greenhouse gases at around 806,406 $CO_2$, 8,002 $CH_4$, and pollutants of about 259 BC, 1,957 OC, 4,118 $PM_{2.5}$ and 5,468 $PM_{10}$ (Jongudomsuk et al., 2015). This affected neighbouring country by raising the 24-hour $PM_{2.5}$ concentrations in Singapore from <50 $\mu g/m^3$ to >100 $\mu g/m^3$ in September 2015 (Shannon et al., 2016). As previously reported, poor ambient air quality is a cause of adverse health and environmental effects, as discussed below.

### 2.7.2 Effects of fires on the forest ecosystem

A forest fire is an important factor in many ecosystems and destroys some ecosystems. Fires impact ecosystem processes such as in vegetation dynamics, nutrient cycling, soil and below ground process and water systems (Chen, 2006). A low severity from the fire regime that leaves >80% of the above-ground dominant vegetation to survive will allow forests to be the fire-resistant because trees will adapt themselves to have thick bark and ability to heal fire scars. Furthermore, the vegetation structures of forest will substantially change if >80% of the above-ground vegetation dies in fires (Neary et al., 2005, Nasi et al., 2002). The removal of species by fires can change forest to grassland (Chen, 2006). The forest ecosystem responses can be roughly estimated by fire intensity and fire severity (Keeley, 2009). Keeley (2009) studied the correlation between fire intensity or fire severity metrics and ecosystem responses including vegetative regeneration, recolonization by plants and animals, and watershed hydrology processes. However, these correlations may be positive, negative or neutral responses from fire intensity and severity (Keeley, 2009).

Fire intensity is a measure of the rate of energy release from the organic matter combustion process. There were studies which showed a relationship between fire intensity or flame length and impacts of fires (Keeley, 2009). Studies (Dickinson and Johnson, 2001, Keeley and McGinnis, 2007) have shown that tree mortality patterns and seed survivals after fires were related to flame length and plume heat from fire intensity and these relations can be generated by using mathematic models. The fire intensity was related to soil heating and survival of seed banks or rhizomes. There also was a significant relationship between flame length and fire intensity in forest and shrubland ecosystems by empirical studies but this was not reliable for grasslands and savanna (Keeley, 2009). Fire severity has been used to describe fire effects on ecosystems (Neary et al., 2005). A common measure of fire severity is measuring the loss of above-ground (i.e. canopy tree, surface litter) and below-ground (i.e. soil organic layer) organic matter without considering re-sprouting after fires (Keeley, 2009). There are many benefits of low to moderately intense fires, such as maintenance of some types of forest (i.e. deciduous and mixed deciduous forests) (Nasi et al., 2002) and an increase in soil's nutrients (Kennard and Gholz, 2001); at the same time, forest fires can cause ecosystem damage. A forest that is sensitive to fire, such as an evergreen forest, may transfer from evergreen forest to deciduous forest and savanna with a consequent significant loss of biodiversity (Cochrane, 2009). Generally, the impacts of fires to ecosystem responds include plant species, wildlife, water, soil, and carbon consequences as shown below.

#### 2.7.2.1 Effects of fires on plant species

In an area where fires often occur, tree species show adaptive characteristics such as thick bark, ability to heal fire scars, re-sprouting capability and seed adaptation. For example, some North American and European pines have thick bark, great crown base and height (Nasi et al., 2002). In North America, after a fire, *Pinus banksiana* (Jack pine) and *Pinus contorta* (Lodgepole pine) have cones that will open and release the seed into the ash bed. Some plants, such as Eucalypts in Australia, require burning for regeneration to occur (Rowell and Moore, 2000)

After a fire in Thailand, for three forest types (deciduous dipterocarp, mixed deciduous, and dry evergreen), seedling mortality was >90% in all forest types. Sapling mortality varied from 27% to 63%. Trees and poles showed mortality rate ranging 0-7% and 0-21%, respectively (Baker and Bunyavejchewin, 2009). For deciduous dipterocarp forests, saplings such as *Arundinaria*are adapted by re-sprouting within 14 days after a fire. Six deciduous species of dipterocarp, namely *Dipterocarpus intricatus Dyer, Dipterocarpus obtusifolius Tei- jsm., Dipterocarpus tuberculatus Roxb., Shorea obtusa Wall., Shorea roxburghii G. Don and Shorea siamensis Miq,.* appeared to adapt themselves to fires by their characteristics, including thick, hard and rough bark, tap roots and lateral roots which are similarly protected, root collars with numerous dormant buds, leading to re-sprouting often within 1 month after fire, or coppicing and seed production and dispersal after the fire has passed through (Stott, 1986).

#### 2.7.2.2 Effects of fires on wildlife

Fires affect wildlife by killing them directly, and also lead to longer-term indirect effects such as stress and loss of habitat, territories, shelter and food (Nasi et al., 2002). Fires can cause the displacement of territorial birds and mammals, which may upset the local balance and ultimately result in the loss of wildlife. The severe fires of 1998 in the Russian Federation led to increased water temperatures and high carbon dioxide concentrations in lakes and waterways, which adversely affected salmon spawning (Shvidenko and Goldammer, 2001). However, fires also give benefits to some species. For instance, grass-layer beetle species in Australia's savannahs show significant resilience to fire, although fires affect abundance, species and family richness (JÉrôme and Andersen, 2001).

#### 2.7.2.3 Effects of fires on water and soil

Fires destroy vegetation that cover forest ground and change soil characteristics such as soil water holding (Neary et al., 2005). For severe fires, Johansen et al. (2001) showed that runoff from burned plots was about 45% of the total 120 mm of applied precipitation. An erosion threshold is reached when the amount of soil exposed by fire increases to 60–70%. Burned plots generated 25 times more sediment than unburned plots (Johansen et al., 2001).

#### 2.7.2.4 Effects of fires on carbon consequences

Generally, fires destroy vegetation and change soil characteristics such as soil water holding capacity and surface evaporation, which– in a complex way - affects the climate system. Forests are a key sink of carbon. The occurrences of fires release a large amount of carbon to the atmosphere. Aerosol particles (e.g. PM, black carbon, and organic carbon) from fires can create direct and indirect changes of solar irradiation by scattering and absorbing solar radiation (Langmann et al., 2009). Early studies showed that the net effect of aerosol particles would be cooling the atmosphere, but recent studies have suggested that climate change by aerosol impacts are complex and still uncertain (Ellicott, 2009). This complexity was also shown by Shindell (2015) who reported that black carbon tends to warm the global mean surface temperature whereas the organic carbon is likely to be the cooling effect. Beside this, the gases including carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$) and carbon monoxide (CO) are global warming gases while nitrogen oxide ($NO_x$) and sulphur dioxide ($SO_2$) are the cooling via nitrate and sulphate aerosol formation respectively.

## 2.8 Socio-Economic evaluation

Bonniex and Rainelli (1999) summarized the use of valuation for project or policy decisions into two stages. First, the translation of environmental changes into monetary values. Second, monetary benefit estimates can influence particular decisions by employing a cost-benefit analysis. Cost-Benefit Analysis is a socio-economic tool that compares the gains with the losses in an investment project or a policy (Pearce, 1998). CBA is used for policy decisions in many countries such as the United States and the United Kingdom. The goals of this tool are typically to evaluate the positive and negative changes associated with proposed policy changes, and to achieve requirements with the condition that the change in benefits must exceed the change in costs (Pearce, 1998, Department of the Interior, 2012). According to Atkinson and Mourato (2008), the important process in environmental CBA is the estimation of monetary values for environmental changes. The estimation of the total economic value of ecosystem changes should be distinguished from the value of all ecosystems i.e. it is what happens at the margins that is important. The total economic value of a forest can be divided into use and non-use values, as shown in Table 2.10.

**Table 2.10** Total economic value of forest **[**adapted from Lette and de Boo **(**2002**)**, Adger et al**.** **(**1994**)** and SCBD **(**2001b**)].**

| | | Descriptions |
|---|---|---|
| 1. Use values | | |
| 1.1 Direct use value | Products that can be directly consumed | Timber and other wood products, hunting, a source of food, medicine plants, recreation/tourism, research/education |
| 1.2 Indirect use value | Natural forest functions | Soil stabilization and erosion, water regulation, climate regulation and carbon sequestration, flood/landslides/avalanche prevention, biological diversity |
| 1.3 Option value | Future direct and indirect uses | Biodiversity, conserved habitats, unknown future medicinal benefits |
| 2. Non-use value | | |
| 2.1 Existence value | Value from knowledge of continued existence, based on e.g. moral conviction | Biodiversity, culture/ heritage |
| 2.2 Bequest values | Value of leaving use and non-use values for offspring | Habitats, irreversible changes |

### 2.8.1 Environmental valuation methods

The occurrences of forest fires have changed forest ecosystems and ambient air quality. These changes could be translated into economic values. There are various methods (see Figure 2.2) to valuing the environment, including: (Chiabai et al., 2010, Lette and de Boo, 2002, Bishop, 1999, DEFRA, 2007)

- Revealed preference (RP) based on actual behaviour associated with the market either directly (e.g. averting behaviour) or indirectly (e.g. hedonic pricing);
- Stated preference (SP) based on hypothetical market surveys of either willingness to pay

(WTP); and willingness to accept compensation and

- Production function approaches or dose-response methods, which involve an attempt to relate human well-being or quantity of a marketed good or service to a measurable change in the quality or quantity of a natural resource.

However, economic welfare approaches based on market prices may be not effectively represent prices for some elements. Risk approaches based on shadow prices are considered for adjustment to take into account the precautionary principle for the environmental valuation process (DEFRA, 2007).

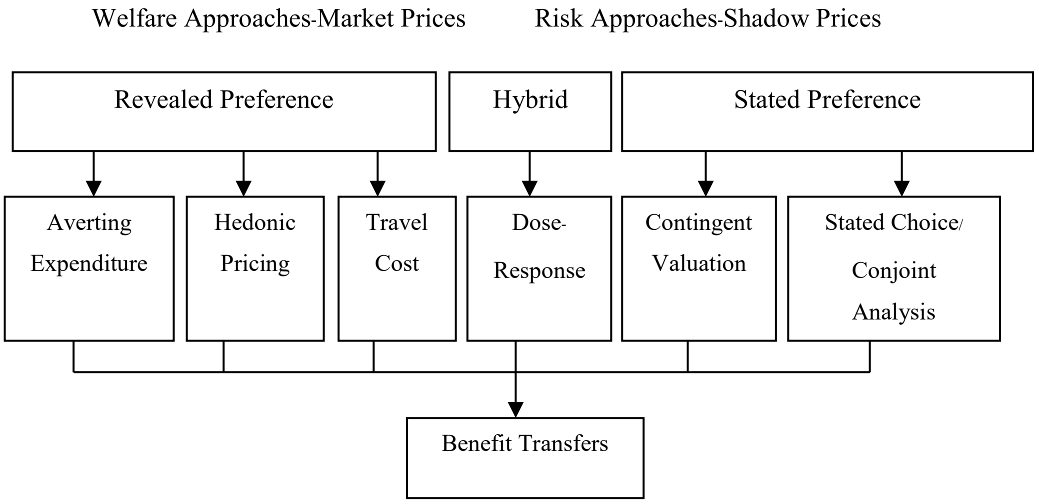



**Figure 2.2** Techniques of monetary valuation for environmental valuation

RP approaches can be processed by using hedonic pricing and travel cost methods. The hedonic pricing method is where the price of a marketed good is related to its characteristics without confounding or correlated factors and transaction costs. In Colorado, the United States, Loomis (2004) applied a hedonic pricing method for property values when their characteristics change. The study showed that forest fires adversely affected house prices near a forest fire area, decreasing them by 15%.

The travel cost method can be used to estimate the value of forest recreation. It is based on measuring travel costs to visit a natural area and the time spent travelling. It is an estimation of the value of time and assumes that there is a single purpose for a particular trip. Hesseln et al. (2003) used the travel cost model to test the effects of prescribed fires on demand for hikers and mountain bikers in New Mexico. Prescribed burns led to a decrease in net benefits for the both of hikers and mountain bikers.

Generally, SP approaches consist of two main methods; contingent valuation and choice experiments. In contingent valuation method (CVM) surveys, a sample of the relevant population provides answers on their willingness-to-pay for the use or conservation of natural goods. However, CVM does not produce valid measurements when it concerns goods that people are not familiar with. Individuals express different preferences when adopting a consumer and a citizen viewpoint, and the latter viewpoint gives more weight to attributes with less direct and obvious visual appeal (van Rensburg et al., 2002). In a choice experiment, the respondent has to choose a preferred alternative for paying for the use or conservation of natural goods or receiving compensation from the losses of natural goods. The difference between choice experiment and contingent valuation is that choice experiment does not directly ask people to state their values in monetary units (e.g. dollars). Moreover, Hanley et al. (2001) showed that choice experiments can provide a cognitive burden to a respondent which may solve some biases associated with standard contingent valuation.

The production function or dose-response approach is often used in studies that aim to estimate the monetary damages of environmental degradation. This method consists of two steps: first, the relation between a dose of pollution/pressure and an effect on production or a response is determined. Secondly, the changes are valued by certain monetary measures including market price. However, DEFRA (2007) suggested that the dose response/production function approach is not a valuation technique. It tends to be an element of several valuation approaches such as dose response functions linking air pollution to various health effects. It provides values either by assuming market prices e.g. an impact of pollution on agricultural productivity or using surrogate prices e.g. the value of a life from a combination of stated and revealed preference valuation methods.

An imbalanced incentive structure frequently occurs in fire management. Costs do not necessarily equal the benefits of environmental improvements or the damage by degradation when costs are not actually incurred, such as for the shadow project technique, where there is a risk of under- or over-estimating the value of the environmental asset. According to DEFRA (2007), the shadow project method refers to the costs of providing an equal alternative good or service elsewhere. These may be the asset reconstruction, asset transplantation or asset restoration. The cost of the chosen option is added to the basic cost of the proposed development project in order to estimate the full cost. The development project will be accepted if the benefits are at least equal to the development project costs plus the shadow project costs.

### 2.8.2 Benefit transfer of forest values

Over the past two decades, there has been an increase in environmental benefit transfer use as an approach for estimating the value of environmental goods and services. Benefits transfer is the process of taking information about economic values from studies already completed and applying it to the target study. Plummer (2009) suggested that the first step is to consider the type of land cover, biome, or some other set of an ecological landscape. The next step is to take the study's estimated value for a particular ecosystem service and divide this by the area of the relevant landscape type, producing a constant value for that ecosystem service–landscape type combination per unit of area. Wilson and Hoehn (2006) studied the relevant papers of benefit transfer and showed that besides geographic location and environmental attitudes, three factors including the ecosystem commodity, the market context, and the formulated welfare measure of the original study and targeted study need to be similar or adjustments are needed if there are differences. Moreover, the study showed that benefit transfer errors consisted of the difference between the original study and target study site, the judgments and methods used in the original study, and publication bias.

### 2.8.3 Socio-economic impact valuation in the United States

According to Dale (2010), forest fire costs are measured as direct costs, rehabilitation costs, indirect costs and additional costs. Firstly, direct costs that appear during or immediately following the fires can be broken down into expenditures on engines, fire fighting crews, property losses, damage of recreation facilities, loss of timber resources, and aid to evacuated residents. Secondly, rehabilitation costs, especially longer-term, are harder to measure. For example, watersheds damaged by fire, in particular, can take many years to recover and require significant restoration activities. Thirdly, indirect wildfire costs include lost tax revenues in a number of categories such as sales and county taxes, as well as business revenue and property losses that accumulate over the longer term. Finally, additional costs or special costs are calculated by assuming a proxy for the cost of lost life, loss of civilian life, ongoing health problems for the young, old, and those with weak respiratory or immune systems, and mental health needs. Additionally, the extensive loss of ecosystem services, some of which are inherently difficult to quantify (e.g. aesthetic and scenic beauty, wildlife existence value), and others are taken into account.

### 2.8.4 Socio-economic impact valuation in Europe

Mavsar et al. (2011) showed that the Europe Forest Fire Information System (EFFIS) has improved a standardized Analytical Assessment Model (AAM) for the assessment of economic impacts. The AAM was developed to estimate fire damage costs of special cases or areas burned that are larger than 500 ha. The economic analysis is based on the missed flow of forest goods and services, aggregated in an additive function. The AAM algorithm is:

$$D_{TOTi} = D_{Wi} + D_{Ci} + D_{NWFPi} + D_{Si} + D_{Bi} + D_{EXi} \qquad (2.2)$$

Where $D_{TOTi}$ is the total damage for pixel i (€);

$D_{Wi}$ is the damage related to wood production losses for pixel i (€);

$D_{Ci}$ is the damage related to carbon sequestration for pixel i (€);

$D_{NWFPi}$ is the damage related to Non-Wood Forest Products and Services (NWFP) for pixel i (€);

$D_{Si}$ is damage related to soil losses (erosion) for pixel i (€);

$D_{Bi}$ is damage related to biodiversity losses for pixel i (€);

$D_{EXi}$ is the extraordinary cost for pixel i (€).

Each damage value of the above forest goods and services was estimated by using area damaged (ha), value of forest goods and services (€), damage level (level 1,2,3) restoration period (year, ~ 1 to 6 years) and discount rate (%). The details are shown as follows:

$$D_{Wi} = A_i * NAI_i * (P_{wi} - C_{wi}) * DL_{wi} *[(n_i*(1-d)-d+d^{ni+1}) / (n_i*(1-d)^2)]; \quad d = 1+r \quad (2.3)$$

$$D_{Ci} = A_i *0.5*NAI_i *BEF*P_c * DL_{Ci} *[(n_i*(1-d)-d+d^{ni+1}) / (n_i*(1-d)^2)]; \quad d = 1+r \quad (2.4)$$

$$D_{NWFPi} = A_i * NWFP_i * P_{NWFPi} * DL_{NWFPi} *[(n_i*(1-d)-d+d^{ni+1})/(n_i*(1-d)^2)]; \quad d = 1+r \quad (2.5)$$

$$D_{Si} = A_i * S_i * P_{Si} * DL_{Si} *[(n_i*(1-d)-d+d^{ni+1}) / (n_i*(1-d)^2)]; \quad d = 1+r \quad (2.6)$$

$$D_{Bi} = A_i * S_i * P_{Bi} * DL_{Bi} *[(n_i*(1-d)-d+d^{ni+1}) / (n_i*(1-d)^2)]; \quad d = 1+r \quad (2.7)$$

$$D_{EXi} = A_i * S_i * P_{EXi} *DL_{EXi} *[(n_i*(1-d)-d+d^{ni+1}) / (n_i*(1-d)^2)]; \quad d = 1+r \quad (2.8)$$

Where $A_i$ is the area of pixel i (ha);

$NAI_i$ is the net annual increment for pixel i ($m^3$ $ha^{-1}$ $yr^{-1}$);

$P_{wi}$ is the market price of wood in pixel i (€/$m^3$);

$C_{wi}$ is the harvesting costs in pixel i (€/m3);

$DL_{wi}$ is the damage level for wood production capacity in pixel i;

BEF is the biomass expansion factor;

$P_C$ is the market price of carbon (€ tC-1);

$DL_{Ci}$ is the damage level for carbon sequestration capacity of forest in pixel i;

NWFPi is the annual quantity of NWFP produced in pixel i (unit1 ha-1 year-1);

$P_{NWFPi}$ is the price of NWFP in pixel i (€ unit-1);

$DL_{NWFPi}$ is the damage level of production potential for NWFP in pixel i;

$S_i$ is the increased soil loss (t ha-1 yr-1);

$P_{si}$ is the price of soil (€ t-1);

$DL_{Si}$ is the damage level of soil erosion prevention of forests in pixel i;

$P_B i$ is the value of biodiversity in pixel i (€ ha-1);
$DL_{Bi}$ is the level of damage to biodiversity of forests in pixel i;
$P_{EXi}$ is the value of extraordinary cost in pixel i (€ ha-1);
$DL_{EXi}$ is the damage level of extraordinary cost in pixel i;
ni is the restoration period for pixel i (years);
r is the discount rate.

Barreto et al. (1998) explained that wood production losses may be calculated with these variables; the net annual increment, market wood price and harvest costs. For the estimation of losses related to the decreased carbon sequestration, the net annual increment, carbon price, Biomass Expansion Factors (BEF) and the damage levels are needed. Sources of carbon price and BEF may be taken from the voluntary market data and the relevant Intergovernmental Panel on Climate Change (IPCC) report. Non-wood forest product losses such as cork, chestnut, resin, mushrooms and truffles, forage, recreational services may be calculated using market prices. The value of forest fire related soil loses may be estimated by considering the increased soil loss, soil price and damage level. The biodiversity loss may be estimated in relation to the biodiversity value, level of naturalness of the damaged forest and the damage level, which depends on the fire severity. Finally, extraordinary losses such as health impacts, property damages and agricultural losses may be calculated with these data; quantity, value and damage level. However, an error of double counting may occur in calculating a value of intermediate and final products because the intermediate services are by default included in the value of the final service (Fisher et al., 2008).

### 2.8.5 Vulnerability

The concept of vulnerability is important for the human dimension and global environmental change studies (Janssen and Ostrom, 2006). Generally vulnerability is a function of exposure and sensitivity to environmental, economic and social change, and the ability to adapt to the effects of hazards (Adger, 2006). This concept can be a tool for linking ecosystem services (e.g.: food production, wildlife habitat) related to different stakeholders and assessing the vulnerability to land use change and its consequence for ecosystem services (Schröter, 2005).

Luers et al. (2003) suggested that vulnerability should shift away from critical areas or vulnerable places and can be applied at any scale. They developed generic metrics for the relationship between a wide range of stressors and the outcome variables:

$$\text{Vulnerability} = (\text{sensitivity to stress} / \text{state relative to threshold}) \times \text{Prob. of exposure to stress} \quad (2.9)$$

Luers (2005) defined sensitivity as the degree to which a system will respond to an external disturbing force. It includes the ability to resist change and the ability to return to a previous condition after a stress has been removed. Exposure refers to the characteristics of forces that could stress the system (e.g. temperature) such as magnitude and frequency. Threshold means reference point which the system may be damaged if above or below.

The vulnerability of each vegetation type affected by forest fires is different. For example, in tropical humid forest, the regeneration rate of plants may be very slow. Too frequent fires can destroy the survival chances of new seedlings (Eva and Lambin, 2000). However, other research argues that the key to understanding vulnerability lies in the interaction between social dynamics within a social-ecological system and that these dynamics are important for resilience (Adger, 2006).

In this context, social vulnerability describes the pre-existing characteristics of groups or conditions within communities that make them more susceptible to the impacts of hazards. It helps to understand segments of society or sections of the community that are more susceptible to disaster impacts than others (Cutter, 2010).

### 2.8.5.1 High income and Low income / Rural and Urban

The poorest households typically rely on forest products (Baikuntha, 2002). In Sub-Saharan Africa, rural households rely heavily on forest products for subsistence (food, fuel and materials) and to supplement their incomes (European Forest Institute, 2002). Destroying forests by fires directly affects poor and rural people. In Alaska, people living in rural villages rely on land areas for hunting, fishing and gathering wild foods. The nutritional needs of local people are closely linked to ecosystem characteristics. Wild fires directly affect their foods (Trainor et al., 2009). A study by Gaither et al. (2011) showed that low socio-economic status of residents can have the effect of exacerbating community risk to wildfire occurrence and devastation because socially vulnerable populations are generally less able to either mitigate wildfire risk or recover from such events.

People in poverty use fires on vegetative land for reasons such as clearing the forest for cultivation, hunting, maintaining pasture, controlling pests, and managing crops (Eva and Lambin, 2000). In places like Amazonia, there are few technologies available to poor indigenous populations and consequently they use fires as a primary agricultural technology. Simmons et al. (2004) have discussed the complex links between poverty, social conditions and causes of wildfires.

### 2.8.5.2 Indigenous and non- indigenous communities

The impacts of forest fires on a settlement have generally been limited to short-term displacement, with no documented cases of permanent abandonment of large areas due to wildfire during the past 200 years or so (Handmer and Reale, 2011). However, this may change in the future. Increased wildfire risk is probably occurring as a result of climate change (Fried et al., 2008) and increased human exposure to the threat of fires.

In a term of disaster management, Mercer et al. (2010) suggested that indigenous and scientific knowledge should be involved to identify a viable strategy that reduces vulnerability to environmental hazards. Indigenous knowledge is considered to be a body of knowledge existing within populations or acquired by local people over a period of time through accumulation of experiences, society-nature relationships, community practices and institutions, and by passing it down through generations (Fernando, 2003).

#### 2.8.5.3 Nomadic and Sedentary Communities

According to Nkem et al. (2012), in the Congo Basin, the contrasting livelihood strategies of two groups (nomadic and sedentary hunter-gatherers) seem to structure their preferences in forest settlement locations. Hunting and gathering of forest products by nomads occurs nearly exclusively in the forest area. This is in contrast to sedentary peoples, who mostly exploit the secondary forest. These differences may be gradually fading with the increasing scarcity of valued forest products. In another major study, Wisner and Luce (1993) reported that all persons at the same level of income do not suffer equally in disaster situations. For instance in the Sahel famine, nomads who may have been less poor than sedentary farmers, actually suffered more as measured by death and dislocation. Watts and Bohle (1993) showed that entitlement approaches have primarily addressed the conditions of starvation because a person must necessarily starve if his/her entitlement set does not include a commodity bundle with enough food. This study showed that, besides income, there are other factors that co-determine whether an individual will go hungry.

### 2.8.6 The integration of ecosystem services and economic approach to the policy

According to Fisher et al. (2008), integrating economics and ecology into a decision support system for policy should consider three key issues including marginal changes in landscapes, insurance for ecosystem service provision, and the ability to capture non-market ecosystem services through some institutional arrangement. The marginality may refer to the price paid to prevent losing one unit. Trade-off decisions and beneficiaries are used to evaluate the monetary value. The insurance value is important because it indicates the minimum level of ecosystem structure needed to provide a continual flow of services. An example of insurance value is the study of the suitable densities for vegetation on hill slopes to supply the soil retention and water regulation during storm events. The third key issue is the benefit capture of ecosystem services that is used to motivate or invests for the payment of nonmarket ecosystem services. This mechanism is regulatory and is generated by using market-based mechanism. Examples of instruments are taxes, user fees and quotas that emphasize on setting taxes and user fees than determine the fixed level of emissions. For a quota-based system, this may set the quantity or scale of activity through the market by issuing permits or credits such as carbon emission permits, carbon credits and wetland banks. In countries in which regulatory and taxation systems are not strong enough, payments for ecosystem services (PES) tend to be popular. In this type of scheme, landowners will be compensated by the government for providing services that conserve the ecosystem.

### 2.9 Means of preventing impacts of forest fires

Fire suppression is a method to relieve the impacts of forest fires when fire occurs. An effective approach is to immediately locate fire occurrences for suppression (Tishkov, 2004). Fire forecasts are applied to specify fire locations for setting plans. Techniques for suppression include building fire barriers, restriction of forest visiting in fire seasons and distribution of information. In addition, fire monitoring is used to discover fire events. The monitoring of fires can be launched via space and aircraft monitoring, car, walking survey, and observation from towers and satellites. The data can be used to evaluate fire severity and the size of an affected area.

#### 2.9.1 The use of air quality models

Modelling is considered as a tool for policy makers to develop abatement strategies to reduce pollutant emissions by predicting pollutant concentrations as a result of changes in emissions and related conditions. Furthermore, it provides an improved understanding of the sources, causes and processes that determine air quality. Source apportionment, including the assessment of transboundary and natural contributions, is an important application of models if sufficient knowledge is to be acquired for the effective implementation of such plans.

An important use of models is the evaluation of different emission reduction scenarios in terms of their efficiency in improving regional and local air pollution levels, by taking into account distant pollutant emission sources (Denby et al., 2010). A relevant study uses a simple model to predict the dispersion of primary particulate material to $PM_{10}$ concentrations across Europe (Denby et al., 2010). The resulting population exposure is compared with that of secondary particulates, and it is found that both primary and secondary contributions will be significantly reduced with the implementation of new protocols under the Convention on Long-Range Transboundary Air Pollution (CLRTAP).

### 2.9.2 Forest fires management in the United States and Australia.

The forest fire management system in the USA is a centralised whilst Canada, Australia and New Zealand operate decentralised systems. The financing, resourcing and coordination of wildfire management in the USA is mainly the responsibility of central government. In Canada and Australia, forest fire management was decentralized to provincial/states, territorial agencies and other stakeholders whereas forestry companies and private land owners are the primary actors in New Zealand (Pierard and Jarvis, 2010).

In the USA, the costs of forest fire management by the Office of Wildland Fire (OWF) in 2011 were spent on 4 main categories, including: 1) preparedness (fire prevention, detection, equipment, training, and baseline personnel), 2) suppression (wildland fire fighting operations), 3) burned area rehabilitation, and 4) hazardous fuel reduction (treatment to protect lands and resources from wildfire damages) (Department of the Interior, 2012). In the past, the forest fire policy of the United States emphasized fire suppression without considering the accumulation of combustible matters (fuels) in forests. After fire suppressions, the accumulation of fuels tended to increase the risk of damage, high-intensity forest fires (Busenberg, 2004).

In 1995, the Federal Wildland Fire Policy included the reduction of fuels for fire management and recognized that fire is a natural part of many ecosystems and the beneficial ecological role of fire (Department of the Interior, 2012). Dale (2006) suggested that the use of fire to manage fuel loads may improve watershed conditions, enhanced wildlife habitat, and more resilient forested ecosystems. Moreover, reduction of fuel loads is appropriate for cost benefits including reduced suppression and fuel treatment costs over the long-term. The reduction of hazardous fuel accumulation appeared in many of the national fire plan's recommendations, especially on lands at the wildland-urban interface (WUI) (Cook and O'Laughlin, 2014). According to the Department of the Interior (2012), WUI - the area where houses meet or intermingle with the undeveloped wildland vegetation - was emphasized when estimating the cost of fire management in the USA in 2001. After that, the WUI fuel treatment funding has continued to increase, and reached 90% of fuel management funds in 2011. Fuel management is a major goal of National Strategy as the vision is to: "safely and effectively extinguish fire when needed; use fire where allowable; manage our natural resources; and as a nation, live with fire" (Cook and O'Laughlin, 2014). Australia has the same patterns of fuel reduction as the USA but Australia may lack fire-fighting resources compared with the USA (Adams, 2013)

## 2.10 Summary

A vegetation fire is an important problem that occurs regularly throughout the world, especially in Africa and Australia. Trends of global fires decreased between 2000 and 2012 but fires in Southeast Asia have tended to increase. Many studies showed that factors that promote the frequency of fires include hot and dry weather, and human activities. These conditions occur in the study area in the north of Thailand. The study area is fire-prone in which fires have been caused by humans and the weather. Forest fires have become a significant problem because they are causes of adverse environmental and human impacts. Emissions from fires include greenhouse gases that contribute to climate change and particulate matter that directly affects people's health. However, there are rarely studies of economic losses from forest fires, especially in developing countries such as Thailand. In addition, there were some studies of the air pollution from forest fires but only Chiang Mai province was studied. The study of people's health and environmental impacts, and economic losses caused by vegetation fires events in the north of Thailand including 8 provinces are needed to investigate for mitigating problems and being the information of Thailand vegetation fires for the future study.

From literature reviews of vegetation fires, people's health and environmental impacts, and economic losses can be estimated by fire emissions and numbers of forest area damaged by fires. The amount of fire emissions can be calculated by using values for areas burned, fuel consumed and emission factors. Many studies have provided these data for calculation of emissions as shown in the literature review. Area burned can be evaluated by using satellite images. A satellite plays an important role for monitoring forest fires throughout the world. It can used to estimate locations and area burned of forest fires for large areas. There are studies of forest fires in some areas in the Southeast Asia. They include the number of areas burned and a wide range of strategies for fire management. Generally, effective solutions for solving problems in each area/country/region are different depending on their geography. There is no study indicating specific solutions for the north of Thailand forest fires. A specific policy to mitigate the problem is needed based on the exactly quantity of impacts from fires and area controlled to meet the air quality standard of Thailand.

An air quality model is a tool to help estimate the pollutant emissions to reduce and can help to provide an improved understanding of the sources, causes and processes that determine air quality. Source apportionment, including the assessment of transboundary and natural contributions, is an important application of models if sufficient knowledge is to be acquired for the effective implementation of such plans. Effective solutions for solving fire emissions can be developed into policies with the economic approaches. Costs-Benefit analysis (CBA) is an effective method for analysing the net benefit to society by comparing the gains with the losses for specific policy decisions. The development of air pollution policy for vegetation fire management is not only mitigating the problem effectively, but it should be also worthy in a term of the maximum net-value of the benefit. Then, the integrated tool from the air quality model and CBA is a selected tool for generating forest fire policies in the north of Thailand in this study. This tool can develop the realistic and practical policy because the exactly of air quality targets, the amount of area-source sizes and possible budgets are set for managing Thailand air pollution caused by vegetation fires

# Chapter 3

## The Simulation of Air Pollution Scenarios

The CALifornia Puff (CALPUFF) is the model selected for air quality evaluation in this study. The CALPUFF model has been approved by the U.S. Environmental Protection Agency that it is suitable for regulatory use for long-range transport and on a case-by-case basis for short-range applications involving complex and non-steady-state flows such as in complex terrain, coastal situations, and where flow stagnation and flow reversals are important (Environmental Protection Agency (US EPA), 2003). The topography of north of Thailand is the complex terrain with mountains, forests and agricultural areas. The study area size is large with the area of about 425,000 $km^2$. This model simulates chemical transformation and removal processes of pollutants along a transportation route. The processes of the model's systems include CALifornia METeorological model (CALMET), pollutant dispersion program named CALPUFF, and a post-processing program named CALPOST (see Figure 3.1). The pollutant simulated in this study is $PM_{10}$ from vegetation fires in the north of Thailand and neighbouring countries. $PM_{10}$ is focused on in this study because it exceeds the daily Thai standard every year. Moreover, $PM_{10}$ measurements in Thailand are more common than $PM_{2.5}$ measurements (Thai Meteorological Department, 2016)Pollution Control department, 2012), and $PM_{10}$ does include the contribution from $PM_{2.5}$. In terms of transboundary pollution, it will be the $PM_{2.5}$ that contributes most to this, so $PM_{10}$ modelling may underestimate this component. In addition, $PM_{10}$ also contains more natural particles than man-made. The air quality model is applied for simulating the pollutant concentrations in the study area from actual fires events and scenarios of fires controlled in target areas.

In this chapter, the meteorological data and the amounts of emissions from each land-use source will be fed to the models. Before starting air quality simulation, the models have to be validated for adjusting to minimize error and to demonstrate that they are working properly. Results from the model simulation can determine the processes that influence fires emissions affecting the ambient air quality of the north of Thailand to exceed the Thai air quality standards. The various scenarios of vegetation fires controlled will be simulated to find the optimal pollution reduction targets from selected areas. This can identify the main pollutant sources and the numbers of areas needed to control atmospheric emissions from fires in order to meet the air quality standards. The policy options will focus on area sources and area size of the scenario that meet the air quality standards.

## 3.1 Dispersion models for air pollution

The air quality model will be applied for evaluating air pollutants concentrations generated from vegetation fires that may affect people's health. The area size, meteorological and terrain conditions are needed to be considered in order to determine the appropriate model for the study. There are three main types of air quality models to simulate the dispersion of the pollutants: Gaussian, Lagrangian and Eulerian. The Gaussian model computes the dispersion of air pollutants by a Gaussian distribution of the plume in the vertical and horizontal directions under steady-state conditions (Scire et al., 2002). This model can process for results almost immediately on common computers, but it is not capable to apply for continental scale dispersion. The examples of Gaussian models are CTDM (Complex Terrain Dispersion Model), AERMOD (American Meteorological Society (AMS)/EPA Regulatory Model), and British ADMS (Atmospheric Dispersion Modelling System) (Leelőssy et al., 2014). For the Lagrangian model, it processes the air dispersion based on the concept that pollutant particles in the atmosphere move along trajectories determined by the wind field, the buoyancy and the turbulence effects (Scire et al., 2002). Finally,the Eulerian model, it is similar to a Lagrangian model, but the Eulerian model uses a fixed grid as a frame of the reference while Lagrangian model uses a moving frame of reference (Oliveri Conti et al., 2017). The details of Lagrangian and Eulerian dispersion model were shown in Table 3.1.

To select models for the study area, European Environment Agency (2011) has suggested that Gaussian and non-Gaussian parameterised models can processes for scale sizes from 1 m to 300 km. For the regional and continental scale, Eulerian chemical transport and Lagrangian chemical models can process for the area size of 25 to 10,000 km. The models with the capacity for the large-scale processing are considered for this study. The large scales of the study area with the diameter at around 735 km would be processed for air pollution concentrations. The considered models are listed in Table 3.1 with details of types, meteorological models and operation systems for the atmospheric study of large scale areas.

**Table 3. 1** The details including types, meteorological models and operation systems for dispersion models on the atmospheric study of large scale areas

| Air quality Models | Details | Meteorological models | Operating system |
|---|---|---|---|
| CALPUFF | - CALPUFF is a non-steady-state Lagrangian Gaussian puff model with chemical removal, wet and dry deposition, building downwash, and complex terrain effects (Scire et al., 2000).<br>- It is preferred model by US EPA for long-range transport of emissions from 50 to several hundred kilometers (US EPA, 2017)<br>- It is free software<br>- It is not suitable for very large distances (>1,000 km) | Meteorological models such as CALMET, WRF, MM5 and RAMS | Windows |
| CAMx | - CAMx (Comprehensive Air Quality Model with extensions) is an Eulerian photochemical dispersion model that assess tropospheric air pollution (Ramboll Environ, 2017)<br>- It can simulate primarily pollutants and secondarily formed pollutants such as $O_3$ and $PM_{2.5}$ (US EPA, 2017)<br>- It can be used for over area scales ranging from neighbourhoods to continents (Ramboll Environ, 2017).<br>- It is an open-source system and a free software | Meteorological models such as WRF, MM5 and RAMS | Linux/ Unix |
| WRF-Chem | - WRF-Chem (Weather Research & Forecasting Model with Chemistry) is the Eulerian model of the chemistry and meteorology over a wide range of scales.<br>- It can simulate primarily pollutants and secondarily formed pollutants such as $O_3$ and $PM_{2.5}$ (US EPA, 2017) in an urban and regional context (Leelőssy et al., 2017).<br>- It is free software | Weather prediction models: WRF | Linux/ Unix |
| HYSPLIT | - HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) is Lagrangian dispersion models, which can process simple air parcel trajectories, complex transport, chemical transformation, and deposition simulations.<br>- It can simulate primarily pollutants and secondarily formed pollutants and forecast the radioactive material, volcanic ash, wildfire smoke, and hazardous chemicals (National Oceanic and Atmospheric Administration, 2017).<br>- It is free software | Meteorological data from National Oceanic and Atmospheric Administration (NOAA) | Windows/ Linux |
| CMAQ | - CMAQ (CommunityMulti-scale Air Quality) is Eulerian model, which can simulate various chemical and physical processes. (Leelőssy et al., 2014)<br>- It can simulate primarily pollutants and secondarily formed pollutants such as $O_3$ and $PM_{2.5}$ (US EPA, 2017)<br>- CMAQ can be used for either urban or regional scale air quality modelling (Leelőssy et al., 2014)<br>- It is an open-source system and a free software | Meteorological models such as WRF | Linux/ Unix |

All of models in Table 3.1 are free programs for downloading, installing and computing the dispersion of air pollutants. HYSPLIT has been used in many studies to understand consequences of pollutants released and sources of regional pollution (Leelőssy et al., 2014). CMAQ and CAMx also have been applied to evaluate the regional air pollution problems and assess strategies for reducing regional air pollution issues. Moreover, these models have been used extensively to study on ozone and $PM_{2.5}$ (Oliveri Conti et al., 2017, US EPA, 2017). WRF-Chem model has the advantages to integrate the meteorological, atmosphreric chemistry module and forecasting platforms for accessing air pollution dispersion (Oliveri Conti et al., 2017). However, this study has selected CALPUFF for the north of Thaialand with the reasons that it is suitable for the study area size, public health studies and easily operated by running on Windows operating system. The US EPA offers the CALPUFF system as a preferred model for environmental protection and public health studies. This model also has been used worldwide for scientific and regulatory purposes (Environmental Protection Agency (US EPA), 2003).

### 3.1.1 The CALPUFF model

The air pollutant concentrations as a result of forest fires of the north of Thailand were investigated by the air quality model, CALifornia Puff (CALPUFF). CALPUFF is a non-steady-state Lagrangian Gaussian puff model with chemical removal, wet and dry deposition, building downwash, and complex terrain effects. Lagrangian models are based on the concept that pollutant particles in the atmosphere move along trajectories determined by the wind field, the buoyancy and the turbulence effects. Gaussian models are based on a Gaussian distribution of the plume in the vertical and horizontal directions under steady-state conditions. The basic equation for the contribution of the pollutant at a receptor is (Scire et al., 2000):

$$C = \frac{Q}{2\pi\sigma_x\sigma_y} g \exp\left[-d_a^2/\left(2\sigma_x^2\right)\right] \exp\left[-d_c^2/\left(2\sigma_y^2\right)\right]$$

$$g = \frac{2}{(2\pi)^{1/2}\sigma_z} \sum_{n=-\infty}^{\infty} \exp\left[-\left(H_e + 2nh\right)^2/\left(2\sigma_z^2\right)\right]$$

Where,

- C is the ground-level concentration ($g/m^3$),
- Q is the pollutant mass (g) in the puff,
- $\sigma_X$ is the standard deviation (m) of the Gaussian distribution in the along-wind direction,
- $\sigma_y$ is the standard deviation (m) of the Gaussian distribution in the cross-wind direction,
- $\sigma_z$ is the standard deviation (m) of the Gaussian distribution in the vertical direction,
- $d_a$ is the distance (m) from the puff centre to the receptor in the along-wind direction,
- $d_c$ is the distance (m) from the puff centre to the receptor in the cross-wind direction,

g is the vertical term (m) of the Gaussian equation,

H is the effective height (m) above the ground of the puff centre, and

h is the mixed-layer height (m).

The CALPUFF model was used to simulate various scenarios of forest fire emissions. It includes three main components: CALifornia METeorological model (CALMET), CALPUFF, and a post-processing program named CALPOST as shown in Figure 3.1. CALMET is a diagnostic meteorological model that produces three-dimensional wind fields. CALMET can be driven either by observations or by three-dimensional data from prognostic models (MM5, WRF, CSUMM etc.) or a combination of both. CALPOST is a post-processing program with options for the computation of time-averaged concentrations and deposition fluxes predicted by the CALPUFF model.

In the first part of running the CALPUFF model, a meteorological model is needed to generate meteorological data for the dispersion model (see Figure 3.1). There are two possible approaches, using raw data or a mesoscale meteorological model for generating the CALMET model file format. In this study, the meteorological file: CAMET.DAT generated by MM5 and MMIF is applied replacing the CALMAT.DAT file from the CALMET model. A meteorological model, Fifth-Generation Penn State/NCAR Mesoscale Model (known as MM5), was used for generating meteorological data including terrain, land use, roughness, wind speed, wind direction, mixing height, precipitation rate and temperature for meteorological modelling.

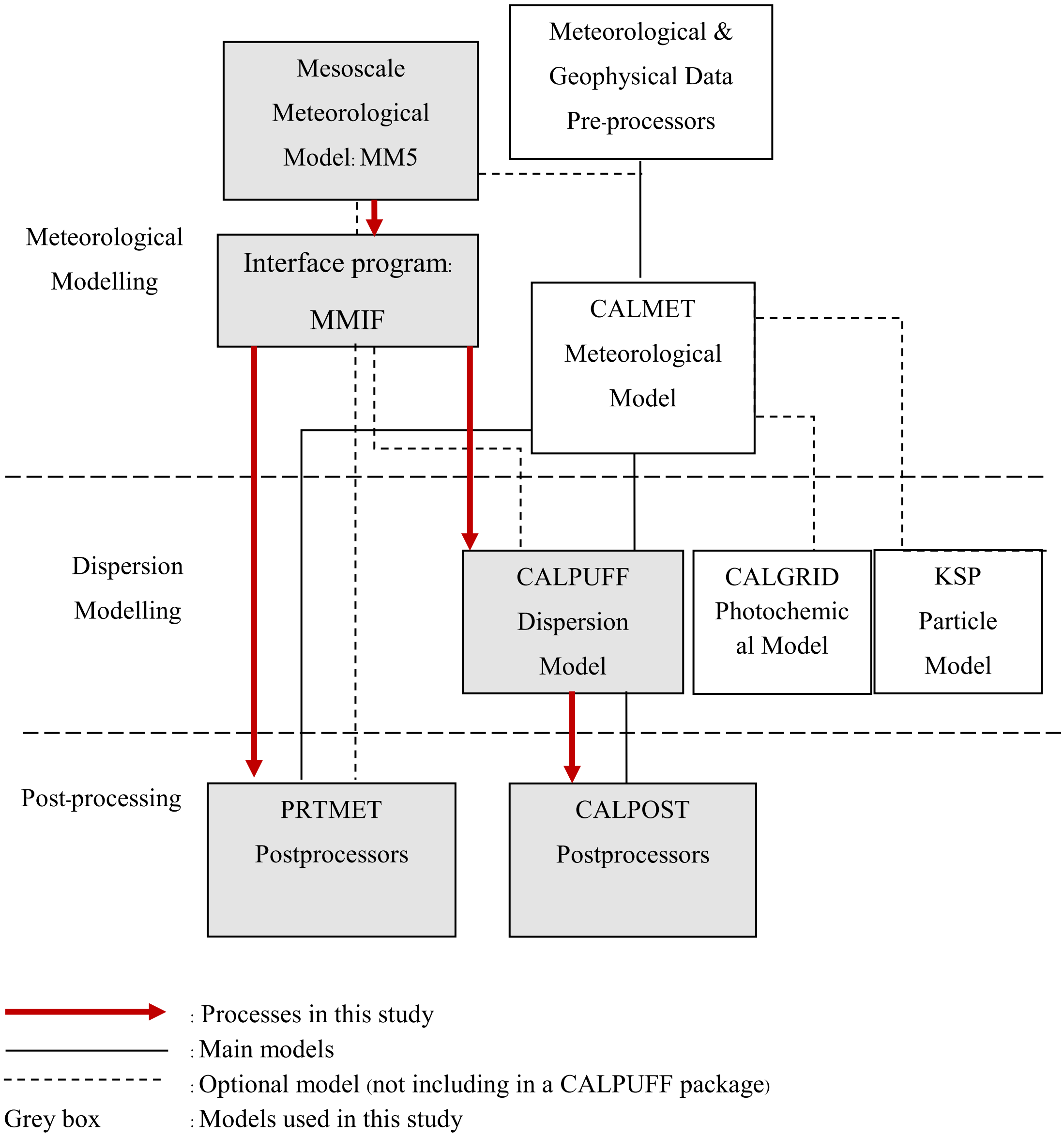



**Figure 3.1** Overview of the main programs for running CALPUFF modelling system [adapted from Scire et al. (2000)]

The input data for running MM5; terrain, land use and meteorology, can be taken from the National Centre for Atmospheric Research (NCAR). However, an output file from the MM5 program had to be changed into compatible file (CALMET file format) for the dispersion model. The Mesoscale Model Interface Program (MMIF) was used to convert this file (see Figure 3.2). The meteorological data was used in the dispersion model to calculate the concentration of pollutants from forest fires at ground-level receptors. The CALPUFF dispersion model was applied for evaluating pollutant concentrations by simulating various scenarios of forest fires emissions. To read the output from the CALPUFF and MMIF models, postprocessors; CALPOST and PRTMET were used to read the output data.

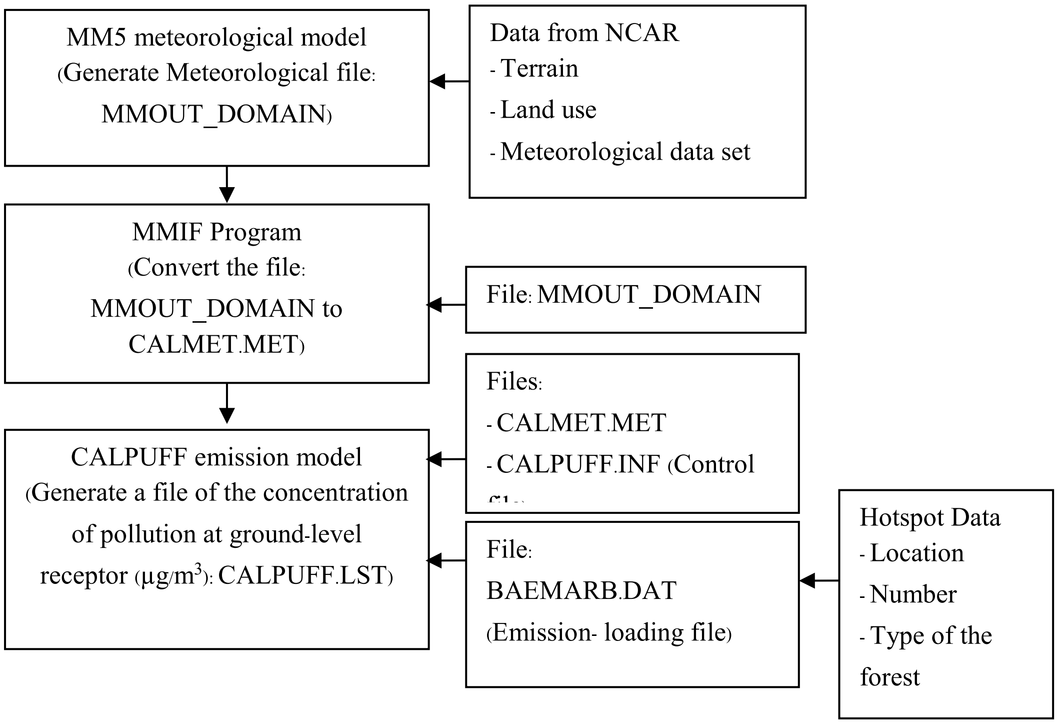



**Figure 3.2** The set of software programs including MM5, MMIF and CALPUFF, and the input data for programs processing**.**

## 3.2 Gathering data about vegetation fires

Details and numbers of forest fires are important for generating input data (emissions) to run the model. Various sensors installed on satellites can observe vegetation fire occurrences. Areas burned in the north of Thailand were estimated by using hotspot data from the Aqua and Terra satellites which had installed a Moderate Resolution Imaging Spectroradiometer (MODIS) (National Aeronautics and Space Administration (NASA), 2014, Department of National Parks Wildlife and Plant Conservation, 2012). The MODIS instrument provides high radiometric sensitivity in 36 spectral bands ranging in wavelength from 0.4 µm to 14.4 µm. Each spectral band is sensitive to the differences in temperature value and spatial resolution for observing clouds, land, aerosols, water vapour, ocean or fire. The MODIS fire products use sensors for 500 m resolution at 1.65 and 2.13µm band channels, and 1 km resolution at 3.96 and 11 µm band channels. For 1 km resolution, MODIS active fire products can detect flaming fires (~1,000 Kelvin, K) as small as 100 $m^2$ under ideal conditions with a 50% detection probability, or a 1,000–2,000 $m^2$ smouldering fire (~600K) (Giglio et al., 2003; Hawbaker et al., 2008; Kaufman et al., 1998).

The hotspot data was provided by the National Aeronautics and Space Administration (NASA) and the National Park, Wildlife and Plant Conservation Department of Thailand (DNP).

The DNP used the same dataset from NASA but audited it before distribution. This study used the data from both DNP and NASA for Thailand and neighbouring country areas. Hotspot data can be downloaded from the websites:
http://www.dnp.go.th/forestfire/hotspot/hotspotmap_Past.htm and
https://earthdata.nasa.gov/data/near-real-time-data/firms/active-fire-data

## 3.3 The study periods

The number of hotspots in the north of Thailand provided by NASA from 2011 to 2012 indicated that the most frequent hotspots in Thailand occurred between February to April (see Figure 3.3). In this study, 26 February to 1 March 2012 was chosen to be a study period because higher concentrations of $PM_{10}$ caused by forest fires occurred during this period (see Figure 3.3). Daily $PM_{10}$ concentrations were likely higher than the national ambient standard of Thailand of 120 µg/m$^3$ from February to March considering the monthly data in Figure 3.3. In a term of air quality management, after simulating the optimum option for solving the problem in the peak period, it can assume that $PM_{10}$ concentrations in rest periods were less than simulating results and met the air quality standard after fire controlled throughout the year. Moreover, the data from air quality monitoring stations were more complete than in previous years.

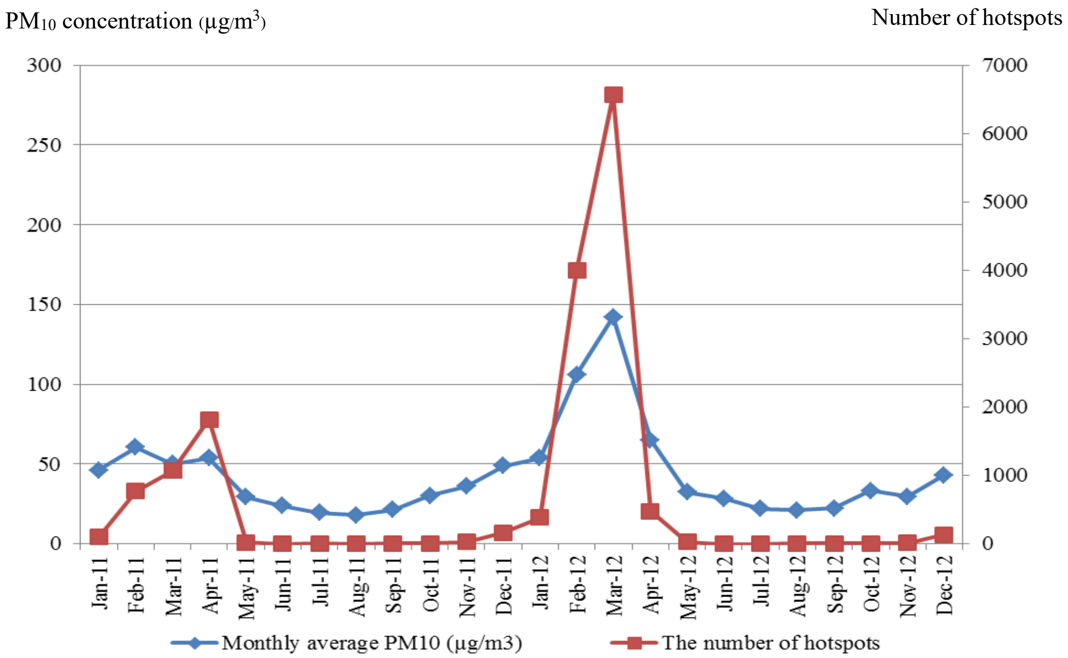



**Figure 3.3** The number of hotspots and the monthly average concentration of $PM_{10}$ in the north of Thailand during January 2011 until December 2012 analysed from the monitored $PM_{10}$ data

byThai Meteorological Department (2016) and the hotspot data by National Aeronautics and Space Administration (NASA) (2014).

The hotspot data from DNP was analysed for the location of fires, vegetation types and landuse by using a geographic information system (GIS). The GIS database was prepared by the Asian Institute of Technology (AIT), Thailand, with the database collected by the Royal Forest Department of Thailand. Previous studies showed that the major cause of forest fires in Thailand (about 88%) was human activities, with around 12% being unidentified causes. Gathering forest products was a major cause of fire at 37% of all causes, followed by hunting, burning agricultural residue, pasture, tourist's activities, conflict between people and government, and neglect as shown in Figure 1.3 of Chapter 1 (Department of National Parks Wildlife and Plant Conservation, 2012). Human activities, which may be a cause of fires events in the National Reserved Forest and National Park, were evaluated by considering the distance between forest fire events and the agricultural area in the forest. The GIS software named ArcGIS 10.1 is used for calculating distance between every hotspots and agricultural area by the "Analysis toolbox" function in the program.

Emissions from vegetation burning consist of many pollutants. However, only $PM_{10}$ exceeded the ambient air quality standard of Thailand and WHO guidelines, which can affect people's health both short-term and long-term exposures (WHO, 2006). For other pollutants, the maximum monitored and mean values of $SO_2$ and $NO_2$ were not exceeded the standard of Thailand (see Figure 3.4). Tools to simulate the problem are needed to find the solution. As result, $PM_{10}$was evaluated by software programs of mathematical models; MM5 and CALPUFF.

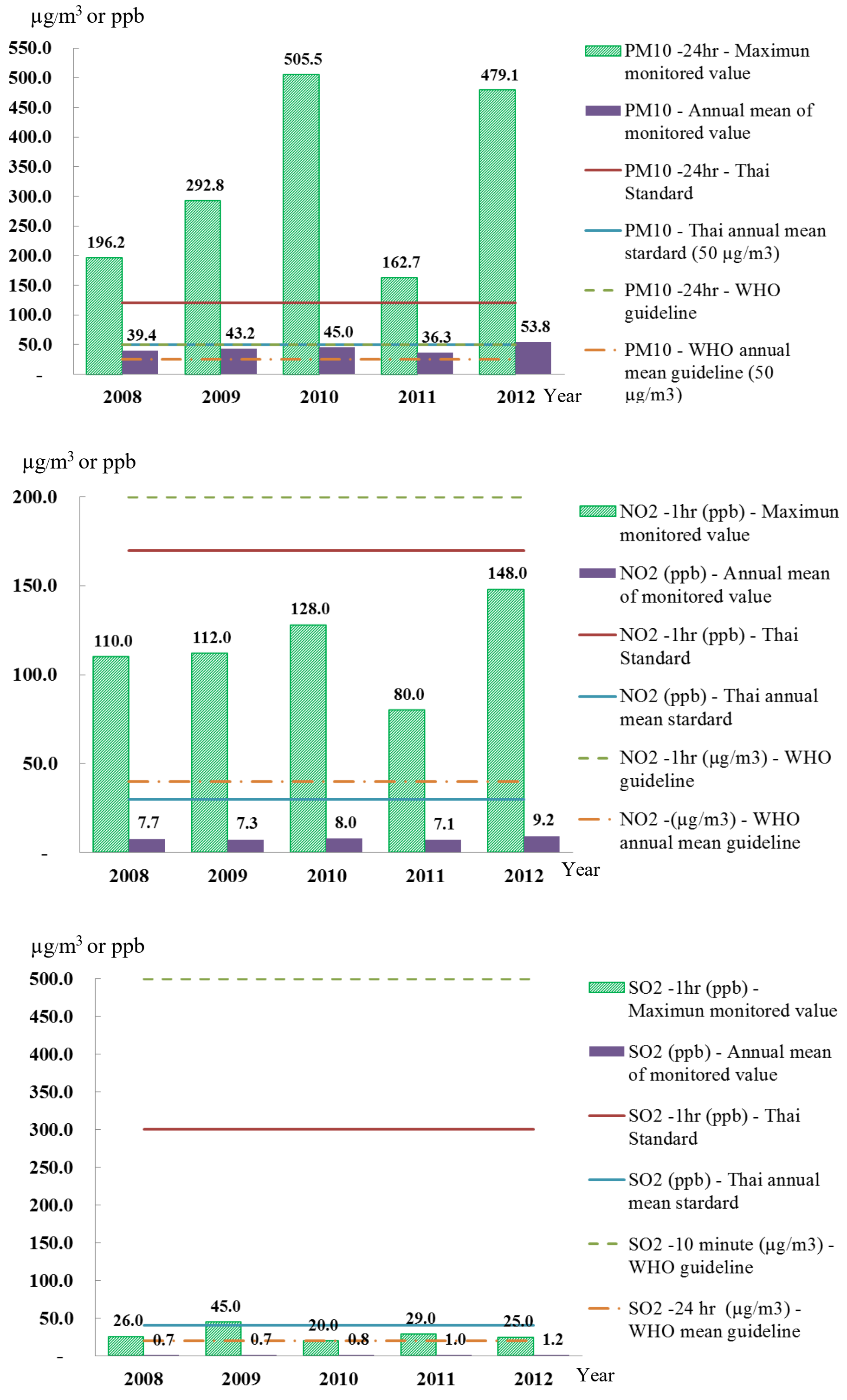



**Figure 3.4** The maximum and average concentration values of $PM_{10}$, $SO_2$ and $NO_2$ monitored by Thai Meteorological Department (2016) during 2008 to 2012 in the north of Thailand compared with the ambient air quality standard of Thailand and WHO guidelines (WHO, 2006)

## 3.4 Software selected for the meteorology evaluation

### 3.4.1 MM5 meteorological model

The Fifth-Generation Penn State/NCAR Mesoscale Model (MM5) software is mostly written in FORTRAN, and was developed at Penn State University and National Centre for Atmospheric Research (NCAR) as and a community mesoscale model with contributions from users worldwide. MM5 is the open source (or free software). Version 3 of MM5 was used in this study and it can be downloaded from the website: http://www.mmm.ucar.edu/mm5/mm5v3/wherev3ftp.html. It executable runs on a Linux PC requiring the FORTRAN compiler to run and the Intel complier (ifort) uncommercial version was used. A scope of domain with 27 km grid resolution was set for MM5 modelling (see Figure 3.5). This covered the area of 3,321 km x 3,348 km including Thailand and neighbouring countries, and the centre of domain was the north of Thailand.

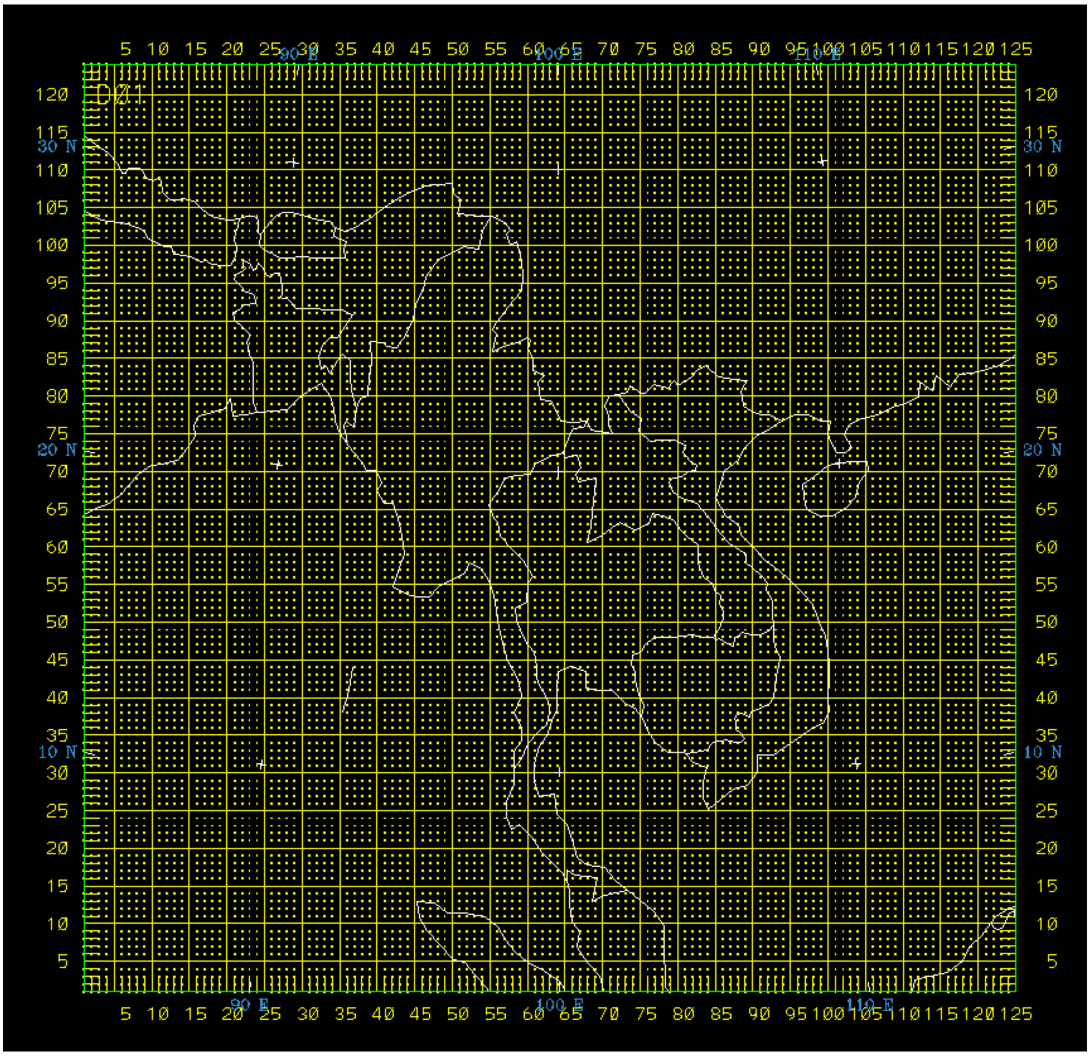



**Figure 3.5** The area of the domain in MM5 covered Thailand and neighbouring countries**.**

The MM5 model system consists of several programs. This study applied TERRAIN, REGRID, INTERPF and MM5 programs to create a metrological file for the CALPUFF as shown in Figure 3.6. There are two main sets of data for running models. A data set of terrain elevation, landuse, vegetation type, and soil data prepared by the National Centre for Atmospheric Research (NCAR) were used in TERRAIN program. These data were downloaded from the website: ftp://ftp.ucar.edu/mesouser/MM5V3/TERRAIN_DATA/.

The set of meteorological data including precipitation, temperature, relative humidity and wind supported by NCAR were applied in the REGRID Program. These meteorological data were prepared for every six hours during 1999 to present. The website that supplies these data is http://rda.ucar.edu/datasets/ds083.2/.

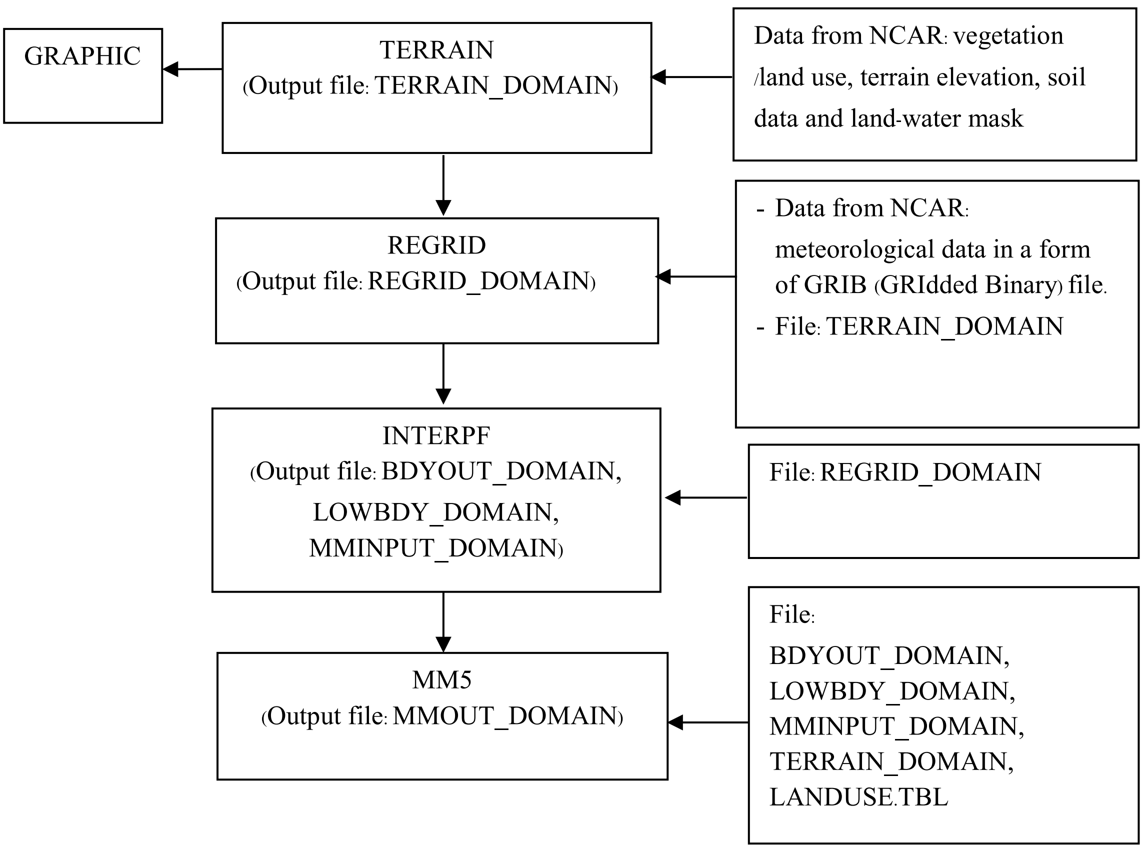



**Figure 3.6** The system flow chart of MM5 programs and data sets that were used in this study**.**

The TERRAIN program analyses the data (vegetation/land use, terrain elevation, soil data and land-water area) onto the chosen domain area. The output from this program is the mesoscale grid (see Figure 3.6) of the input data in MM5 format. The summary setting for this program is shown in Table 3.2.

**Table 3.2** Description of parameter setting for TERRAIN program.

| Parameter | TERRAIN program setting | Description |
|---|---|---|
| Central Latitude and Longitude | PHIC = 18.1, XLONC = 99.7 | The centre of the domain (the north of Thailand) |
| Number of domains to process | MAXNES = 1 | Building one domain to process |
| Grid dimension in Y direction | NESTIX = 124 | Number of grids = 124 in Y direction |
| Grid dimension in X direction | NESTJX = 125 | Number of grids = 125 in X direction |
| Grid distance | DIS = 27 | Dimension of each grid = 27 km |
| Input data resolution | NTYPE = 2 | 2: ~56 km resolution of global terrain and land use to input |

The REGRID program reads meteorological data in a form of a GRIB (GRIdded Binary) file. The fields of temperature, horizontal wind components, relative humidity, and height of pressure levels, sea-level pressure, sea-surface temperature, and snow-cover data were interpolated to the grid and map projection as defined by the MM5 pre-processor program TERRAIN. The vertical interpolation of meteorological data is processed by the INTERPF program by generating an input file on sigma levels which are vertical coordinates showing the ratio of the pressure at a coordinate point in the atmosphere and the actual surface pressure of the earth. The output data contains the time-dependent 3D and 2D fields, such as wind, temperature, moisture, and pressure, the lateral and lower boundaries, and surface air temperature. The summary settings of REGRID and INTERPF are shown in Table 3.3.

**Table 3.3** Description of parameter setting for REGRID and INTERPF program**.**

| Parameter | REGRID and INTERPF setting | Description |
|---|---|---|
| The starting date | START_YEAR_MONTH_DAY_HOUR = 2012, 02, 25, 00 | The starting time which the time zone is GMT+00 |
| The ending date | END_YEAR_MONTH_DAY_HOUR = 2012, 03, 01, 00 | The ending time which the time zone is GMT+00 |
| Time interval | INTERVAL = 21600 | Time interval in seconds. (GRIB files contain the meteorological data for every six hours, 21,600 sec) |
| Sigma levels | 24 sigma levels | Coarse sigma level setting. |

Finally, the MM5 program applied the output files: BDYOUT_DOMAIN, LOWBDY_DOMAIN, MMINPUT_DOMAIN, TERRAIN_DOMAIN, which were generated from the INTERPF and TERRAIN programs to predict the weather. For each time period, the outputs of MM5 including U, V, W-wind (m/s), temperature (K), water vapour mixing ratio (kg/kg), cloud water mixing ratio (kg/kg) , rain water mixing ratio (kg/kg), turbulent kinetic energy (J/kg), atmospheric radiation tendency (K/day), ground temperature (K), rainfall (cm), surface sensible heat flux ($W/m^2$), surface latent heat flux ($W/m^2$), frictional velocity (m/s), shortwave and longwave radiation ($W/m^2$), surface moisture availability, soil temperature in a few layers (K), mixing ratio (kg/kg), terrain elevation (m), land-use category, sea surface temperature (K). Wind components are usually expressed in terms of U, V, and W. The U and V are defined as the horizontal wind speed (along and across wind) and W was the vertical component of the wind speed. Parameters to consider when setting up the MM5 program are summarized inTable 3.4.

**Table 3.4** Description of parameter setting for MM5 program.

| Parameter | MM5 setting | Description |
|---|---|---|
| Forecast length in minutes | TIMAX= 7200 | Running period time starting 25/02/2012 00.00 am to 01/03/2012 00.00 am |
| The frequency of output model results (in minutes) | TAPFRQ = 60 | Output results for every hour |
| Soil moisture initialization | ISMRD = 0 | = 0, use moisture available from LANDUSE.TBL |

### 3.4.2 The MMIF Program

The output file from MM5 was fed to the Mesoscale Model Interface program (MMIF) for converting prognostic meteorological model output fields to the parameters and formats required for direct input into dispersion modes, CALPUFF. The MMIF program was developed by the ENVIRON International Corporation. This study used the MMIF version 3.0, meeting the request of EPA to support multiple outputs from a single run and bug fixes. The program processes data directly from the MM5 (file: MMOUT_DOMAIN), into a CALPUFF-ready form (file: CALMET.MET) without additional modification or additional performance evaluation. However, the time zone of the study area (GMT +07) was set in this program because the time zone of output file from MM5 was GMT +00.

## 3.5 Source and emission data inputs

There are three main groups of input files for running CALPUFF, including hourly meteorological data (CALMET.MET), CALPUFF control file (CALPUFF.INP) and optional files. Only CALMET.MET and CALPUFF.INP can complete running CALPUFF model. Emissions that are emitted constantly can be set in the CALPUFF.INF file. However, this study used an optional file, time-varying area source emission (BAEMARB.DAT) for generating the input of forest fire emissions.

### 3.5.1 The forest fire emissions calculation

The emissions (E) of each vegetative type can be estimated using the equation from Seiler and Crutzen (1980) as shown in section 2.4.1 of Chapter 2. The burned area, fuel load or biomass density, combustion completeness or burning efficiency and emission factor will be used for estimating each hotspot and total area burned.

### 3.5.2 The estimation of the area burned

The area burned in the north of Thailand will be estimated by using the hotspot data from the satellite, the MODIS Active Fire Product. The detection probability of active fires depends on a number of factors, including fire temperature and satellite viewing angle. MODIS active fires at 1 km resolution can detect flaming fires (~1000 Kelvin, K) as small as 100 $m^2$ under ideal conditions with a 50% detection probability, or a 1,000–2,000 $m^2$ smouldering fire (~600K) (Giglio et al., 2003; Hawbaker et al., 2008; Kaufman et al., 1998). This study used hotspot data from the NASA and National Park, Wildlife and Plant Conservation Department of Thailand (DNP). The DNP has validated the numbers of hotspots with actual fires events in 2013. Its accuracy was 97.50% (National Park Wildlife and Plant Conservation Department of Thailand, 2014b). The approximate area burned of each hotspot was calculated by using the average value of the forest fire frequency and the total area burned in year 2012 from (Jongudomsuk et al., 2015). There were 2,686 fire occurrences in the National parks in the north of Thailand that destroyed 34.24 $km^2$. Therefore, as an averaged approximation it can be said that one fire event can burn forest areas of around 12,750 $m^2$ (or 1.275 ha).

### 3.5.3 The use of the fuel load, combustion completeness and emission factor

Six parameters (NO, $NO_x$, $NO_2$, $SO_2$, $O_3$ and $PM_{10}$) were recorded by an air quality monitoring station in the north of Thailand. This study will focus on $PM_{10}$ because $PM_{10}$ was the main air pollution problem and NO was an important pollutant caused by combustion. In the part of the fuel load, combustion completeness and emission factor, there were studies classifying vegetation type in the different ways. However, grouping the type of vegetation was processed for calculating fire emissions as shown in Table 3.5. This study used the maximum range of $PM_{2.5}$ value in Table 3.5 and the ratio of 0.5 between $PM_{2.5}$ and $PM_{10}$, which is found in developing country to estimating $PM_{10}$ values (WHO, 2006). Moreover, studies with the maximum values of combustion completeness and fuel load as shown in Table 2.3 and Table 2.5 of Chapter 2 are selected for running models. These selections are results from model calibration part in section 3.7.1. The use of the minimum range value of $PM_{10}$, combustion completeness and fuel load values have influenced simulated values much less than observed values.

**Table 3.5** The fuel load, combustion completeness and emission factors that were used for calculating forest fire emissions.

| | | | **EF (Emission Factor) (g/kg dry matter)** | | | | | | | | | | | | **Combustion Completeness** | **Fuel Load** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | CO | | | NOx | | | $SO_2$ | | | $PM_{10}$ | | | | |
| **Forest Type** | | | Andreae and Merlet (2001) | Akagi et al. (2011) | **Used in this study** | Andreae and Merlet (2001) | Akagi et al. (2011) | **Used in this study** | Andreae and Merlet (2001) | Akagi et al. (2011) | **Used in this study** | $PM_{2.5}$ Andreae and Merlet (2001) | $PM_{2.5}$ Akagi et al. (2011) | Used $PM_{2.5}$ to estimate $PM_{10}$ in this study | Used $PM_{10}$ in his study from $PM_{2.5}$ and $PM_{10}$ ratio = 0.5 | IPCC (2003) &Michel et al. (2005) & Heil (2007) | Michel et al. (2005)& Wiedinmyer et al (2011) (kg/m$^2$) |
| Pine Forest | Evergreen needle leaf forest | Boreal Forest | | 127 ± 45 | 172 | | 0.9 ± 0.69 | 1.59 | | 0.52 ± 0.15 | 0.67 | | 15.3 ± 5.9 | 21.2 | 42.4 | 0.34 | 36.70 |
| Hill Evergreen Forest | Evergreen broadleaf forest | Tropical Forest | 104 ± 20 | | 124 | 1.6 ± 0.7 | | 2.3 | 0.57 ± 0.23 | | 0.80 | 9.1 ± 3.5 | | 12.6 | 35.2 | 0.39 | 27.97 |
| Tropical Evergreen Forest | Evergreen broadleaf forest | Tropical Forest | 104 ± 20 | | 124 | 1.6 ± 0.7 | | 2.3 | 0.57 ± 0.23 | | 0.80 | 9.1 ± 3.5 | | 12.6 | 35.2 | 0.39 | 27.97 |
| Dry Evergreen Forest | Evergreen broadleaf forest | Tropical Forest | 104 ± 20 | | 124 | 1.6 ± 0.7 | | 2.3 | 0.57 ± 0.23 | | 0.80 | 9.1 ± 3.5 | | 12.6 | 35.2 | 0.55 | 27.97 |
| Dry Dipterocarp Forest | Deciduous broadleaf forest | Extratropical Forest | 107 ± 37 | | 137 | 3.0 ± 1.4 | | 4.4 | 1 | | 1 | 13.0 ± 7.0 | | 20 | 40.0 | 0.55 | 27.97 |
| Mixed Deciduous Forest | Mixed forest | Extratropical Forest | 107 ± 37 | | 137 | 3.0 ± 1.4 | | 4.4 | 1 | | 1 | 13.0 ± 7.0 | | 20 | 40.0 | 0.55 | 27.97 |
| Plantation | Mixed forest | Extratropical Forest | 107 ± 37 | | 137 | 3.0 ± 1.4 | | 4.4 | 1 | | 1 | 13.0 ± 7.0 | | 20 | 40.0 | 0.55 | 27.97 |
| Eucalyptus Plantation | Mixed forest | Extratropical Forest | 107 ± 37 | | 137 | 3.0 ± 1.4 | | 4.4 | 1 | | 1 | 13.0 ± 7.0 | | 20 | 40.0 | 0.63 | 23.35 |
| Bamboo Forest | Mixed forest | Extratropical Forest | 107 ± 37 | | 137 | 3.0 ± 1.4 | | 4.4 | 1 | | 1 | 13.0 ± 7.0 | | 20 | 40.0 | 0.250 | 23.35 |
| Savannah and Grassland | Wooded grassland | Savanna and Grassland | 65 ± 20 | | 85 | 3.9 ± 2.4 | | 6.3 | 0.35 ± 0.16 | | 0.51 | 5.4 ± 1.5 | | 6.9 | 13.8 | 0.55 | 11.01 |
| Secondary Forest | Mixed forest | Savanna and Grassland | 65 ± 20 | | 85 | 3.9 ± 2.4 | | 6.3 | 0.35 ± 0.16 | | 0.51 | 5.4 ± 1.5 | | 6.9 | 13.8 | 0.55 | 22.25 |
| Old Clearing, Encroachment and active Shifting Cultivation | Wooded grassland | Savanna and Grassland | 65 ± 20 | | 85 | 3.9 ± 2.4 | | 6.3 | 0.35 ± 0.16 | | 0.51 | 5.4 ± 1.5 | | 6.9 | 13.8 | 0.74 | 3.30 |
| Agricultural Area | Cropland | Crop Residue | 92 ± 84 | | 176 | | 2.5 ± 1.0 | 3.5 | 0.4 | 0.32 ± 0.14 | 0.4 | 3.9 | 6.26 ± 2.36 | 8.62 | 17.24 | 0.93 | 5.10 |

## 3.6 Model validation

A file of wind speed generated by MM5 and MMIF was validated against surface observations. These files were extracted using the PRTMET program. Results were shown in the pattern of wind speeds and their location coordination. The wind speeds with the same location of the observation station were collected for validating the model. Results from the CALPUFF were extracted by the CALPOST program and shown with the same pattern of the PRTMET program. Both simulated and observed data from meteorological and air quality models were compared using the correlation and bias/error statistics. Details are given in Section 3.7.

## 3.7 Simulation of fire scenarios

After the results from the air quality model were validated, scenarios to find the optimal pollution reductions from forest fires by reducing biomass-burning emissions from each type of land use were simulated as shown in Figure 3.7. The simulation focused on controlling emissions from fires that occurred near agricultural areas because previous studies showed that most of the fires were caused by human activities. A study by Dontree et al. (2011) showed that the most fires in Chiang Mai province between 2000 and 2010 occurred near villages within 1 km and were in the area that agricultural areas expanded to the forests, and 89.4%of fire events were located less than 4 km from villages. The fire locations near agricultural areas within 1 km were selected for control in terms of fires from agricultural activities and burning for expanding agricultural areas to forest areas. The fire locations near agricultural areas 1-4 km were selected in terms of activities for gathering forest goods. Transboundary haze pollution was the option used to control fire emissions with the local fire controlled. However, the local fire controlled is the main option of the fire policy in a term of the national procedure that can be achieved by Thai people.

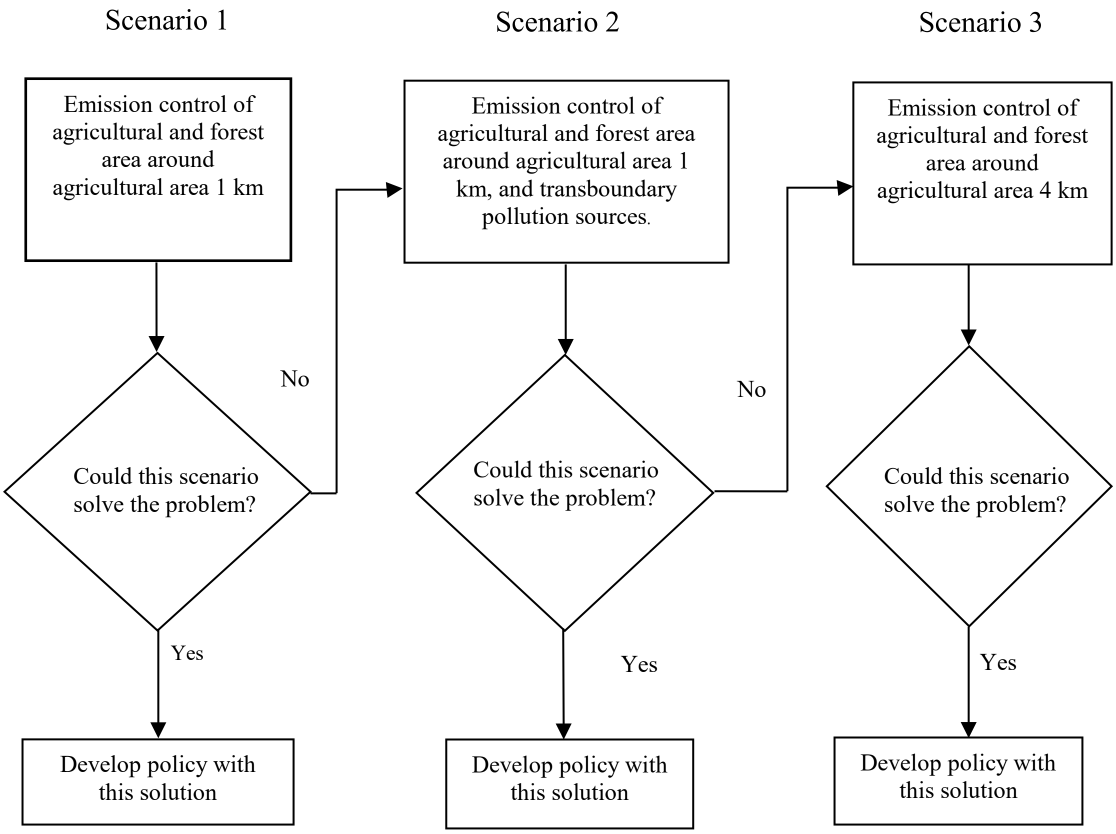



**Figure 3.7** Outline of the simulation scenarios by focusing on fires caused by humans as the most significant for the policy developing**.**

## 3.8 Results of Air Quality Evaluation

The results from the meteorological and air quality models are presented and discussed in this chapter. The validations of the model results were processed at the first step to check the accuracy of the model by comparing predicted results with the real data from observation stations. After that, simulation was processed by simulating various scenarios (see Figure 3.7) of concentrations after reducing the emission from the target area.

### 3.8.1 Model validation

The validation is used to adjust the model to minimum errors. Simulation results of the meteorological data from the MM5 and the pollution concentration from the CALPUFF were validated by comparing with the observation data from the Pollution Control Department's monitoring stations in seven provinces: Chiang Mai, Lamphun, Lampang, Mae Hong Son, Phayao, Phrae and Nan. The locations of the stations are shown in Figure 3.8.

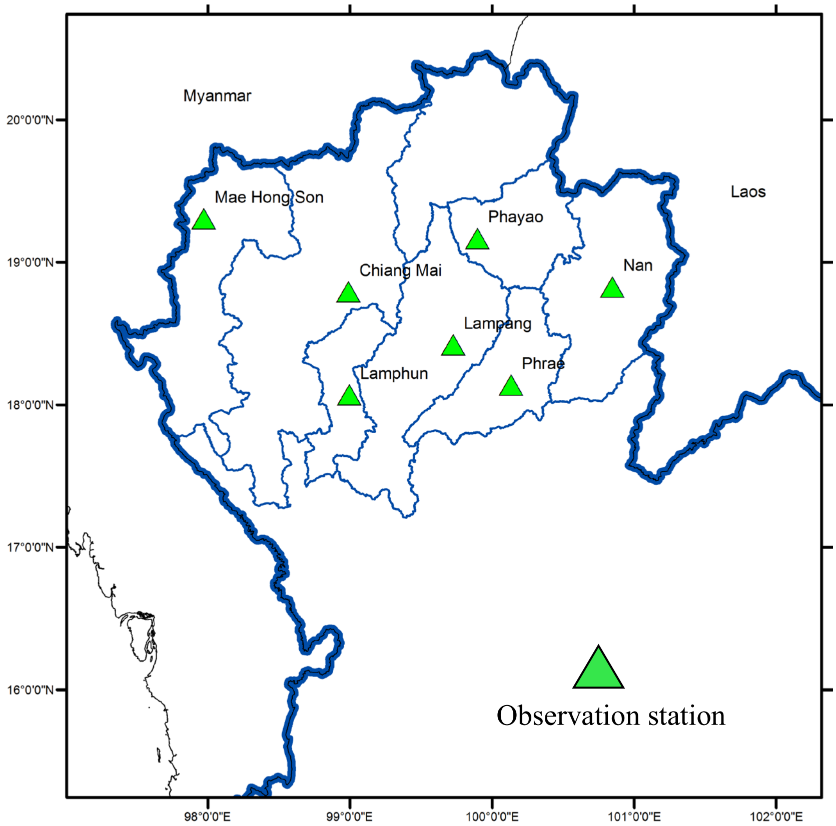



**Figure 3.8** The location of observation stations in the north of Thailand for model validations

Evaluating performance of models can be assessed by using statistics. There are statistical approaches to compare model predictions to observation data. The coefficient of determination ($R^2$), normalised mean bias (NMB), normalised mean error (NME), mean normalized bias (MNB), mean normalized absolute error (MNAE), and root mean square error (RMSE) were used to evaluate between model simulations (M) with observations (O). An acceptable value of model performance for NMB should lie within the range between -0.2 and +0.2 (Derwent et al., 2010), for MNB and MNAE were ±0.05-0.15 and 0.35 respectively (Vivanco et al., 2009). Relative measures including NMB, MNB, MNAE and NME are particularly useful when model performance for one pollutant is compared with that for another pollutant for which concentrations are generally quite different. The equations for these statistics are shown in Table 3.6.

**Table 3.6** The statistics for evaluating performance of models

| Metrics | Equation | Reference |
|---|---|---|
| Coefficient of determination ($R^2$) | $\left[\frac{\sum_{i=1}^{N}(M_i-\bar{M})(O_i-\bar{O})}{\sqrt{\sum_{i=1}^{N}(M_i-\bar{M})^2\sum_{i=1}^{N}(O_i-\bar{O})^2}}\right]^2$ | Microsoft Corporation (2016) and Yu et al. (2006) |
| Mean normalized bias (MNB) | $\frac{1}{N}\sum_{i=1}^{N}\left(\frac{M_i-O_i}{O_i}\right)$ | Yu et al. (2006) |
| Mean normalized absolute error (MNAE) | $\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\lvert M_i-O_i\rvert}{O_i}\right)$ | Yu et al. (2006) |
| Normalised mean bias (NMB) | $\frac{\sum_{i=1}^{N}(M_i-O_i)}{\sum_{i=1}^{N}O_i}$ | Yu et al. (2006) |
| Normalised mean error (NME) or Normalized mean absolute error (NMAE) | $\frac{\sum_{i=1}^{N}(\lvert M_i-O_i\rvert)}{\sum_{i=1}^{N}O_i}$ | Yu et al. (2006) |
| Root mean square error (RMSE) | $\sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i-M_i)^2}$ | Yu et al. (2006) |

M = Modelled value, O = Observed value, N = pairs of modelled and observed values.

### 3.8.2 The results of the MM5 Model

The simulated area was about 3,078 x 3,240 $km^2$ with 27 km resolution. This area covers Thailand and neighbouring countries; Myanmar, Laos, Cambodia, China and Vietnam. This model provided the input data including terrain elevation, land use and meteorological data for the air quality model. The graphic outputs from the TERRAIN program of the MM5 model are shown in Figure 3.9. Thailand was in the South-East Asian peninsula closed to the Gulf of Thailand and the Andaman Sea in the central and the south part of Thailand. In the north of Thailand part, the terrain elevation is more than 300 meters above sea level. There are a number of valleys formed by mountains that were parallel from north to south direction and the type of land use is mostly the forest.

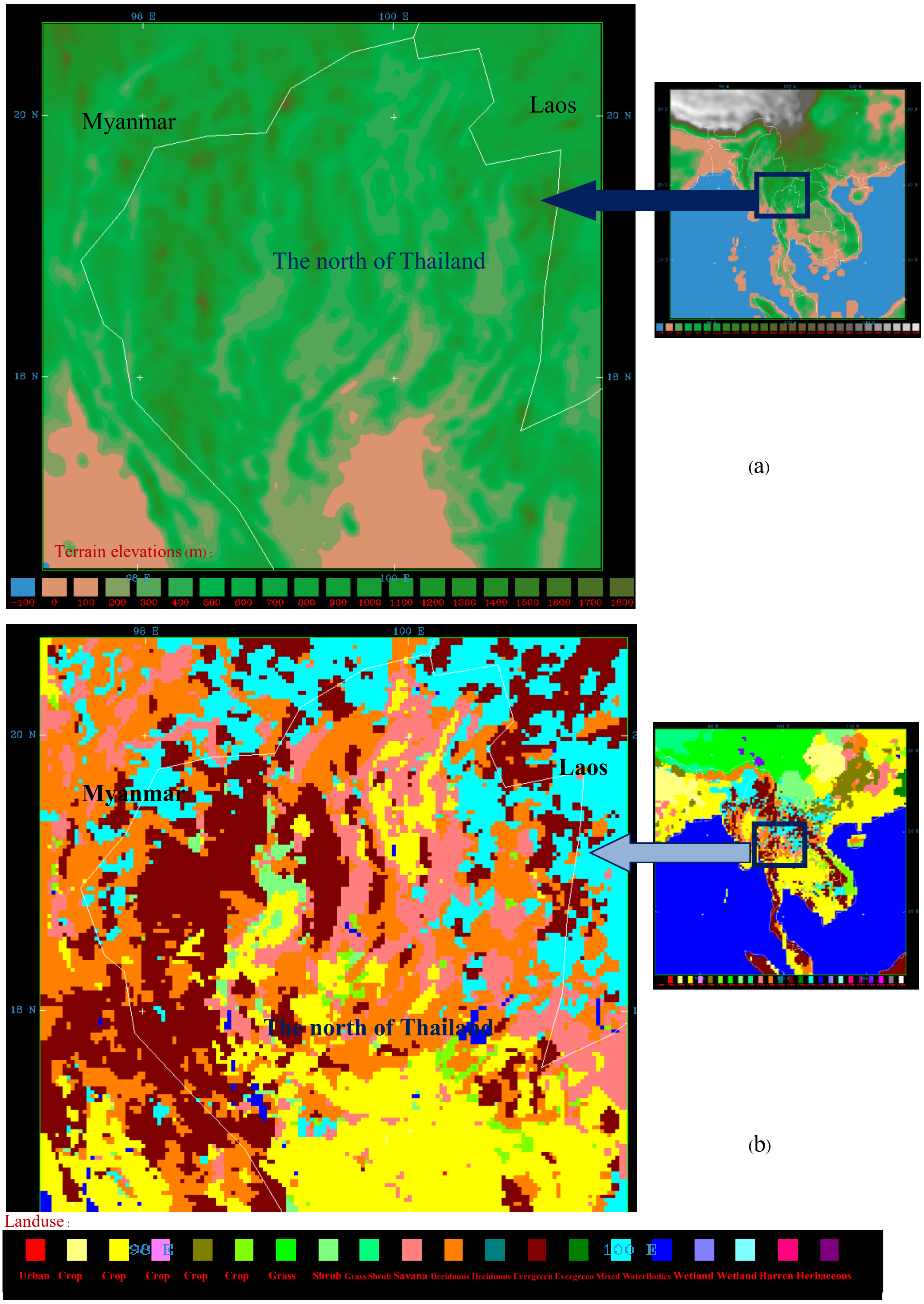



**Figure 3.9** The terrain elevations (a) and land use types (b) generated by TERRAIN program in the MM5 model

The meteorological input files from NCAR were fed to the MM5 model and were processed with the file of the land use and the terrain elevation to simulate the metrological data for study area. The output file from the MM5/MMIF was translated by the PRTMET program to report in a form of the meteorological data with its coordination. Simulation results of the meteorology were validated by compared to the observation data from the Pollution Control Department's monitoring stations in six provinces: Chiang Mai, Lamphun, Lampang, Mae Hong Son, Phrae and Phayao. The simulations started from 26 February to 1 March 2012. Wind speeds and statistics results are shown in Table 3.7 and Figure 3.10.

**Table 3.7** Summary of the statistical results of coefficient of determination ($R^2$), mean normalized bias (MNB), mean normalized absolute error (MNAE), normalised mean bias (NMB), normalised mean error (NME) or normalized mean absolute error (NMAE), and root mean square error (m/s) (RMSE) by comparing modelled and simulated wind speeds in the north of Thailand during 26 February to 1 March 2012.

| | $R^2$ | MNB | MNAE | NMB | NME | RMSE (m/s) |
|---|---|---|---|---|---|---|
| Chiang Mai | 0.52 | 0.11 | 0.18 | 0.09 | 0.16 | 0.36 |
| Lamphun | 0.67 | 0.27 | 0.30 | 0.23 | 0.27 | 0.31 |
| Lampang | 0.89 | 0.85 | 0.85 | 0.85 | 0.85 | 0.34 |
| Mae Hong son | 0.56 | -0.07 | 0.10 | -0.08 | 0.11 | 0.09 |
| Phrae | 0.54 | 0.01 | 0.16 | -0.04 | 0.16 | 0.22 |
| Phayao | 0.56 | 0.01 | 0.14 | -0.01 | 0.15 | 0.21 |

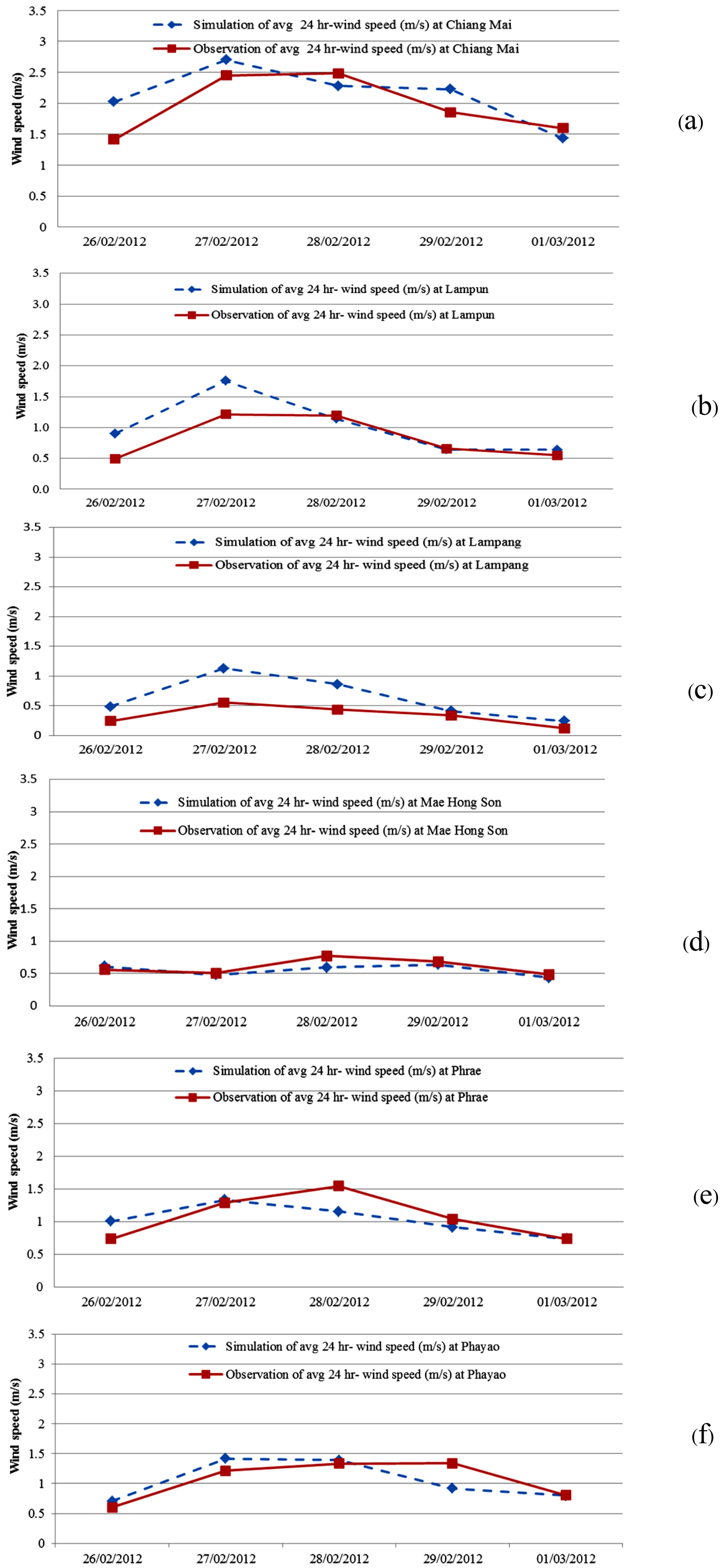
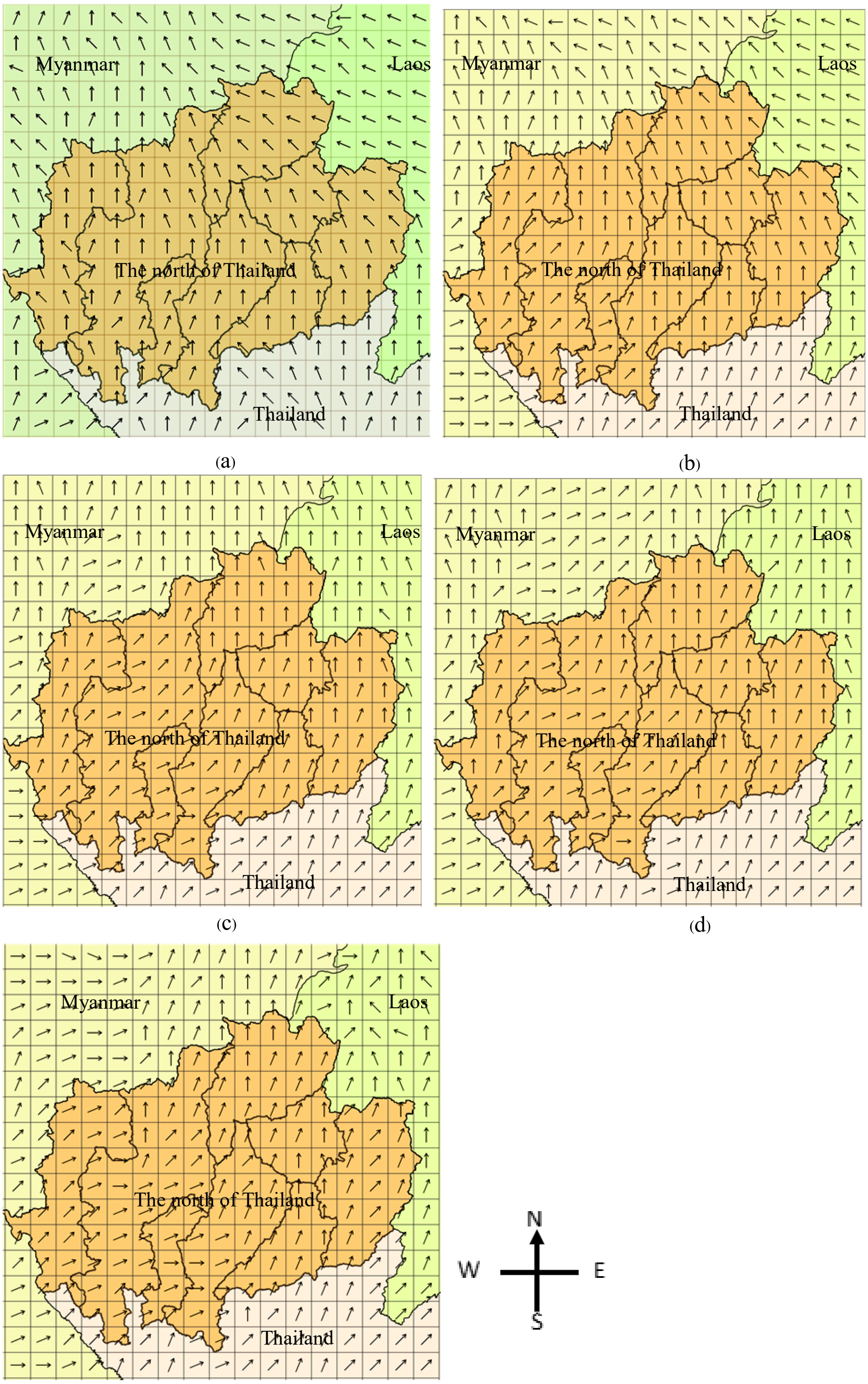



**Figure 3.10** The results of model validation for MM5 model between 26 February to 1 March 2012 in Chiang Mai (a), Lamphun (b), Lampang (c), Mae Hong Son (d), Phrae (e) and Phayao (f) provinces.

These validation results may be acceptable for model accuracy. The $R^2$ values of all station are more than 0.5. Most error and bias values compared with monitoring stations are in the guideline. However, the MNB, MNAE, NMB and values in Lampang provinces are more than the suggestion values. These errors may be caused by errors in monitoring because the observed values from another organization were different. The Thai Meteorological Department has shown the wind speeds during 26 February to 1 March 2012 in Lampang area as 0.58, 1.08, 1.08, 0.61 and 0.53 m/s. These values will change the $R^2$, MNB, MNAE, NMB and NME to 0.90, -0.24, 0.25, -0.19 and 0.22 which are closer to the acceptable values. Moreover, the resolution of model area (27 x 27 km or 729 $km^2$) is an important factor that affects the accuracy of wind speed results because the observation data from only one station cannot represent for the wind speed of the large area of the model domain.

The wind directions from the MM5 of each day was analysed by the PRTMET program and plotted by the ArcMap program as shown in Figure 3.11. The most common of wind directions in the north of Thailand were the south and the southwest directions.




(e)

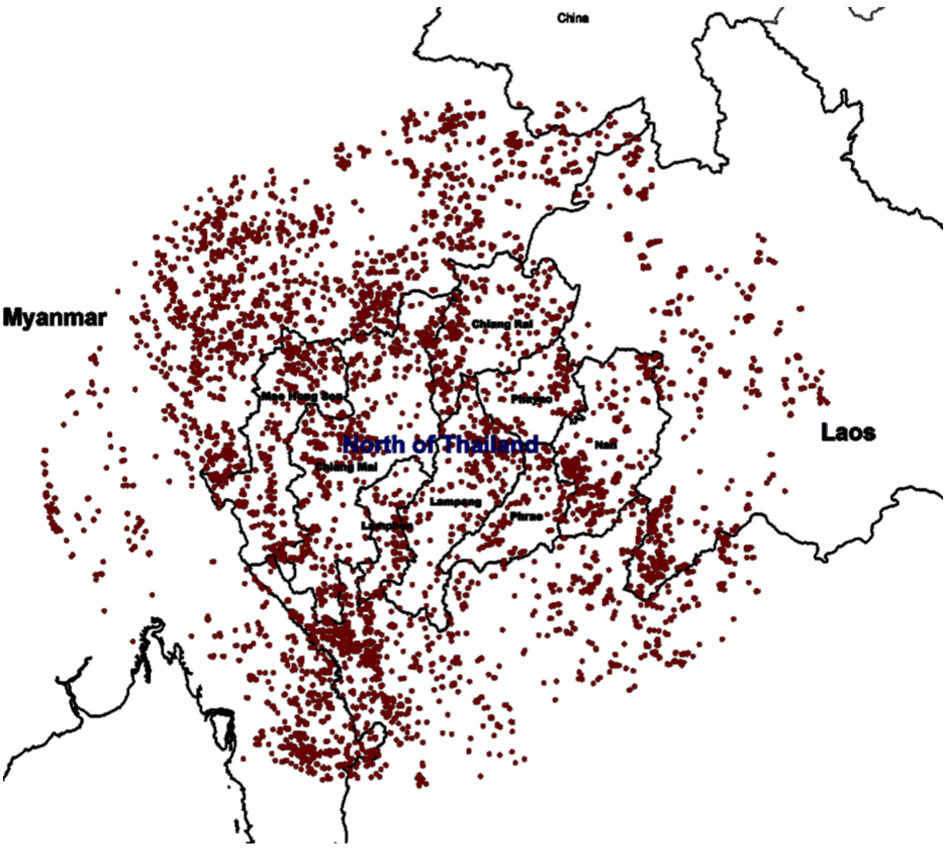
**Figure 3.11** Simulation results of wind direction from the MM5 Model in 26 February 2012 (a), 27 February 2012 (b), 28 February 2012 (c), 29 February 2012 (d), and 1 March 2012 (e)

### 3.8.3 The distribution of fire events in the north of Thailand

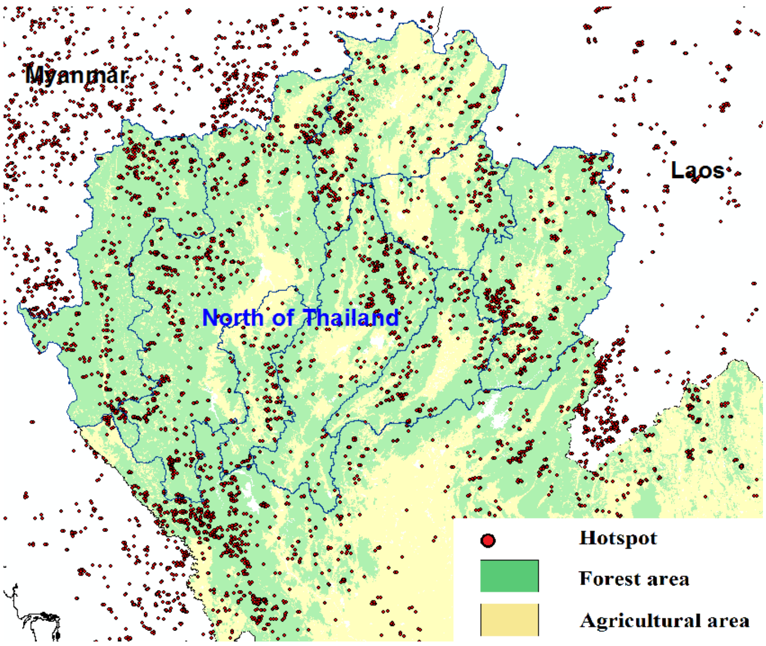
Forest fire events in the north of Thailand and neighbouring countries are evaluated by a GIS program and air quality models. The results from these programs are shown in this chapter. In the first part, the GIS program is used to analyse the locations and land use types of each fire. Results from plotting hotspots in the geographic information system (GIS), ArcMap program, shows that there were 2,406 out of 4,320 hotspots in Thailand which existed in the north of Thailand; Chiang Mai, Chiang Rai, Nan, Phrae, Lampang, Lamphun, Phayao and Mae Hong Son, during 26 February to 1 March 2012. These hotspots appeared in the forest and agricultural area approximately 1,969 and 437 hotspots (see Figure 3.12). The details of hotspots are shown in Table 3.8. Mixed deciduous forests had the greatest frequency of fire events followed by agricultural areas for every province.

**Table 3.8** The type of landuse of the hotspot in Chiang Mai, Chiang Rai, Nan, Phrae, Lampang, Lamphun, Phayao and Mae Hong Son provinces.

| | The number of hotspot | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Landuse type | Chiang Mai | Mae Hong Son | Nan | Chiang Rai | Lampang | Phrae | Phayao | Lamphun | Total (%) |
| Mixed deciduous forest | 321 | 287 | 260 | 207 | 197 | 77 | 58 | 74 | 1,481 (61.55) |
| Agricultural area | 93 | 31 | 72 | 104 | 44 | 30 | 35 | 28 | 437 (18.16) |
| Hill evergreen forest | 71 | 25 | 7 | 2 | 6 | 3 | 18 | 1 | 133 (5.53) |
| Dry evergreen forest | 65 | 8 | 0 | 14 | 18 | 4 | 3 | 0 | 112 (4.66) |
| Dry dipterocarp forest | 41 | 9 | 16 | 1 | 8 | 13 | 8 | 16 | 112 (4.66) |
| Old Clearing, Encroachment and active Shifting Cultivation | 17 | 12 | 14 | 6 | 4 | 3 | 2 | 0 | 58 (2.41) |
| Forest plantation | 1 | 1 | 3 | 1 | 17 | 6 | 0 | 0 | 29 (1.21) |
| Pine forest | 5 | 3 | 0 | 11 | 0 | 0 | 0 | 0 | 19 (0.79) |
| Secondary forest | 0 | 1 | 0 | 6 | 5 | 3 | 1 | 0 | 16 (0.67) |
| Savannah and Grassland | 4 | 0 | 0 | 0 | 0 | 0 | 3 | 1 | 8 (0.33) |
| Bamboo forest | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 (0.04) |
| Total | 618 | 377 | 372 | 352 | 299 | 139 | 129 | 120 | 2,406 (100) |




(a)




(b)

**Figure 3.12** The locations of all hotspots in the north of Thailand and the surrounding area within 200 km (a), and hotspots in forest and agricultural areas of the north of Thailand (b) during 26th February and 1st March 2012

The distance between fire events and the agricultural areas were classified by the GIS program. The details of the distance are shown in Table 3.9. Results indicated that most fire occurrences were related to human activities in terms of the location of fires that occurred in the agricultural area with 437 hotspots and distance between fire events and the agricultural area were less than 1 km with 1,259 hotspots out of 2,406 hotspots. The simulation scenarios for fires controls in agricultural areas and nearby forests during 26 February to 1 March 2012 were set as follows.

1) The simulation of actual fires events, the 6,679 hotspots in the north of Thailand and the around area within 200 km (see Figure 3.11) including central Thailand, Myanmar, Laos and China were used for this simulation.

2) The simulation of scenario 1, fires in agricultural areas and forest areas range 1 km are controlled. The 437 and 1,259 hotspots of agricultural and forest area range 1 km were taken off from the input data. The input data in this scenario are from 4,983 hotspots in the north of Thailand (excepting agricultural areas and forest areas range 1 km) and the around area within 200 km including central Thailand, Myanmar, Laos and China.

3) The simulation of scenario 2, fires in neighbouring countries and agricultural areas and forest areas range 1 km are controlled. The 2,359, 437 and 1,259 hotspots of neighbouring countries, agricultural and forest area range 1 km were taken off from the input data. The input data in this scenario are from 2,624 hotspots in the north of Thailand (excepting agricultural areas and forest areas range 1 km) and central Thailand.

4) The simulation of scenario 3, fires in agricultural areas and forest areas range 4 km are controlled. The 437 and 1,872 hotspots of agricultural and forest area range 4 km were taken off from the input data. The input data in this scenario are from 2,415 hotspots in the north of Thailand (excepting agricultural areas and forest areas range 4 km) and the around area within 200 km including central Thailand, Myanmar, Laos and China.

**Table 3.9** The distance between fire events and the agricultural area in Chiang Mai, Chiang Rai, Phrae, Mae Hong Son, Nan, Phayao, Lampang and Lamphun.

| Distance between fire events and the agricultural area | Chiang Mai | Mae Hong Son | Nan | Chiang Rai | Lampang | Phrae | Phayao | Lamphun | Total (%) |
|---|---|---|---|---|---|---|---|---|---|
| In agricultural area | 93 | 31 | 72 | 104 | 44 | 30 | 35 | 28 | 437 (18.16) |
| < 1 km | 382 | 174 | 199 | 194 | 146 | 56 | 61 | 47 | 1,259 (52.33) |
| 1-2 km | 83 | 73 | 68 | 41 | 60 | 21 | 19 | 13 | 378 (15.71) |
| 2-3 km | 34 | 41 | 22 | 12 | 22 | 19 | 11 | 6 | 167 (6.94) |
| 3-4 km | 13 | 23 | 5 | 1 | 15 | 3 | 2 | 6 | 68 (2.83) |
| 4-5 km | 4 | 10 | 4 | 0 | 9 | 4 | 1 | 9 | 41 (1.70) |
| >5 km | 9 | 25 | 2 | 0 | 3 | 6 | 0 | 11 | 56 (2.33) |
| Total | 618 | 377 | 372 | 352 | 299 | 139 | 129 | 120 | 2,406 (100) |

The emissions from each fire are evaluated by meteorological and air quality models. Before applying results from these models to simulate various scenarios, the model validations are needed to adjust model's accuracy.

### 3.8.4 Results from the CALPUFF model

The input data of fire emissions were calculated from 6,679 hotspots from fires in the north of Thailand and the surrounding area within 200 km (see Figure 3.12) including Myanmar, Laos and China, from 26 February to 1 March 2012. $PM_{10}$ and NO results from simulating 6,679 hotspots are validated by comparing with six observation stations for $PM_{10}$ and four stations for NO and $NO_2$ are shown in Figure 3.13 and Figure 3.14.

**Table 3.10** Statistic results of $PM_{10}$ validation between simulated and observed values in Chiang Mai, Lampang, Lamphun, Phayao, Mae Hong Son, and Phrae during 24 February to 1 March 2012.

| $PM_{10}$ | $R^2$ | MNB | MNAE | NMB | NME | RMSE (μg/m$^3$) |
|---|---|---|---|---|---|---|
| Chiang Mai | 0.55 | -0.05 | 0.13 | -0.05 | 0.12 | 16.66 |
| Lampang | 0.55 | 0.06 | 0.10 | 0.06 | 0.10 | 20.75 |
| Lamphun | 0.50 | -0.13 | 0.25 | -0.18 | 0.26 | 44.23 |
| Phayao | 0.53 | -0.08 | 0.16 | -0.09 | 0.15 | 37.29 |
| Mae Hong son | 0.61 | -0.18 | 0.18 | -0.18 | 0.18 | 36.50 |
| Phrae | 0.51 | -0.18 | 0.24 | -0.16 | 0.23 | 48.83 |

**Table 3.11** Statistic results of $NO_2$ and NO validation between simulated and observed values in Chiang Mai, Phayao, Phrae, and Nan during 24 February to 1 March 2012.

| $NO_2$ | $R^2$ | MNB | MNAE | NMB | NME | RMSE (ppb) |
|---|---|---|---|---|---|---|
| Chiang Mai | 0.59 | 0.004 | 0.10 | -0.01 | 0.09 | 3.01 |
| Phayao | 0.66 | 0.05 | 0.08 | 0.05 | 0.07 | 2.10 |
| Phrae | 0.88 | 0.09 | 0.12 | 0.10 | 0.12 | 2.80 |
| Nan | 0.59 | 0.11 | 0.13 | 0.11 | 0.13 | 2.60 |
| NO | $R^2$ | MNB | MNAE | NMB | NME | RMSE (ppb) |
| Chiang Mai | 0.94 | -0.04 | 0.09 | -0.06 | 0.10 | 0.68 |
| Phayao | 0.91 | 0.58 | 0.58 | 0.48 | 0.48 | 0.63 |
| Phrae | 0.81 | 0.16 | 0.29 | 0.10 | 0.22 | 1.27 |
| Nan | 0.76 | 0.57 | 0.57 | 0.54 | 0.54 | 0.63 |

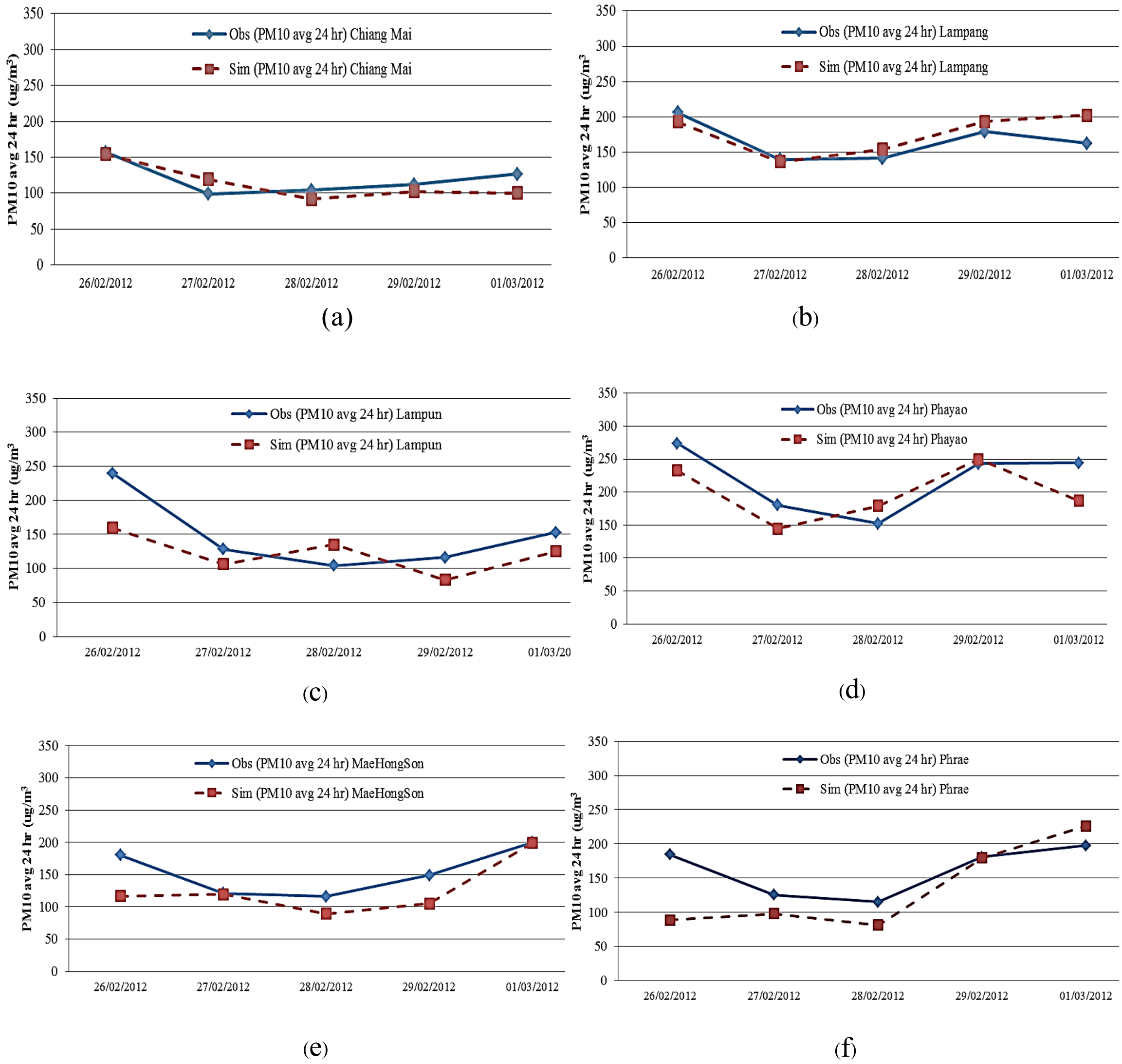



**Figure 3.13** The results of $PM_{10}$ validation for the CALPUFF model between 26 February to 1 March 2012 in Chiang Mai (a), Lampang (b), Lamphun (c), Phayao (d), Mae Hong Son (e), and Phrae (f) provinces.

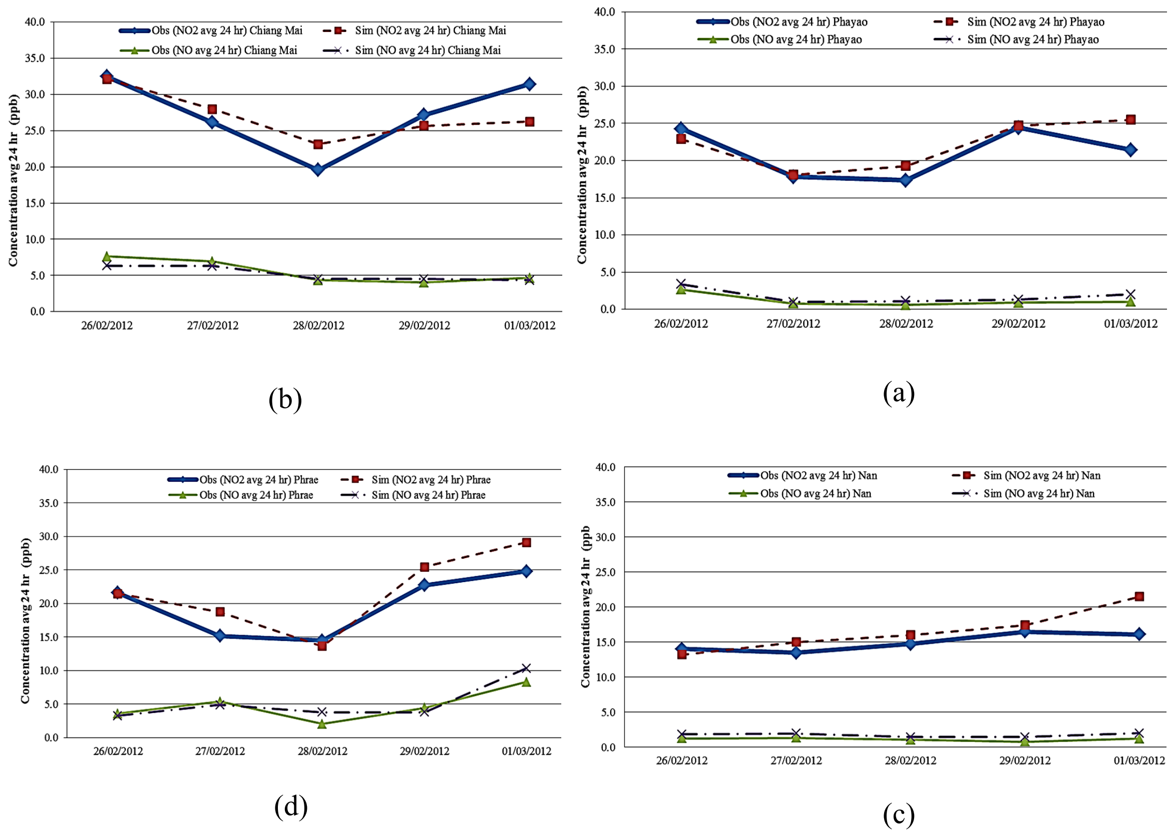



**Figure 3.14** The results of NO and $NO_2$ validation for the CALPUFF model between 26 February to 1 March 2012 in Chiang Mai (a), Phayao (b), Phrae (c), and Nan (d) provinces.

The $PM_{10}$ and NO validation from the CALPUFF model could be acceptable with the $R^2$ values >0.5 for all station. This indicates that simulated results of $PM_{10}$ and NO from models are fitted with the observed data. The model can explain >50% of the variability of the response data around its mean. In addition, other statistics values of NMB, MNB and MNAE which are proposed to quantify the relative difference between modelled and observed values of $PM_{10}$, are met the suggestion values by Derwent et al. (2010) and Vivanco et al. (2009). This shows that model performance is acceptable. However, the NMB values of NO in Phayao and Nan provinces are more than the suggestion values of 0.2. The low concentrations of NO in Phayao and Nan tend to be a cause for calculating the NMB value.

In addition, the concentrations of the background pollution also are causes of the errors of the CALPUFF model. The main emissions for inputting into the model were from the forest fires while monitoring stations were located in the city, which also represent to pollutants from the traffic. Therefore, background concentrations were added in the model results. The background values for $PM_{10}$ in the urban areas are about 50 μg/m$^3$ estimated by using values of

$PM_{10}$ in days without fire occurrences (~33-73 μg/m$^3$) and 20 μg/m$^3$ estimated by using values of $PM_{10}$ in days without fire occurrences (~10-33 μg/m$^3$) in rural areas between February to April. For the background values of NO, background values for NO in the urban areas are 3.0 ppb (from 0.8-7.9 ppb) in Chiang Mai, 2.0 ppb (from 0.8-5.0 ppb) in Lampang, 0.5 ppb (from 0.2-0.9 ppb) in Phayao, 0.4 ppb (from 0.1-0.9 ppb) in Nan, 3.0 ppb (from 1.8-4.8 ppb) in Phrae, and 0.1 ppb for all rural area. However, the large range of the background concentration in each day may be a cause of the errors.

The $PM_{10}$ concentrations in the north of Thailand and neighbouring countries from the CALPUFF model are shown in Figure 3.15. These values already added the background values. The results show that the wind direction is an important factor that influences the $PM_{10}$ transporting from the sources to other areas. Considering the wind direction, this may indicate that in this study period, pollutants were transported by wind from the lower part of Thailand and some parts of Myanmar and Laos to the north of Thailand.

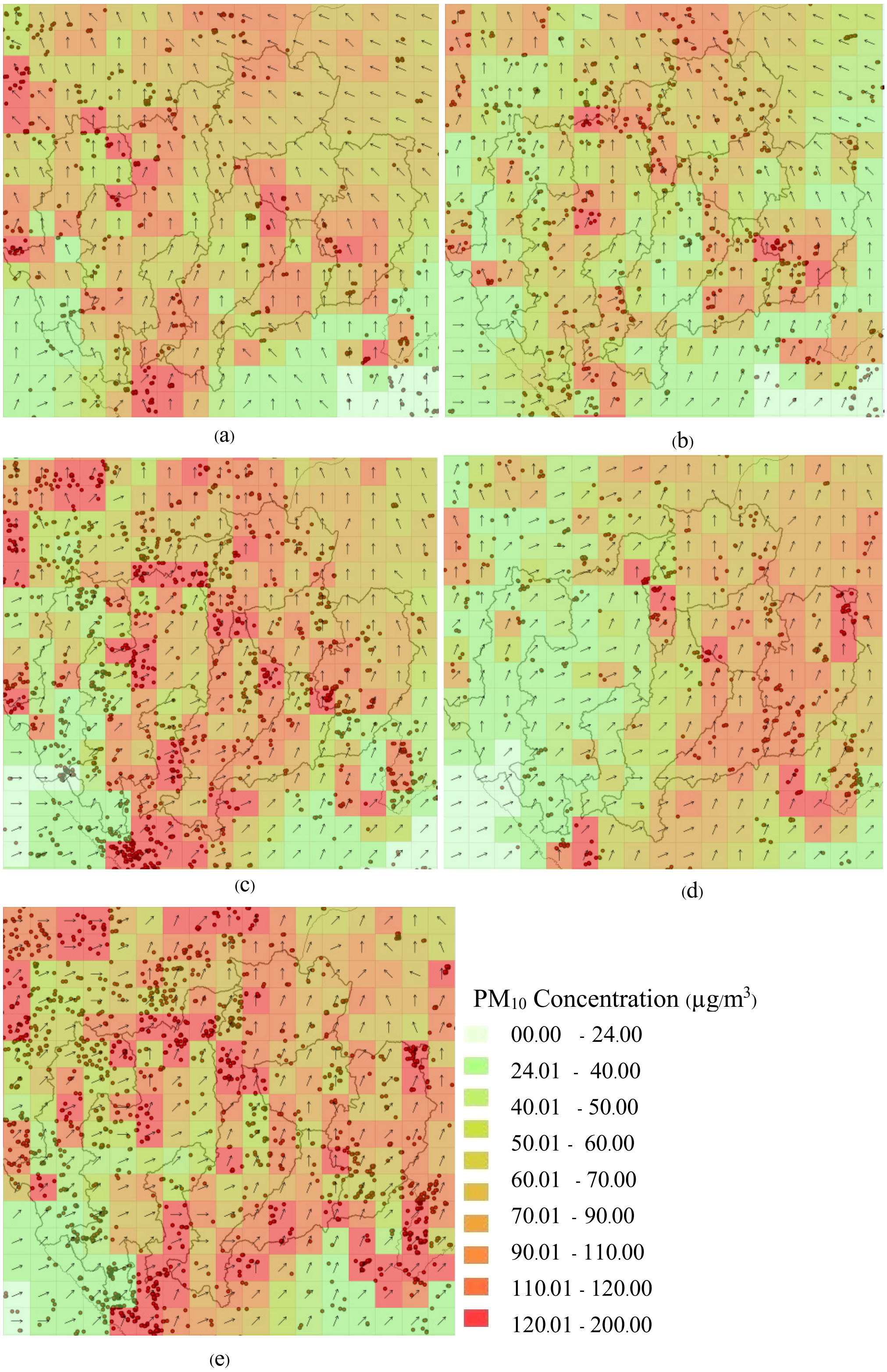



**Figure 3.15** The results of $PM_{10}$ concentrations in the north of Thailand from the CALPUFF model in 26 February 2012 (a), 27 February 2012 (b), 28 February 2012 (c), 29 February 2012 (d), and 1 March 2012 (e)


**Figure 3.16** Maps show provinces **(**below**)** and districts in each province **(**above**)** in the study area

From Figure 3.15, ranges of estimated $PM_{10}$ of 5 days in the district scale ($\mu g/m^3$) of Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae were 31 to 312, 56 to 23, 30 to 305, 38 to 285, 27 to 240, 31 to 309, 43 to 275 and 34 to 294. The $PM_{10}$ concentration >150 $\mu g/m^3$ were found in many districts for more than 3 days. The pollutant in their areas and nearby area and country caused this impact. Districts that had $PM_{10}$ >150 $\mu g/m^3$ because of fires in their area were:

- Wiang Haeng, Omkoi, Chiang Dao and Samoeng districts in Chiang Mai,
- Wiang Pa Pao and Mae Suai districts in Chiang Rai,
- Chae Hom and Ngao districts in Lampang,
- Wiang Sa district in Nan,
- Rong Kwan, Song, Long and Muang districts in Phrae,
- Pai, Muang, Khunyuam, Mae Sariang and Pang Ma Pha district in Mae Hong Son

In addition, $PM_{10}$ from neighbouring country and nearby provinces also affected some districts to have $PM_{10}$ >150 μg/$m^3$ including:

- Omkoi and Chiang Dao districts in Chiang Mai affected by $PM_{10}$ from neighbouring provinces,
- Pai, Muang, Khunyuam, Mae Sariang and Pang Ma Pha district in Mae Hong Son affected by $PM_{10}$ from neighbouring country,
- Muang Nan district in Nan affected by $PM_{10}$ from Weing Sa district,
- Muang Phayao district in Phayao affected by $PM_{10}$ from Ngao district in Lampang.

The average 5-days $PM_{10}$ in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae were 102, 100, 111, 95, 86, 102, 97 and 119 μg/$m^3$. The ranges of estimated $PM_{10}$ of 5 days in the province scale (μg/$m^3$) of Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae were 86 to 132, 82 to 122, 64 to 142, 54 to 144, 40 to 112, 69 to 150, 70 to 120 and 100 to 146. Most provinces had the $PM_{10}$ exceeding Thai daily air quality standard at 120 μg/$m^3$.

For the results of $NO_2$ concentrations in the north of Thailand were in the standard (see Figure 3.17). The scenario for $NO_2$ mitigation may be not needed for the policy development. Then scenarios were simulated for only $PM_{10}$ concentration.

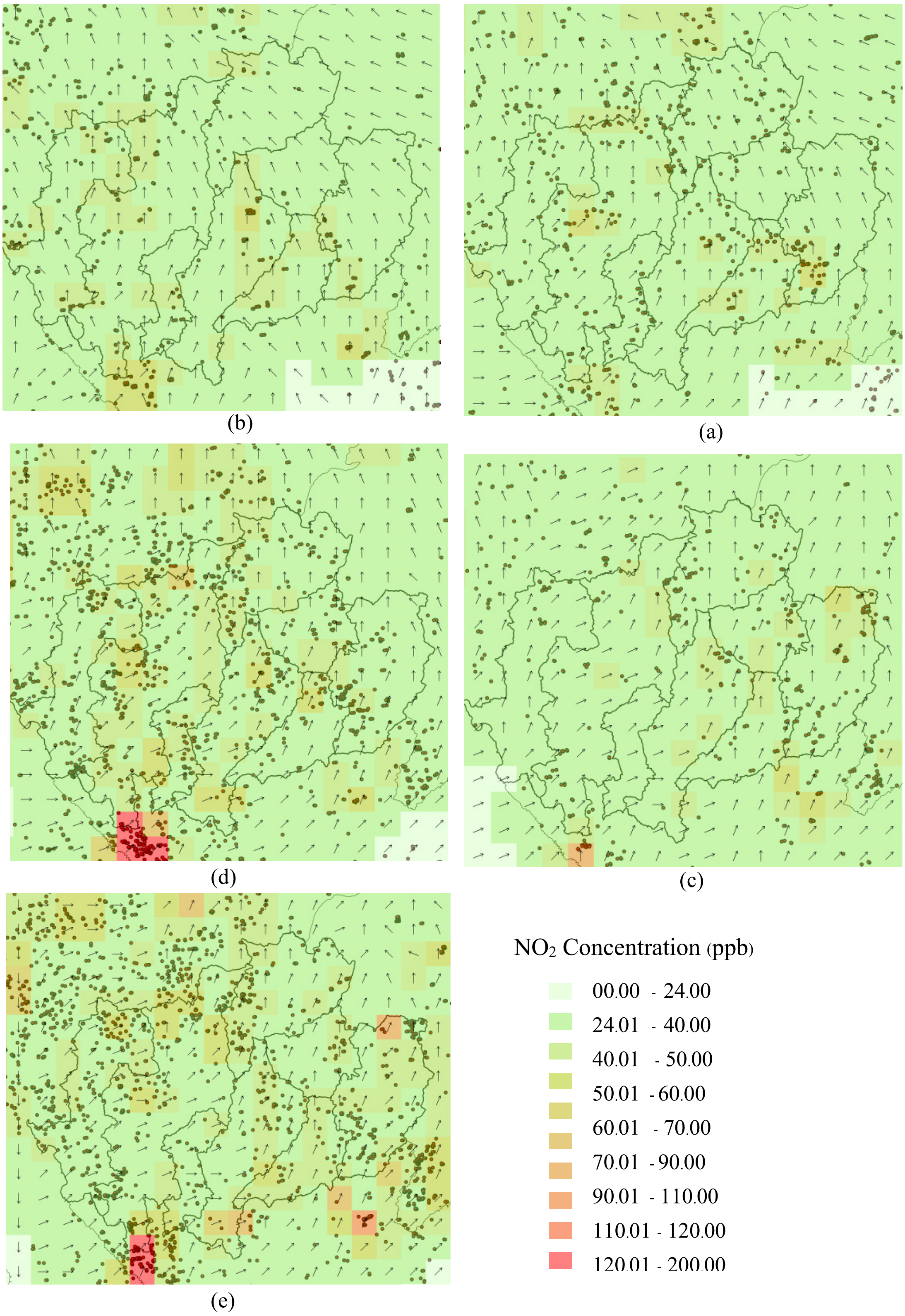



**Figure 3.17** The results of $NO_2$ concentrations in the north of Thailand from the CALPUFF model in 26 February 2012 (a), 27 February 2012 (b), 28 February 2012 (c), 29 February 2012 (d), and 1 March 2012 (e)

### 3.8.5 Simulation of fire scenarios

The simulation focused on controlling emissions from fires occurring near agricultural areas within 1 km. The fire locations are selected in terms of fires from agricultural activities, burning for expanding agricultural areas to forest areas, and activities for gathering forest goods. From actual fires with 6,679 hotspots, the emissions from 2,460 hotspots in the agricultural area and forest area range 1 km were taken off from the input data for the simulation of air quality model. There were only emissions from 4,219 hotspots from forests that were located far from agricultural area more than 2 km feeding to the CALPUFF model.

The results of $PM_{10}$ concentration after controlling fires in the agricultural area and forest area range 1 km in the north of Thailand are shown in Figure 3.18. Results showed that there were areas with $PM_{10}$ concentration >120 µg/m$^3$ at around 4.06% of all area in the north of Thailand. Therefore, the emissions from neighbouring countries also were removed from the simulation for find the scenario mitigating $PM_{10}$ problems. The results of $PM_{10}$ concentration after controlling fires in the agricultural area and forest area range 1 km in the north of Thailand and hotspots in the neighbouring countries are shown in Figure 3.19. This also showed the results same as the previous simulation with $PM_{10}$ concentration >120 µg/m$^3$ in many areas.

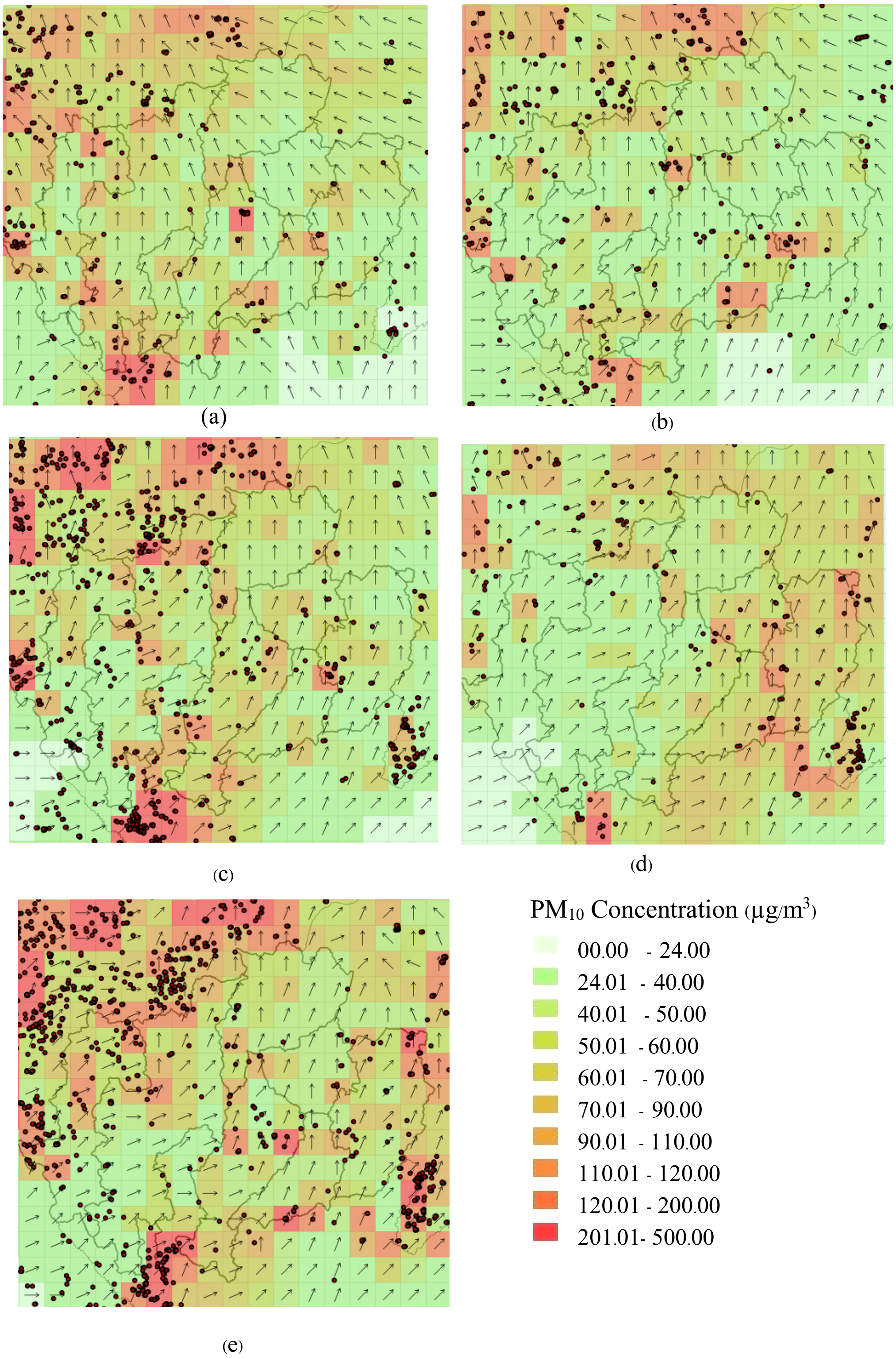



**Figure 3.18** The results of $PM_{10}$ concentrations in the north of Thailand from the CALPUFF model by fires controlled in agricultural and forest area ranging 1 km in 26 February 2012 (a), 27 February 2012 (b), 28 February 2012 (c), 29 February 2012 (d), and 1 March 2012 (e)

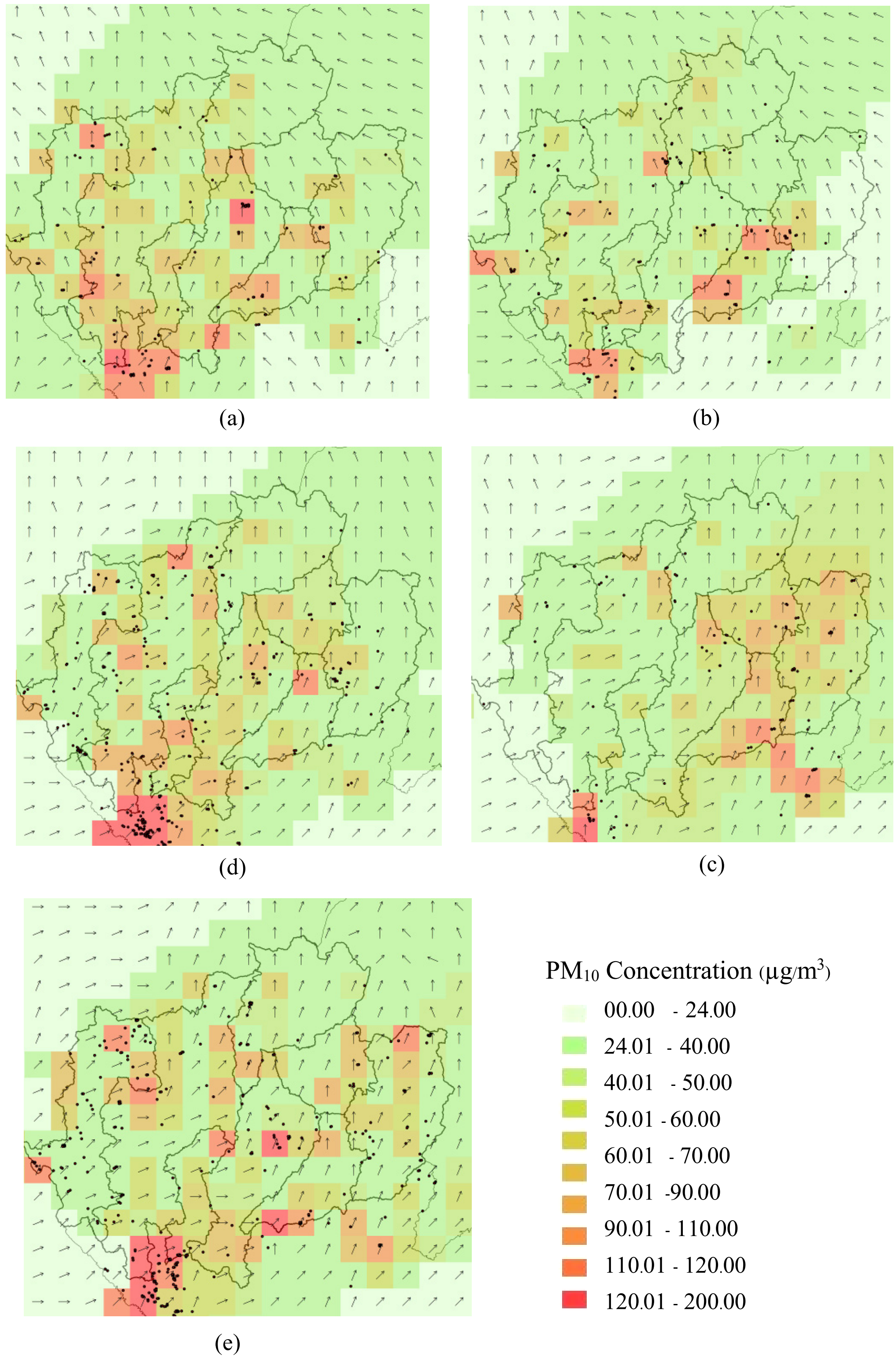



**Figure 3.19** The results of $PM_{10}$ concentrations in the north of Thailand from the CALPUFF model by fires controlled in agriculture and area around 1 km, and neighbouring countries in 26 February 2012 (a), 27 February 2012 (b), 28 February 2012 (c), 29 February 2012 (d), and 1 March 2012 (e)

The last simulation, the simulation focused on controlling emissions from fires occurred in agricultural area and near agricultural areas within 4 km. The fire locations are selected in terms of fires from agricultural activities, burning for expanding agricultural areas to forest areas, and activities for gathering forest goods. The remaining 3,238 hotspots after removal of ones within 4 km were fed to the CALPUFF model. The results of $PM_{10}$ concentration after controlling fires in the north of Thailand are shown in Figure 3.20.

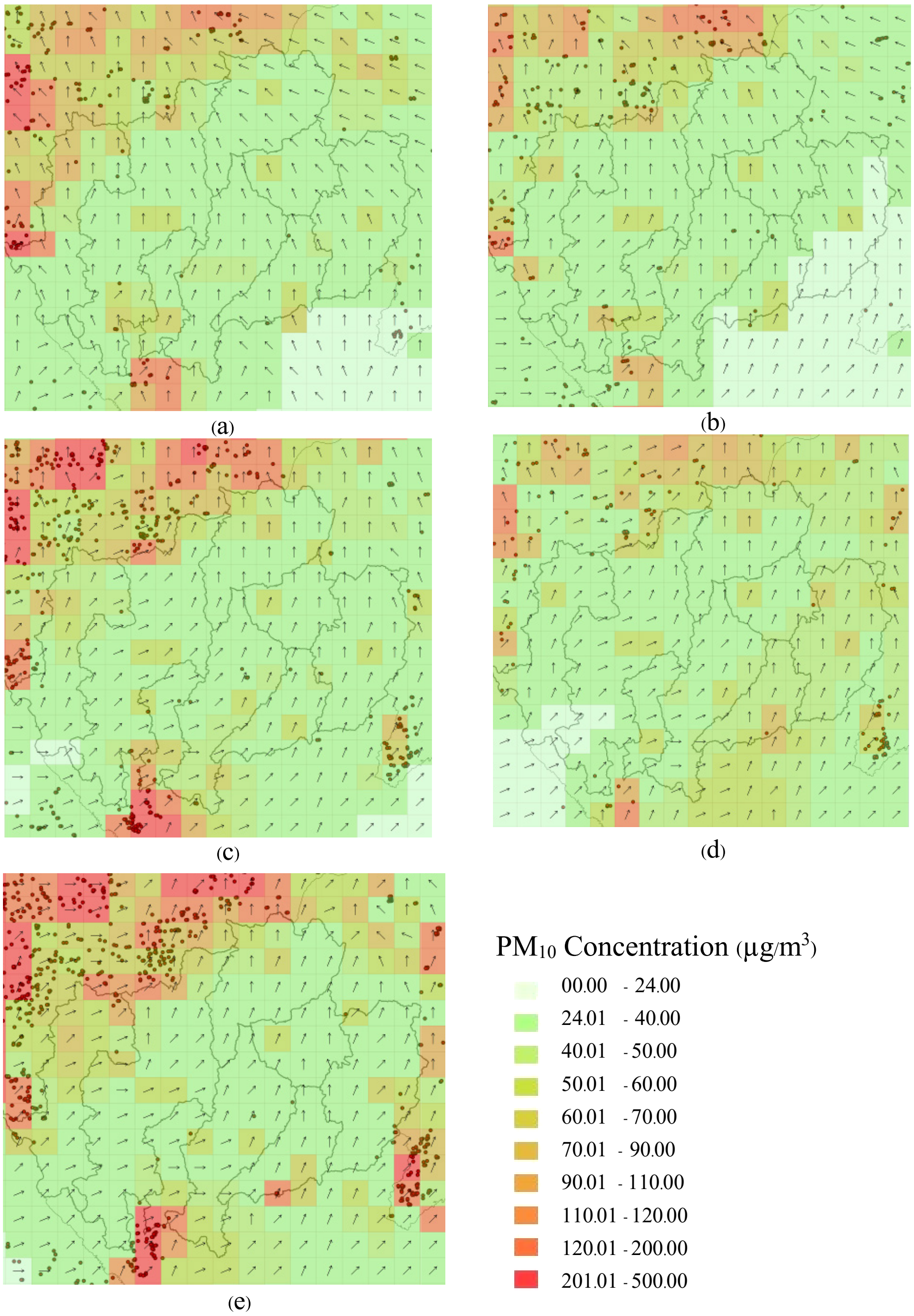



**Figure 3.20** The results of $PM_{10}$ concentrations in the north of Thailand after fires controlled in agricultural area and forest around agricultural area within 4 km in 26 February 2012 (a), 27 February 2012 (b), 28 February 2012 (c), 29 February 2012 (d), and 1 March 2012 (e)

The results of $PM_{10}$ concentrations from various scenarios simulation are shown in Table 3.12. Before fire controlled, the high level of $PM_{10}$ in some district areas which more than 200 µg/m$^3$occurred in every province. Moreover, the averaged $PM_{10}$ throughout the province exceeded the Thai daily standard at 120 µg/m$^3$ occurred in six provinces. After fires controls both agricultural and forest around agricultural area 1 km, $PM_{10}$ in most district areas have decreased until below 200 µg/m$^3$. $PM_{10}$ throughout the province meet the Thai daily standard at 120 µg/m$^3$ in every province with the value 33 to 79 µg/m$^3$. Lastly, fires controls both agricultural and forest around agricultural area 4 km, $PM_{10}$ have decreased until below 120 µg/m$^3$ in every district area except three districts which close to nearby provinces or neighbouring countries. $PM_{10}$ throughout the province meet the Thai daily standard at 120 µg/m$^3$ in every province with values ranging from 28 to 63 µg/m$^3$.

To mitigate $PM_{10}$ pollution from fires, above results show that after controlling fires in agricultural and surrounding area within 4 km in Thailand, most areas have $PM_{10}$ concentration not more than 120 µg/m$^3$ excepting areas closed to nearby provinces or neighbouring countries and in Mae Hong Son, Lamphun and Phrae.

**Table 3.12** Summary of $PM_{10}$ concentrations from three scenarios; 1) actual fires, 2) fires controls both agricultural and forest around agricultural area ranging 1 km, and 3) fire controls both agricultural and forest around agricultural area ranging 4 km areas, in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao, and Phrae during 26 February to 1 March 2012

| | Chiang Mai | Chiang Rai | Mae Hong Son | Lampang | Lamphun | Nan | Phayao | Phrae |
|---|---|---|---|---|---|---|---|---|
| $PM_{10}$ concentration from actual fires | | | | | | | | |
| - Ranges of estimated $PM_{10}$ during 5 days in the district scale ($\mu g/m^3$) | 31 to 312 | 56 to 231 | 30 to 305 | 38 to 285 | 27 to 240 | 31 to 309 | 43 to 275 | 34 to 294 |
| - Ranges of estimated $PM_{10}$ during 5 days in the province scale ($\mu g/m^3$) | 86 to 132 | 82 to 122 | 64 to 142 | 54 to 144 | 40 to 112 | 69 to 150 | 70 to 120 | 100 to 146 |
| - Estimated average 5-days $PM_{10}$ of the province area ($\mu g/m^3$) | 102 | 100 | 111 | 95 | 86 | 102 | 97 | 119 |
| $PM_{10}$ concentration after fires controlled both agricultural and forest around agricultural area 1 km to be no fire areas | | | | | | | | |
| - Ranges of estimated $PM_{10}$ during 5 days in the district scale ($\mu g/m^3$), | 26 to 138 | 30 to 109 | 26 to 141 | 27 to 188 | 27 to 234 | 27 to 143 | 30 to100 | 27 to214 |
| - Ranges of estimated $PM_{10}$ during 5 days in the province scale ($\mu g/m^3$) | 40 to 63 | 43 to 59 | 40 to 64 | 47 to 79 | 43 to 74 | 33 to 75 | 36 to 54 | 37 to 73 |
| - Estimated average 5-days $PM_{10}$ of the province area ($\mu g/m^3$) | 51 | 49 | 58 | 52 | 60 | 47 | 41 | 57 |
| $PM_{10}$ concentration after fires controlled both agricultural and forest around agricultural area 4 km to be no fire areas | | | | | | | | |
| - Ranges of estimated $PM_{10}$ during 5 days in the district scale ($\mu g/m^3$) | 26 to 96 | 30 to 72 | 26 to 170 | 27 to 59 | 27 to 152 | 26 to 68 | 27 to 59 | 26 to 129 |
| - Ranges of estimated $PM_{10}$ during 5 days in the province scale ($\mu g/m^3$) | 35 to 43 | 36 to 43 | 32 to 41 | 35 to 63 | 32 to 57 | 28 to 46 | 31 to 41 | 33 to 50 |
| - Estimated average 5-days $PM_{10}$ of the province area ($\mu g/m^3$) | 39 | 40 | 45 | 37 | 46 | 37 | 35 | 40 |

## 3.9 Conclusion and discussion

Scenarios for fire management indicated that open burning in the study heavily affected the $PM_{10}$ pollution. The $PM_{10}$ distribution in the most study areas can meet the Thai air-quality standard by controlling fires in agricultural and around area within 4 km. This is almost zero burning for the north of Thailand area. However, $PM_{10}$ concentrations still exceed the standard in some districts of Mae Hong Son, Lamphun and Phrae provinces (see Table 3.12). The haze from neighbouring countries and the central part of Thailand could transport to those districts, as shown in Figure 3.11. The south-west wind, generated from the ocean, distributed pollutants from Myanmar to Thailand while the southeast wind induced pollutants from Laos to the north of Thailand. Beside southwest and southeast winds, pollutants from the central part of Thailand also transported to the north part by the south wind. Therefore, fire controls in neighbouring countries and the central part of Thailand should be carried out with fire control in agricultural and around area within 4 km for managing air pollution in all districts to meet Thai air quality standard. For fire control in the agricultural area and forest area range of 1 km, this option can achieve the target of averaged $PM_{10}$ concentrations of whole province area meeting Thai air-quality standard. However, air pollution problems still occur in many districts for this option. This could be the first option when the limitation of the government budget is the first priority of the government. For the target of all districts achieving the air quality meeting standards, fire control in agricultural and surrounding area within 4 km and no transboundary haze from neighbouring countries may be the best option for the Thai government.

Fire management in the north of Thailand need more effort to achieve the target of good air quality for all area than other areas. This is because other factors also affected the $PM_{10}$ concentration (Yensong et al., 2016). The high $PM_{10}$ concentration not only was caused by the $PM_{10}$ released from fires sources, but also was a result from the meteorology as mixing height. Mixing height is the height which rapid vertical mixing occurs. High mixing heights are good for the dispersion of pollutants whereas low mixing heights tend to be stagnant and pollutants usually are trapped near the ground surface (Hardy et al., 2001). The mixing height at which may lead to smoke problem near the ground level is less than 1,700 feet or 500 meters (NWS and NOAA, 2015). With this weather condition, the prescribe burning (or controlled burning) are not allowed in many states in the United States. Results from models showed that most of the study area had the averaged values of mixing height during 26 February to 1 March 2012 less than 1,700 feet (see Figure 3.21). From Pollution Control Department (2017), the range of monthly-averaged mixing heights in February 2017were from 1,920 feet (in Chiang Mai) to 2,440 feet (in Phrae).

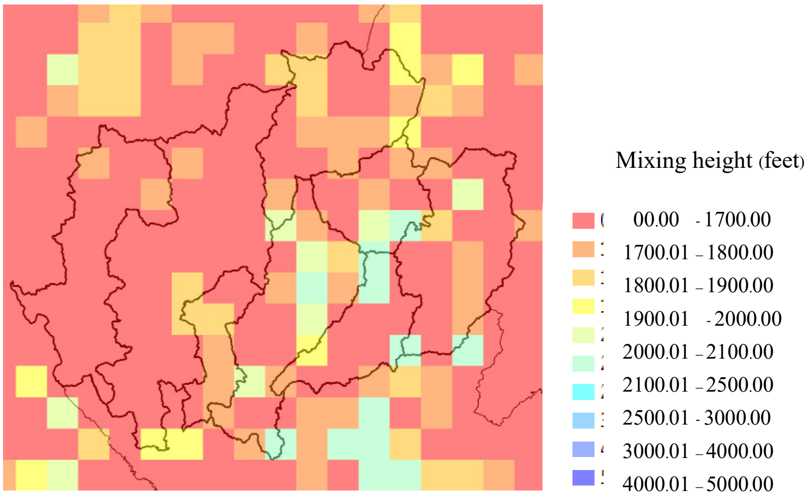



**Figure 3.21** Averaged mixing height (feet) in the study area during 26 February 2012 to 1 March 2012

Kim Oanh and Leelasakultum (2011) showed the meteorology which influences pollutants become high concentration level in Chiang Mai is the weather with all condition of low pressure in the north and north-east of Thailand and some part of south China, dry weather, clear sky, low wind speed and low mixing height. This weather condition occurred at around 50% during February and April 2001 to 2008. In addition, the topography of many areas in the north of Thailand is surrounded by mountains (see Figure 3.9) which affect the pollutant ventilation. These values may lead to stable conditions that induce the pollutants to become trapped near the ground surface in the north of Thailand area. All weather conditions of low pressure, dry weather, and low wind speed also occurred in February to April 2012. Meteorological information from the Thai Meteorological Department (2016) (see Figure 3.22) showed that more than 95% of all wind speed values in the north of Thailand were less than 1 m/s. The pressure values both the north and north-east area were low (purple and dark blue colour) during February to April. The low humidity (light blue colour) occurred only from February until the end of April 2012.

Beside the meteorological conditions, the number of hotspots was the important factor for $PM_{10}$ concentrations. From section 2.2 in Chapter 2, high temperatures and low air humidity and fuel moisture tend to induce fire occurrences (Pinol et al., 1998, Daniau et al., 2012). Rain is the most influential meteorological variable with a negative effect followed by temperature with positive influence on fire ignition (Vasilakos et al., 2009). In Figure 3.3, the high frequencies of fires were starts from the middle of February to the middle of April, which low air humidity, high temperature, and low precipitation occurred in this period (see Figure 3.22).

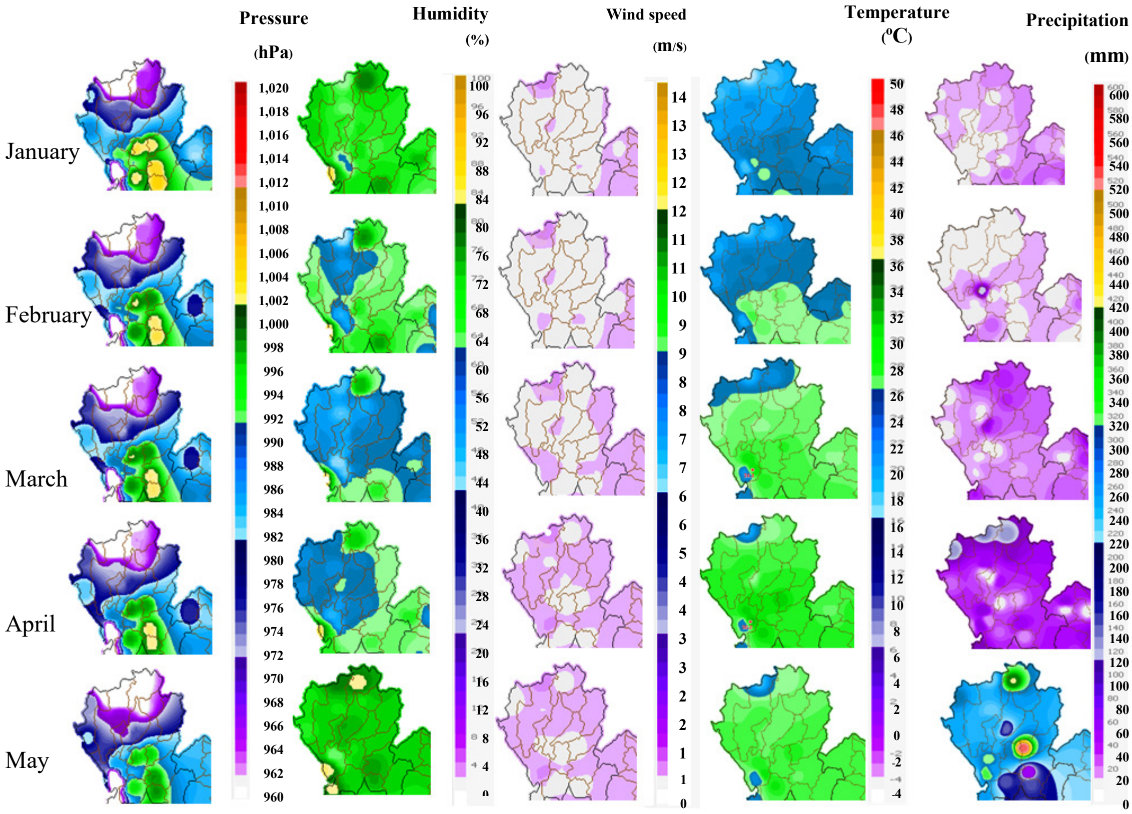



**Figure 3.22** Contour maps of monthly meteorological data of pressure (hPa), humidity (%), wind speed (m/s), temperature (°C) and precipitation (mm) in the north of Thailand in January, February, March, April and May year 2012 [adapted from Thai Meteorological Department (2016)]

In the north of Thailand, hotspots had occurred from December 2011 until 4 May 2012. In January and April, averaged daily of hotspot numbers were 12 and 16 and averaged daily of $PM_{10}$ concentration were 53 and 65 µg/m$^3$ (background $PM_{10}$ ~ 50 µg/m$^3$) in the urban area. The high frequency fires (average >150 hotspots per day) occurred from 9 February to 31 March 2012 with averaged daily of $PM_{10}$ concentration around 135 µg/ m$^3$ in the urban area. $PM_{10}$ concentrations have started to reach the unhealthy level (>75 µg/m$^3$ by Daily Air Quality Index of United Kingdom) in 29 January 2012 with 53 hotspots and reached 90 µg/m$^3$ in 8 February 2012 with only 13 hotspots. Therefore, the significant factors for fires impacts, weather conditions and fire numbers, should be in the period of February to April 2012. The mitigation of vegetation fire impacts need to focus in this period for the short-term management plan.

However, the error of air-quality model results may occur because the error of input data including the area burned size and the number of hotspots. The actual area burned of each hotspot is not the same size. It vary from 1,600 to 454,400 m$^2$ (0.16 to 45.44 ha) (Department of National

Parks Wildlife and Plant Conservation, 2012). This study selects 12,750 $m^2$ (1.275 ha) which is the averaged approximation of areas burned for each hotspot size because of lacking the area size of all hotspots. This approximation may influence $PM_{10}$ concentrations from the model simulation being higher or lower than the observed data as shown in the model validation part (see section 3.7.1).

# Chapter 4

## Cost Benefit Analysis

Cost Benefit Analysis (CBA) is used in this study to evaluate the potential gains and losses arising from policy options for the fire management of vegetation. Monetary values were estimated on a range of benefits from forest fire mitigation that has not to date been valued previously in northern Thailand. The method will utilize valuation of impacts from fires alongside comparison of policy options. Generally, vegetation fires affect the socio-economy via two main paths, namely air pollution and the depletion of ecosystem goods and services. The health impacts from air pollution at a "large area" scale is a primary problem for policy setting in Thailand. Therefore, the process of the policy development has started from air pollution control. An air quality model (CALPUFF) was used to find a solution for achieving the relevant Thai air quality standards by evaluating the size and location of vegetation areas to be managed (see Chapter 3). For the monetary assessment of forest fire impacts, the health and socio-economic impacts and the changes in ecosystem services value are estimated by comparing values before and after government intervention. The health impacts and ecosystem baseline from actual forest fire events was valued, and then the health impacts and ecosystem changes after the policy options were estimated. Health impacts and ecosystem goods/services valuations after government intervention and the area burned after fire control (estimated via CALPUFF) were fed to these valuation processes. The locations that showed a high level of air pollution and land use types to be controlled from the model were used to indicate stakeholders from fire occurrences. These stakeholders were then considered for their costs and benefits from the government intervention. These led to the development the policy options.

### 4.1 The integration of air quality models and cost benefit analysis

The purpose of integrating outputs from air quality models and cost benefit analysis in this study is to develop policy options for practical air quality management based on people's health as the main target and ecosystem goods and services to demonstrate the additional benefits of taking action. For air pollution impacts, the different levels of air pollutant concentration are associated with numbers of illness and death incidents. The higher the pollutant concentrations, the greater the increase of these incidents. Consequently, air pollutant concentrations are the important variable for valuing health impacts. A limitation of air quality monitoring stations is that they cannot cover the entirety of the affected areas, so an air quality model was used to estimate the concentrations of air pollutants in the north of Thailand. Air pollution concentration results from the air quality model are subsequently fed to the monetary part of the health impact valuation. Generally, air pollutants also affect human welfare in terms of ecosystem, climate, material and visibility (US EPA, 2009). The climate impact is estimated via ecosystem services valuations whilst materials (e.g. paint, metal and stone) impacts were not estimated because of a lack of previous studies to draw upon.

The results from air quality models are linked to ecosystem goods and services valuation during estimation for ecosystem values after the Thai government interventions. The ecosystem losses from fires are computed by estimating the total economic value of ecosystem goods and services changes (see Table 4.1). The forest areas burned including forest types and sizes are needed to estimate the socio-economic value of ecosystem. These values are calculated both before and after area fire controls scenarios. The integration between air models and cost benefit analysis is shown as Figure 4.1.

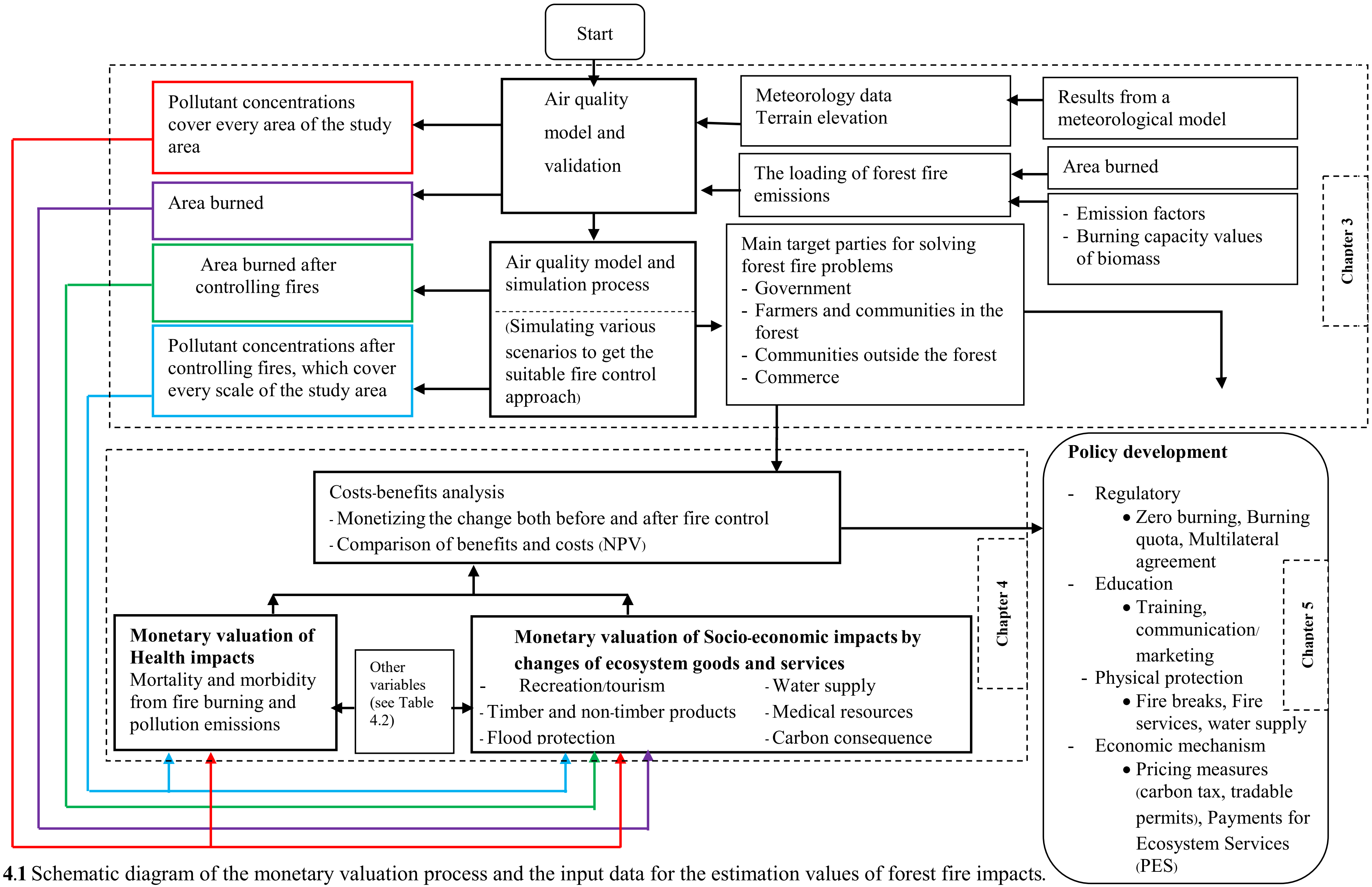



**Figure 4.1** Schematic diagram of the monetary valuation process and the input data for the estimation values of forest fire impacts.

In continental South and Southeast Asia in the year 2001, tropical forest was the main forest type with an area of 1,363,200 $km^2$ or around 89% of all forest type, and 47% of tropical forest were deciduous and semi-deciduous broadleaf followed by moist hardwood (~22%) of all vegetation type (SCBD, 2001b). Thailand is located in continental Southeast Asia and the deciduous forest is the main forest with a proportion of ~60% (Chien et al., 2011). Deciduous forests were also the main forest fires in Thailand (Chien et al., 2011, Wiriya, 2010). In the north part of Thailand during 24 February to 1 March, fires at 61.55% of all vegetation type occurred in mixed deciduous forests as shown in Table 3.7.

To avoid double counting, only some ecosystem services are collected to feed into the monetary part of health, socio-economic and ecological impacts. The values of pollution concentrations, area burned, benefit transfer and other variables for calculation of impact values are listed in Table 4.2.

**Table 4.1** Summary of economic value of goods and services from semi-deciduous forests and plantations [adapted from Secretariat of the Convention on Biological Diversity (SCBD, 2001a) and Millennium Ecosystem Assessment (MEA, 2005)]

| Total economic value of forest | Ecosystem good and service | Economic value | |
|---|---|---|---|
| | | Deciduous | Plantation |
| DIRECT USE VALUES[1] | | | |
| Timber | Provision - wood and fibre | Benefit[2] | Benefit |
| Fuel wood / charcoal | Provision - fuel | Benefit | Depend on vegetation type |
| Non-timber forest products | Provision – food, fuel and raw material | Benefit | No Effect[3] |
| Genetic information: | | | |
| • Pharmaceutical | Provision -medical resources | Benefit | No Effect |
| Recreation / tourism | Cultural service | Benefit | No Effect |
| Research / education | Cultural service | Benefit | No Effect |
| Cultural / religious | Cultural service | Benefit | No Effect |
| INDIRECT USE VALUES | | | |
| Watershed functions: | | | |
| • Water supply | Provision – fresh water | Benefit | No Effect |
| • Water quality | Regulation services – water purification | Benefit | No Effect |
| • Flood/storm protection | Regulation – natural hazard prevention | No Effect (SCBD,2001a) Benefit (MEA,2005) | No Effect |
| • Fisheries protection | Provision – being a food in a term of a final product | Benefit | No Effect |
| Global climate: | | | |
| • Carbon storage | Regulation – climate regulation | Benefit | No Effect |
| Biodiversity | Provision – genetic resource | Benefit | No Effect |
| OPTION VALUES | | Benefit | No Effect |
| EXISTENCE VALUES | | Benefit | No Effect |

[1] See Table 2.10 for explanation of terms
[2] Benefit = Positive economic value, Cost = Negative economic value
[3] No Effect = Economic value approximately zero

**Table 4.2** The health, socio-economic and ecological impacts from vegetation fires in the north of Thailand and variables for calculating in the monetary processes.

| Forest fire impacts | Input data | | Output data | Economic calculation/ Methods/ Equations | Remark |
|---|---|---|---|---|---|
| | Variables | Sources of the input data | | | |
| **1. Health impact** | | | | | |
| 1.1 Mortality and morbidity from air pollution | - Numbers of the population in a study area<br>- Health impact incident rate in study area | - Government records:<br>- Numbers of the population in study area from Department of Provincial Administration (2015)<br>- The actual rate of the death and illness from National Statistical Office (2015) and Bureau of Policy and Strategy (2015) | Numbers and economic values of mortality and morbidity people before and after fire controls | Numbers of mortality and morbidity x the unit cost of mortality and morbidity (US$) | Estimated in this study |
| | - Pollution concentration ($PM_{10}$) in a study area before and after fire controls | Results of pollutant concentration from an air quality model | | | |
| | - The percent of mortality and illness from the increase of $PM_{10}$ concentration | Previous studies (see Table 4.3) | | | |
| | - The unit cost of mortality and morbidity (US$) | Previous studies (see Table 4.17) | | | |
| 1.2 Mortality and morbidity from fire burning | - Numbers of mortality and morbidity from fire burning in a study area | Thai agency/ government records | Numbers of and economic values mortality and morbidity people before and after fire controls | Numbers of mortality and morbidity x the unit cost of mortality and morbidity (US$) | Nobody was killed by fires (Department of National Parks Wildlife and Plant Conservation, 2012) |

| Forest fire impacts | Input data | | Output data | Economic calculation/ Methods/ Equations | Remark |
|---|---|---|---|---|---|
| | Variables | Sources of the input data | | | |
| **2 Socio-economic impact** | | | | | |
| 2.1 Transportation | | | | | |
| 2.1.1 Flights cancelled | - The relation between the minimum visibility (km) for flying and $PM_{10}$ concentration in the atmosphere | Previous studies | Numbers of flights cancelled before and after fire controls | Numbers of flights cancelled x the income of each flight | Estimated in this study |
| | - Numbers of flights cancelled | Airport and airline records or news | | | |
| | - Pollution concentration ($PM_{10}$) in a study area before and after fire controls | Results from an air quality model | | | |
| 2.2 Forest tourism | - Income from forest tourism (US$/ha per annum) | Previous studies (see Table 4.25) | The value of the forest tourism before and after fire controls (US$) | Area burned x the value of forest tourism (US$/ha per annum) (benefit transfer approach) | Estimated in this study |
| | - Area burned before and after fire controls | Results from an air quality model | | | |
| 2.3 Water supply | | | | | |
| 2.3.1 Water supply | - The value of water supply by forests (US$/ha per annum) | Previous studies (see Table 4.25) | The value of water supply before and after fire controls (US$) | Area burned x the value of water supply by forests (US$/ha per annum) (benefit transfer approach) | Estimated in this study |
| | - Area burned before and after fire controls | Results from an air quality model | | | |

| Forest fire impacts | Input data | | Output data | Economic calculation/ Methods/ Equations | Remark |
|---|---|---|---|---|---|
| | Variables | Sources of the input data | | | |
| 2.3.2 Water quality | - The value of water purifying by forests to domestic (US$/ha per annum) | Previous studies (see Table 4.25) | The value of water quality by forests before and after fire controls (US$) | Area burned x the value of water quality by forests to domestic (US$/ha per annum) (benefit transfer approach) | Estimated in this study |
| | - Area burned before and after fire controls | Results from an air quality model | | | |
| 2.3.3 Flood protection | - The value of flood prevention by forests to domestic (US$/ha per annum) | Previous studies (see Table 4.25) | The value of flood prevention by forests before and after fire controls (US$) | Area burned x the value of flood protection by forests to domestic (US$/ha per annum) (benefit transfer approach) | Estimated in this study |
| | - Area burned before and after fire controls | Results from an air quality model | | | |
| 2.4 Forest goods | | | | | |
| 2.4.1 Timber product | - The value of timber product (US$/ha per annum) | Previous studies (see Table 4.25) | The value of timber product from forest before and after fire controls (US$) | Area burned x the value of timber product (US$/ha per annum) (benefit transfer approach) | Estimated in this study for evergreen forests |
| | - Area burned before and after fire controls | Results from an air quality model | | | |
| 2.4.2 Non-timber products | - The value of non-timber products (US$/ha per annum) | Previous studies (see Table 4.25) | The value of non-timber product from forest before and after fire controls (US$) | Area burned x the value of non-timber products (US$/ha per annum) (benefit transfer approach) | Estimated in this study |
| | - Area burned before and after fire controls | Results from an air quality model | | | |

| Forest fire impacts | Input data | | Output data | Economic calculation/ Methods/ Equations | Remark |
|---|---|---|---|---|---|
| | Variables | Sources of the input data | | | |
| 2.5 Job opportunities | - The number of staff employed for forest fire management | Agency/ government records | The value of the employment from fire events | | Estimated in this study |
| 2.6 Property loss from fire burning | - The number of property burned from forest fires in a study area | Agency/ government records | The value of property losses from fire burning | | There was no property loss from directly burnt by fire (Department of National Parks Wildlife and Plant Conservation, 2012) |
| 2.7 Cultural, research and education from forests | - The value of cultural, research and education (US$/ha per annum)<br>- Area burned before and after fire controls | Previous studies | The value of cultural, research and education from forest before and after fire controls (US$) | Area burned x the value of cultural, research and education (US$/ha per annum) (benefit transfer approach) | Lacking previous study data |
| 2.8 Fisheries protection | - The value of fishery products (US$/ha per annum)<br>- Area burned before and after fire controls | Previous studies | The value of fishery products from forest before and after fire controls (US$) | Area burned x the value of fishery products (US$/ha per annum) (benefit transfer approach) | This value was included in the Non-timber products |
| 2.9 Medical resources | - The value of medical resources (US$/ha per annum)<br>- Area burned before and after fire controls | Previous studies (see Table 4.25) | The value of medical resources from forest before and after fire controls (US$) | Area burned x the value of medical resources (US$/ha per annum) (benefit transfer approach) | Estimated in this study |
| 2.10 Hydro-electricity | - The value of electricity supply from water flow (US$/ha per annum) | Previous studies | The value of hydro-electricity from water generated by the forest before and after fire controls (US$) | | There is no hydro-electricity power plant in the study area |

| Forest fire impacts | Input data | | Output data | Economic calculation/ Methods/ Equations | Remark |
|---|---|---|---|---|---|
| | Variables | Sources of the input data | | | |
| 3. Ecology impact | | | | | |
| 3.1 Carbon storage | - The value of carbon storage (US$/ha per annum | Previous studies (see Table 4.25) | The value of carbon storage before and after fire controls (US$) | Area burned x the value of Carbon storage (US$/ha per annum) (benefit transfer approach) | Estimated in this study |
| | - Area burned before and after fire controls | Results from an air quality model | | | |
| 3.2 Biodiversity | - The value of biodiversity (US$/ha per annum<br>- Area burned before and after fire controls | Previous studies (see Table 4.25)<br>Results from an air quality model | The value of biodiversity before and after fire controls (US$) | Area burned x the value of biodiversity (US$/ha per annum) (benefit transfer approach) | Estimated in this study for evergreen forests |

## 4.2 Health impact valuation

The forest fires in the study area started between February to April 2012 and affected people's health via short-term exposure. $PM_{10}$ can affect the cardiovascular and respiratory systems, and increased mortality is a typical short-term effect (US EPA, 2009). Older adults (age >65 years old) tend to respond to cardiovascular morbidity and the children (age 1-14 years old) are at risk from respiratory symptoms from PM. The time frame for health evaluation is as follows: set for specific health outcomes. The time between air pollutant measurement and health endpoint, the lag time for short-term PM exposure is 0 to 5 days, 0-2 days for cardiovascular and 2-5 days for respiratory effects (2 days for older adults and 3-5 days for children).

### 4.2.1 Health effects of short-term $PM_{10}$ exposure

The number of the people affected from fire events in the study area was accounted by using the percent increase of illness by $PM_{10}$ increment from previous studies. The relation between the numbers of mortality, cardiovascular and respiratory hospital admissions, respiratory symptoms and $PM_{10}$ levels by previous studies are shown in Table 4.3. Considering the threshold for respiratory mortality, Samoli et al. (2005) suggested a value of around 20 μg/m$^3$ because it was indicated by the pooled spline graph curves of the mortality increase whereas Daniels et al.

(2000) suggested that a value of about 50 μg/m$^3$ was the significant initial-value of the mortality increase. Therefore, threshold levels of 20μg/m$^3$ and 50μg/m$^3$ were selected for calculating the high and low baseline of mortality numbers. From Table 4.3, Sakulniyomporn et al. (2011) showed that the mortality rate values from the vegetation fires were higher than the free fire days by the percent increase of the mortality at around 1.78% with the range of daily $PM_{10}$ in the reference area between 1 to >65 μg/m$^3$. The study in Thailand by Vichit-Vadakan et al. (2008) showed a similar value at 1.3% but this value was a result from deaths in the Bangkok area. Transportation is the major source of $PM_{10}$ in Bangkok, which is different from the north of Thailand. However, particles generated by vegetation fires and by urban sources are similar in size distribution but may be different in chemical constituents (Hime et al., 2015). Diesel emissions from vehicles may cause more health and toxicity-effects than other PM emission sources (Hime et al., 2015). However, wood smoke also contains toxic pollutants (dioxin and semi-volatile organic compounds (SVOCs) such as polycyclic aromatic hydrocarbons (PAHs)) that have shown to be carcinogenic (Afshar-Mohajer et al., 2016). Emissions from both transportation and vegetation fires also contain toxic substances. A range of studies have shown that more toxic PM arises from vehicles than other sources (Hime et al., 2015). Many studies have shown that $PM_{10}$-related mortality was higher on smoky days from fires than $PM_{10}$ mortality in other days in urban area (Faustini et al., 2015, Sakulniyomporn et al., 2011). In addition, the value of 1.3% from Vichit-Vadakan et al. (2008) and Sakulniyomporn et al. (2011) at 1.78%is a similar value. These values can be applied for calculating the number of deaths from $PM_{10}$ in the north of Thailand. However, the study by Vichit-Vadakan et al. (2008) is more suitable than another study because the study incorporated similar circumstances (e.g. climate, temperature and population). Thus the value of 1.3% by Vichit-Vadakan et al. (2008) was selected for this study.

With the lack of Thai study related with health impacts from vegetation fires, studies from various countries were used to quantitatively estimate illness caused by fires in the north of Thailand. Thailand is classified as a developing country, but the Thai health care service is a good standard. The self-reliance in health-care workforce production of Thailand is high quality standards with density per 1,000 populations, which is slightly above the 2.28 indicative of WHO benchmark of doctors, nurses and midwives. Moreover, by 2002, the entire population was covered by three public health insurance schemes including civil servants and their dependents by the Civil Servant Medical Benefit Scheme (CSMBS), private sector employees by the Social Health Insurance Scheme (SHI) and the rest of the population by the Universal Coverage Scheme (UCS) (Jongudomsuk et al., 2015). Generally, there is no payment needed by patients for each visit for illness treatments in cases of CSMBS and SHI, but the low cost of 30 Baht (~0.9 US$) is need for UCS (Damrongplasit and Melnick, 2015). Thai people both poor and rich, and in rural and urban can receive treatments equally with less expenses and sufficient medical staff provided. This led the actual number of Thai illness relevant the hospital admissions and visits. Therefore, the number of hospital admissions and visits from developed countries can be applied for Thailand.

The increased risk of the morbidity was estimated by considering hospital admissions for respiratory and cardiovascular illness and outpatient for all respiratory symptoms (see Table 4.3). The percent increment for all respiratory hospital admission of 1.24 from the study of Morgan et al. (2010) and cardiovascular hospital admission of 0.91 by Ballester et al. (2006) were used because the $PM_{10}$ concentrations in the reference study area had high $PM_{10}$ concentrations. The percent increment for respiratory outpatient of 1.3% by Peel et al. (2005) is used in this study. Peel et al., (2005) had collected the large number of respiratory outpatients between 1993 and 2000 around 484,800 cases from emergency department (ED) visits. With the long period and large amount of illness visits, this may be a good study.

**Table 4.3** The percent increase of mortality, cardiovascular and respiratory illness from $PM_{10}$ increase of 10 μg/m$^3$

| Health effect | Study area | $PM_{10}$ concentration in the study area (μg/m$^3$) | Percent increase of Health- effect from $PM_{10}$ by an increasing of 10 μg/m$^3$ | Relative risk (RR), Odds ratio (OR) of health effect | References | Age |
|---|---|---|---|---|---|---|
| **Mortality** | | | | | | |
| | Europe (29 cities) | 14-166 (average of 2 consecutive days) | 0.6 | | Katsouyanni et al. (2001) | All |
| | United Stated (110 cities) | 15.3-53.2 | 0.5 (for in all-natural-cause of mortality) | | Samet et al. (2000) | All |
| | Mexico City, Toluca, Monterrey (3 cities in Mexico) | Avg.=57.3, Max.= 101.9<br>Avg.=66.7, Max.= 136.4<br>Avg.=71.5, Max.= 130.9 | 1.02 (0.87-1.17)<br>1.26 (0.85-1.66)<br>1.01 (0.83-1.20)<br>(for in all-natural-cause of mortality) | | Linares et al. (2015) | All |
| | Madrid, Barcelona in Spain; Marseille in France; Turin, Milan, Bologna, Parma,Modena, Reggio Emilia, Rome and Palermo in Italy; Thessaloniki and Athens in Greece; year 2003-2010 | 1 to >64 by vegetation fires | 1.78 (−0.91-4.53), for vegetation-fire days<br>0.53 (0.30 to 0.76), for free vegetation-fire days<br>(both mortality values for in all-natural-cause of mortality) | | Sakulniyomporn et al. (2011) | All |
| | Madrid, Spain (year 2004-2009) | 0-149 by vegetation fires | | 1.035 (1.011–1.060), RR | Linares et al. (2015) | All |
| | Bangkok, Thailand | 5$^{th}$ percentile=29.6<br>95$^{th}$ percentile=93.2<br>Min. = 21.3<br>Avg. = 52<br>Max. =169.2 | 1.3 (0.8-1.7), ERR (%) for non-accidental mortality (RR=1.013) | | Vichit-Vadakan et al. (2008) | All |

| Health effect | Study area | $PM_{10}$ concentration in the study area (μg/m$^3$) | Percent increase of Health- effect from $PM_{10}$ by an increasing of 10 μg/m$^3$ | Relative risk (RR), Odds ratio (OR) of health effect | References | Age |
|---|---|---|---|---|---|---|
| **Cardiovascular hospital admissions** | | | 0.85 (0.7-1.0) | | | |
| | Spain (5 cities) | 10$^{th}$ percentile=17.3<br>90$^{th}$ percentile=62.6 | 0.91 (0.35-1.47) | | Ballester et al. (2006) | All |
| | France (8 urban area) | 21.0-28.9 | 0.7 (0.1-1.2) | | Larrieu et al. (2007) | All |
| **All respiratory hospital admission** | | | 1.48 (1.24-1.71) | | | |
| | Sydney, Australia | >42 (at 90$^{th}$ percentile) by vegetation fires | 1.24 (0.22-2.27) | | Morgan et al. (2010) | All |
| | Darwin, Australia | 6.4-70.0 by vegetation fires | | 1.08 (0.98-1.18), OR | Johnston et al. (2007) | All |
| | Literature reviews | N/A | 1.71 (1.19-2.23) | | Walton et al. (2014) | All |
| **Asthma hospital admission** | | | | | | |
| | Darwin, Australia | 6.4-70.0 by vegetation fires | | 1.14 (0.90-1.44), OR | Johnston et al. (2007) | All |
| | Literature reviews | N/A | 1.69 (0.5-2.96) | | Walton et al. (2014) | Children |
| **Asthma in all age (Emergency-Departments (ED) visits)** | | | | 1.009, RR | | All |
| | Atlanta (31 hospitals) | 19.2 | | 1.009 (0.996-1.022), RR | Peel et al. (2005) | All |
| **Asthma in children (asthma symptoms)** | | | | | | |
| | North American (8 cities) | 21.0 | | 1.13 (1.04-1.22), OR | Slaughter et al. (2003) | 133 Children |
| **Respiratory illness and symptoms (ED visits, outpatients) 1.05 (0.8-1.3)** | | | | | | |
| | Atlanta (31 hospitals) | 10$^{th}$ percentile =13.2<br>90$^{th}$ percentile =44.7 | 1.3 (0.4-2.1) | 1.013 (1.004-1.021), RR | Peel et al. (2005) | All |
| | Kermanshah City, Iran | 50-100 | 0.8 (0.5-1.1) | | Zallaghi et al. (2014) | All |

Excess relative risk (ERR) is an epidemiological risk measure that quantifies how much the level of risk among persons with a given level of exposure exceeds the risk of non-exposed persons:

$$ERR = (RR - 1) \times 100,$$

$$RR = (ERR/100) + 1 \quad (4.1)$$

The studies of the health impacts arising from increases in $PM_{10}$ (see Table 4.3) were generated basing on Poisson regression. The predicted mean of the Poisson distribution can be calculated as the equation (4.2):

$$E(Y|x) = e^{\beta x} \qquad (4.2)$$

where E(Y|x) is the expected value of the event Y given x (the relative risk (RR) value of a respiratory hospital admission/ a death in this study), x is the value of the concentration ($PM_{10}$), and β is the concentration-response coefficient.

Then a 1.3% death increase, (ERR= 1.3 equals RR= 1.013 (from equation (4.1)) per 10 μg/m$^3$ (x=10) of $PM_{10}$ concentration can be calculated for β value (concentration-response coefficient) as the equation (4.3).

$$\beta = (\ln RR)/x \qquad (4.3)$$

$$= (\ln 1.013)/10$$

$$\beta = 0.00129 \text{ (per 1 μg/m}^3\text{)}$$

New β of new concentration change = 0.00129 x new concentration change (ΔC) (4.4)

From equation (4.1), (4.3) and (4.4), the new β can be converted to an equation as:

New β of new concentration change = ((ln(ERR/100) +1)/10) × (ΔC) (4.5)

If the value of $PM_{10}$ concentration is 72 μg/m$^3$, then $PM_{10}$ change (ΔC or x = 52) from base line value of 20 μg/m$^3$ is 52 μg/m$^3$, the new RR will also increase.

From equation (4.2), RR $= e^{\beta x}$

New % increase or new ERR $= (RR - 1) \times 100$

$$= (e^{((\ln(ERR/100)+1)/10] \times (\Delta C))} - 1) \times 100 \qquad (4.6)$$

$$= 6.95\ \%$$

The numbers of deaths and patients were calculated by using the average value of the $PM_{10}$ concentration during the study period (5 days) and the high and low baseline levels at 20 μg/m$^3$ and 50 μg/m$^3$. The baseline levels are the threshold values of the death risk. Then $PM_{10}$ concentration values below the baseline levels may be assumed not to affect the premature death risk. Moreover, the minimum variable value of $PM_{10}$ in the referenced study by Vichit-Vadakan et al. (2008) was >20 μg/m$^3$ and other references for respiratory and cardiovascular illnesses were >10 μg/m$^3$. For the other health impacts, the $PM_{10}$ value of 20 μg/m$^3$ for annual air quality guideline and 50 μg/m$^3$ for daily guideline suggested by WHO (2005) are applied to be the baseline values for other illnesses. The resulting numbers of deaths and patients will show the range of low and high numbers from the concentration changes (ΔC) from the baseline values of

20 µg/m$^3$ and 50 µg/m$^3$, ΔC = simulated $PM_{10}$ concentration - $PM_{10}$ baseline. The numbers of people relating to mortality, respiratory and cardiovascular hospital admissions, and respiratory illness were estimated by the equation adapted from Vichit-Vadakan et al. (2004) and Walton et al. (2014) ((New % increase of mortality or the health effect from the $PM_{10}$ concentration change) x (% of total death by all natural causes or % of health impacts in the study area) x (number of population in the study area)) which is shown below.

The number of mortality by $PM_{10}$ change = (New % increase of mortality) x (Number of all natural deaths in study area) (4.7)

Where

New % increase of mortality = $e^{((\ln(ERR/100)+1)/10] \times (\Delta C))}-1$

Number of all-natural death in study area = (% of total actual deaths by all-natural causes in the study area) x (number of population in the study area)

The number of the hospital admissions or outpatients by = by $PM_{10}$ change (New % increase of hospital admissions or outpatients) x (Number of all respiratory or cardiovascular admissions or number of outpatients in the study area in study area) (4.8)

Where

New % increase of the hospital admissions or outpatients = $e^{((\ln(ERR/100)+1)/10] \times (\Delta C))}-1$

Number of all natural deaths in study area = (% actual hospital admissions of total respiratory or cardiovascular diseases or number of outpatients in the study area) x (number of population in the study area)

Population statistics were derived from the Department of Provincial Administration (2015) and the actual mortality by all natural causes in 2012 was taken from National Statistical Office (2015). The actual natural mortality was selected by all causes of death but exclude the death code number V01-Y89, which was classified following the International Statistical

Classification of Diseases and Related Health Problems 10th Revision (ICD-10) code. The V01-Y89 code includes death caused by accidents, intentional self-harm, assault, event of undetermined intent, legal intervention and operations of war, complications of medical and surgical care, and sequelae of external causes of morbidity and mortality. The numbers of actual respiratory and cardiovascular patients (both inpatients and outpatients) in Thailand were from the recorded data from Bureau of Policy and Strategy (2015). The population and health impacts baseline are summarized in the Table 4.4.

**Table 4.4** Population, actual cardiovascular, respiratory illness and death rate from the government records in year 2012 in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae.

| Province | Number of population | Natural mortality rate per 1,000 people per year | Cardiovascular hospital admission rate per 1,000 people per year | All respiratory hospital admission rate per 1,000 people per year | All respiratory outpatient visit rate per 1,000 people per year |
|---|---|---|---|---|---|
| Chiang Mai | 1,655,642 | 7.5 | 35.8 | 31.2 | 543.1 |
| Chiang Rai | 1,200,423 | 6.7 | 28.1 | 25.3 | 524.9 |
| Mae Hong Son | 244,356 | 4.5 | 16.1 | 26.7 | 710.5 |
| Lampang | 756,811 | 8.1 | 38.4 | 29.6 | 486.1 |
| Lamphun | 404,673 | 8.2 | 27.6 | 25.4 | 623.6 |
| Nan | 447,193 | 6.0 | 44.3 | 33.7 | 258.1 |
| Phayao | 488,120 | 7.4 | 33.2 | 28.0 | 535.9 |
| Phrae | 457,607 | 8.4 | 36.4 | 25.6 | 472.9 |

A 10 $\mu g/m^3$ increment of $PM_{10}$ causes an increase of mortality of about 1.3% or 0.013. From Table 4.4, in Chiang Mai in 2012, all-natural cause of mortality was ~7.5 per 1,000 persons (or 0.75 per 100 persons or 0.75% or 0.0075) and the population was around 1,655,640 persons. Then the number of all-natural deaths in year 2012 was (7.5/1000) x 1,655,640 = 12,417.3 persons. Therefore, the estimated mortality from the 10 $\mu g/m^3$ increase of $PM_{10}$ can be calculated using equation (4.7) as follows:

The number of mortality by $PM_{10}$ change

$$= (e^{((\ln(ERR/100)+1)/10] \times (\Delta C))}-1) \times (\% \text{ of total actual deaths by all natural causes in the study area}) \times (\text{number of population in the study area})$$

$$= (e^{((\ln(1.3/100)+1)/10] \times (10))}-1) \times (7.5/1,000) \times 1,655,640$$

$$= 0.013 \times 0.0075 \times 1,655,640$$

$$=0.013 \times 12,417.3$$

$$= 161 \text{persons}$$

If the concentration of $PM_{10}$ increases from the baseline value (50 μg/m$^3$) to 102 μg/m$^3$ ($PM_{10}$ concentration change is 52 μg/m$^3$) the new percent increase of the estimated death number will be 6.95% (see equation (4.6)). It leads to an estimated mortality (see equation (4.7))

$$=(e^{((\ln(1.3/100)+1)/10] \times (102-50))}-1) \times (7.5/1,000) \times 1,655,640$$

$$= 0.0695 \times 0.0075 \times 1,655,640$$

$$= 863 \text{ persons}$$

Considering morbidity, a 10 μg/m$^3$ increment of $PM_{10}$ affected the percent increase of all respiratory hospital admissions of 1.24 (see Table 4.3), and actual respiratory hospital admissions rate in Chiang Mai year 2012 was 31.2 per 1,000 persons (see Table 4.4). Then the estimated number of the respiratory hospital admissions caused by 10 μg/m$^3$ $PM_{10}$ increment can be calculated using equation (4.8) as (0.0124) x (31.2/1,000) x 1,655,640 = 640 admissions.

If the concentrations of $PM_{10}$ increase from the baseline value (50 μg/m$^3$) to 102 μg/m$^3$ ($PM_{10}$ concentration change is 52 μg/m$^3$), the new percent increase for respiratory admissions will be $(e^{((\ln (1.24/100) +1)/10] \times (102-50))}-1) = 0.0662$ or 6.62% (see equation (4.6)). It leads to an estimated number of admissions of (0.0662) x (31.2/1,000) x 1,655,640 = 3,419 admissions (see equation (4.7)).

For estimating the number of cardiovascular hospital admissions and outpatients from respiratory illness, the percent increase values for the 10 μg/m$^3$ increment of $PM_{10}$ at 0.91% and 1.3% are used. If the $PM_{10}$ concentration change is 52 μg/m$^3$, the new percent increase for cardiovascular admissions will be $(e^{((\ln (0.91/100) +1)/10] \times (102-50))} -1) = 0.0482$ or 4.82% and outpatients from respiratory illness will be $(e^{((\ln (1.3/100) +1)/10] \times (102-50))} -1) = 0.0695$ or 6.95%. The actual cardiovascular hospital admissions rate in Chiang Mai year 2012 was 35.8 per 1,000 persons. The estimated number of admissions will be (0.0482) x (35.8/1,000) x 1,655,640 = 2,857 admissions and (0.0695) x (543/1,000) x 1,655,640 = 62,481 outpatients.

However, these mortality and morbidity values were estimated using the whole year rate in 2012. The estimated number of daily cases can be calculated by dividing by 365.25 days (1 year). Then the estimated number of mortality, respiratory hospital admissions, cardiovascular hospital admissions, and respiratory outpatients during the study period (5 days) with averaged $PM_{10}$ change by 52 µg/m$^3$ in Chiang Mai province (increasing from the baseline value 50 µg/m$^3$ to 102 µg/m$^3$) as follows:

- Mortality = (863/365.25) x 5 = 12 persons,
- Respiratory hospital admissions = (3,419/365.25) x 5 = 47 admissions,
- Cardiovascular hospital admissions = (2,857/365.25) x 5 = 39 admissions and
- Respiratory outpatients = (62,481/365.25) x 5 = 855 outpatient visits

If the concentration of $PM_{10}$ increases from the baseline value (20 µg/m$^3$) to 102 µg/m$^3$ ($PM_{10}$ concentration change is 82 µg/m$^3$). The estimated number of mortality, respiratory and cardiovascular hospital admissions and respiratory outpatients from 5 days impact in Chiang Mai will be as follows:

- Mortality = [[(e $^{((\ln(1.3/100)+1)/10] \times (102-20))}$-1) x (7.5/1,000) x 1,655,640] / 365.25] x 5=19 persons,
- Respiratory hospital admissions = [[(e $^{((\ln(1.24/100)+1)/10] \times (102-20))}$-1) x (31.2/1,000) x 1,655,640] / 365.25] x 5=75 admissions,
- Cardiovascular hospital admissions = [[(e $^{((\ln(0.91/100)+1)/10] \times (102-20))}$-1) x (35.8/1,000) x 1,655,640] / 365.25] x 5=63 admissions,
- Respiratory outpatients = [[(e $^{((\ln(1.3/100)+1)/10] \times (102-20))}$-1) x (543/1,000) x 1,655,640] / 365.25] x 5= 1,375 outpatient visits.

The average 5-days $PM_{10}$ caused by fires in the rest of study areas including Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae were estimated by air quality models as same as Chiang Mai. The $PM_{10}$ concentration in every grid, 27 x 27 km per grid, which cover every district in each province was used to estimate the average 5-days $PM_{10}$ in these provinces. Results of $PM_{10}$ concentration of these provinces are 100, 111, 95, 86, 102, 97 and 119 µg/m$^3$, respectively. The total estimated number of mortality, respiratory and cardiovascular hospital admissions and respiratory outpatients from 5 days impact in the study area are 38 persons, 123 and 142 admissions, and 2,767 outpatient visits for comparing with baseline value at 50 µg/m$^3$ and 62 persons, 198 and 233 admissions, and 4,815 outpatient visits for comparing with baseline value at 20 µg/m$^3$ (see Table 4.5).

Health impacts after fire controls in target areas including agricultural area and near agricultural areas within 1 km and 4 km that were simulated as no fire areas by government measures were calculated for the numbers of illness cases. The average 5-days $PM_{10}$ concentration results from the air quality models after reducing emissions through fires controlled in agricultural areas and near agricultural areas within 1 km and 4 km, in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae have decreased for all areas. $PM_{10}$

concentration of these provinces are 51, 49, 58, 52, 60, 47, 41 and 57 μg/m$^3$ after controlled fires, both agricultural and forest around agricultural area 1 km, and 39, 40, 45, 37, 46, 37, 35 and 40 μg/m$^3$ after controlled fires both agricultural and forest around agricultural area 4 km. The total estimated number of mortality, respiratory and cardiovascular hospital admissions and respiratory outpatients from 5 days impact in the study area after controlled fire are shown in Table 4.6 and Table 4.7. These numbers of these cases are also used to estimate the economic value of health impacts and are compared with health impact values before employing the government measures.

**Table 4.5** Summary of estimated deaths, hospital admissions for respiratory and cardiovascular illness, and respiratory outpatient visits caused by average 5-days $PM_{10}$ increase from actual fires during 26 February to 1 March 2012 in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae provinces

| | Chiang Mai | Chiang Rai | Mae Hong Son | Lampang | Lamphun | Nan | Phayao | Phrae | Total |
|---|---|---|---|---|---|---|---|---|---|
| Number of population (persons) | 1,655,640 | 1,200,423 | 244,356 | 756,811 | 404,673 | 447,193 | 488,120 | 457,607 | 5,654,823 |
| Ranges of estimated $PM_{10}$ during 5 days in the district scale (µg/m$^3$), results from air quality models | 31 to 312 | 56 to 231 | 30 to 305 | 38 to 285 | 27 to 240 | 31 to 309 | 43 to 275 | 34 to 294 | |
| Ranges of estimated $PM_{10}$ during 5 days in the province scale (µg/m3), results from air quality models | 86 to 132 | 82 to 122 | 64 to 142 | 54 to 144 | 40 to 112 | 69 to 150 | 70 to 120 | 100 to 146 | |
| Estimated average 5-days $PM_{10}$ of the province area (µg/m$^3$), results from air quality models | 102 | 100 | 111 | 95 | 86 | 102 | 97 | 119 | |
| $PM_{10}$ change between estimated average 5-days $PM_{10}$ and baseline value at 50 µg/m$^3$ (µg/m$^3$) | 52 | 50 | 61 | 45 | 36 | 52 | 47 | 69 | |
| $PM_{10}$ change between estimated average 5-days $PM_{10}$ and baseline value at 20 µg/m$^3$ (µg/m$^3$) | 82 | 80 | 91 | 75 | 66 | 82 | 77 | 99 | |
| Estimated deaths from $PM_{10}$ change | | | | | | | | | |
| Actually natural mortality rate (per 1,000 persons per year) | 7.5 | 6.7 | 4.5 | 8.1 | 8.2 | 6.0 | 7.4 | 8.4 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 50 µg/m$^3$ | 6.95 | 6.67 | 8.20 | 5.98 | 4.76 | 6.95 | 6.26 | 9.32 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 20 µg/m$^3$ | 11.17 | 10.89 | 12.47 | 10.17 | 8.90 | 11.17 | 10.46 | 13.64 | |
| Estimated deaths from 5-days impacts of $PM_{10}$ change (baseline value 50 µg/m$^3$) (persons) | 12 | 7 | 1 | 5 | 2 | 3 | 3 | 5 | 38 |
| Estimated deaths from 5-days impacts of $PM_{10}$ change (baseline value 20 µg/m$^3$) (persons) | 19 | 12 | 2 | 9 | 4 | 4 | 5 | 7 | 62 |
| Estimated hospital admissions of cardiovascular illness from $PM_{10}$ change | | | | | | | | | |
| Actually cardiovascular hospital admission rate (per 1,000 persons per year) | 36.0 | 28.0 | 16.0 | 38.4 | 27.6 | 44.3 | 33.2 | 36.4 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 50 µg/m$^3$ | 4.82 | 4.63 | 5.63 | 4.16 | 3.31 | 4.82 | 4.35 | 6.45 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 20 µg/m$^3$ | 7.71 | 7.52 | 8.59 | 7.03 | 6.16 | 7.71 | 7.22 | 9.38 | |
| Estimated admissions from 5-days impacts of $PM_{10}$ change (baseline value 50 µg/m$^3$) (admissions) | 39 | 21 | 3 | 17 | 5 | 13 | 10 | 15 | 123 |
| Estimated admissions from 5-days impacts of $PM_{10}$ change (baseline value 20 µg/m$^3$) (admissions) | 63 | 35 | 5 | 28 | 9 | 21 | 16 | 21 | 198 |
| Estimated hospital admissions of respiratory illness from $PM_{10}$ change | | | | | | | | | |
| Actually all respiratory hospital admission rate (per 1,000 persons per year) | 31.2 | 25.3 | 26.7 | 29.6 | 25.4 | 33.7 | 28.0 | 25.6 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 50 µg/m$^3$ | 6.62 | 6.36 | 7.81 | 5.70 | 4.54 | 6.62 | 5.96 | 8.88 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 20 µg/m$^3$ | 10.63 | 10.36 | 11.87 | 9.68 | 8.47 | 10.63 | 9.95 | 12.98 | |
| Estimated admissions from 5-days impacts of $PM_{10}$ change (baseline value 50 µg/m$^3$) (admissions) | 47 | 26 | 7 | 17 | 6 | 14 | 11 | 14 | 142 |
| Estimated admissions from 5-days impacts of $PM_{10}$ change (baseline value 20 µg/m$^3$) (admissions) | 75 | 43 | 11 | 30 | 12 | 22 | 19 | 21 | 233 |
| Estimated outpatient visits of respiratory illness from $PM_{10}$ change | | | | | | | | | |
| Actually all respiratory outpatient visit rate (per 1,000 persons per year) | 543.1 | 524.9 | 710.5 | 486.1 | 623.6 | 258.1 | 535.9 | 472.9 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 50 µg/m$^3$ | 6.95 | 6.67 | 8.20 | 5.98 | 4.76 | 6.95 | 6.26 | 9.32 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 20 µg/m$^3$ | 11.17 | 10.89 | 12.47 | 10.17 | 8.90 | 11.17 | 10.46 | 13.64 | |
| Estimated visits from 5-days impacts of $PM_{10}$ change (baseline value 50 µg/m$^3$) (visits) | 855 | 575 | 195 | 301 | 164 | 177 | 224 | 276 | 2,767 |
| Estimated visits from 5-days impacts of $PM_{10}$ change (baseline value 20 µg/m$^3$) (visits) | 1,375 | 939 | 296 | 512 | 307 | 177 | 374 | 404 | 4,384 |

**Table 4.6** Summary of estimated deaths, hospital admissions for respiratory and cardiovascular illness, and respiratory outpatient visits caused by average 5-days $PM_{10}$ increase after fires controlled both agricultural and forest around agricultural area 1 km to be no fire areas during 26 February to 1 March 2012 in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae provinces

| | Chiang Mai | Chiang Rai | Mae Hong Son | Lampang | Lamphun | Nan | Phayao | Phrae | Total |
|---|---|---|---|---|---|---|---|---|---|
| Number of population (persons) | 1,655,640 | 1,200,423 | 244,356 | 756,811 | 404,673 | 447,193 | 488,120 | 457,607 | 5,654,823 |
| Ranges of estimated $PM_{10}$ during 5 days in the district scale (µg/m$^3$), results from air quality models | 26 to 138 | 30 to 109 | 26 to 141 | 27 to 188 | 27 to 234 | 27 to 143 | 30 to100 | 27 to214 | |
| Ranges of estimated $PM_{10}$ during 5 days in the province scale (µg/m3), results from air quality models | 40 to 63 | 43 to 59 | 40 to 64 | 47 to 79 | 43 to 74 | 33 to 75 | 36 to 54 | 37 to 73 | |
| Estimated average 5-days $PM_{10}$ of the province area (µg/m$^3$), results from air quality models | 51 | 49 | 58 | 52 | 60 | 47 | 41 | 57 | |
| $PM_{10}$ change between estimated average 5-days $PM_{10}$ and baseline value at 50 µg/m$^3$ (µg/m$^3$) | 1 | -1 | 8 | 2 | 10 | -3 | -9 | 7 | |
| $PM_{10}$ change between estimated average 5-days $PM_{10}$ and baseline value at 20 µg/m$^3$ (µg/m$^3$) | 31 | 29 | 38 | 32 | 40 | 27 | 21 | 37 | |
| Estimated deaths from $PM_{10}$ change | | | | | | | | | |
| Actually natural mortality rate (per 1,000 persons per year) | 7.5 | 6.7 | 4.5 | 8.1 | 8.2 | 6.0 | 7.4 | 8.4 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 50 µg/m$^3$ | 0.13 | 0 | 1.04 | 0.26 | 1.3 | 0 | 0 | 0.91 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 20 µg/m$^3$ | 4.09 | 3.82 | 5.03 | 4.22 | 5.3 | 3.55 | 2.75 | 4.9 | |
| Estimated deaths from 5-days impacts of $PM_{10}$ change (baseline value 50 µg/m$^3$) (persons) | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Estimated deaths from 5-days impacts of $PM_{10}$ change (baseline value 20 µg/m$^3$) (persons) | 7 | 4 | 1 | 4 | 2 | 1 | 1 | 3 | 23 |
| Estimated hospital admissions of cardiovascular illness from $PM_{10}$ change | | | | | | | | | |
| Actually cardiovascular hospital admission rate (per 1,000 persons per year) | 36.0 | 28.0 | 16.0 | 38.4 | 27.6 | 44.3 | 33.2 | 36.4 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 50 µg/m$^3$ | 0.09 | 0.73 | 0.18 | 0.18 | 0.91 | 0 | 0 | 0.64 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 20 µg/m$^3$ | 2.85 | 2.66 | 3.50 | 2.94 | 3.69 | 2.48 | 1.92 | 3.41 | |
| Estimated admissions from 5-days impacts of $PM_{10}$ change (baseline value 50 µg/m$^3$) (admissions) | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 4 |
| Estimated admissions from 5-days impacts of $PM_{10}$ change (baseline value 20 µg/m$^3$) (admissions) | 23 | 12 | 2 | 12 | 6 | 7 | 4 | 8 | 74 |
| Estimated hospital admissions of respiratory illness from $PM_{10}$ change | | | | | | | | | |
| Actually all respiratory hospital admission rate (per 1,000 persons per year) | 31.2 | 25.3 | 26.7 | 29.6 | 25.4 | 33.7 | 28.0 | 25.6 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 50 µg/m$^3$ | 0.12 | 0 | 0.99 | 0.25 | 1.24 | 0 | 0 | 0.87 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 20 µg/m$^3$ | 3.89 | 3.64 | 4.79 | 4.02 | 5.05 | 3.38 | 2.62 | 4.67 | |
| Estimated admissions from 5-days impacts of $PM_{10}$ change (baseline value 50 µg/m$^3$) (admissions) | 1 | - | 1 | 1 | 2 | - | - | 1 | 6 |
| Estimated admissions from 5-days impacts of $PM_{10}$ change (baseline value 20 µg/m$^3$) (admissions) | 28 | 15 | 4 | 12 | 7 | 7 | 5 | 7 | 85 |
| Estimated outpatient visits of respiratory illness from $PM_{10}$ change | | | | | | | | | |
| Actually all respiratory outpatient visit rate (per 1,000 persons per year) | 543.1 | 524.9 | 710.5 | 486.1 | 623.6 | 258.1 | 535.9 | 472.9 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 50 µg/m$^3$ | 0.13 | 0 | 1.04 | 0.26 | 1.3 | 0 | 0 | 0.91 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 20 µg/m$^3$ | 4.09 | 3.82 | 5.03 | 4.22 | 5.3 | 3.55 | 2.75 | 4.9 | |
| Estimated visits from 5-days impacts of $PM_{10}$ change (baseline value 50 µg/m$^3$) (visits) | 16 | - | 25 | 13 | 45 | 56 | - | 27 | 182 |
| Estimated visits from 5-days impacts of $PM_{10}$ change (baseline value 20 µg/m$^3$) (visits) | 503 | 329 | 120 | 213 | 183 | 56 | 98 | 145 | 1,647 |

**Table 4.7** Summary of estimated deaths, hospital admissions for respiratory and cardiovascular illness, and respiratory outpatient visits caused by average 5-days $PM_{10}$ increase after fires controlled both agricultural and forest around agricultural area 4 km to be no fire areas during 26 February to 1 March 2012 in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae provinces

| | Chiang Mai | Chiang Rai | Mae Hong Son | Lampang | Lamphun | Nan | Phayao | Phrae | Total |
|---|---|---|---|---|---|---|---|---|---|
| Number of population (persons) | 1,655,640 | 1,200,423 | 244,356 | 756,811 | 404,673 | 447,193 | 488,120 | 457,607 | 5,654,823 |
| Ranges of estimated $PM_{10}$ during 5 days in the district scale ($\mu g/m^3$), results from air quality models | 26 to 96 | 30 to 72 | 26 to 170 | 27 to 59 | 27 to 152 | 26 to 68 | 27 to 59 | 26 to 129 | |
| Ranges of estimated $PM_{10}$ during 5 days in the province scale (µg/m3), results from air quality models | 35 to 43 | 36 to 43 | 32 to 41 | 35 to 63 | 32 to 57 | 28 to 46 | 31 to 41 | 33 to 50 | |
| Estimated average 5-days $PM_{10}$ of the province area ($\mu g/m^3$), results from air quality models | 39 | 40 | 45 | 37 | 46 | 37 | 35 | 40 | |
| $PM_{10}$ change between estimated average 5-days $PM_{10}$ and baseline value at 50 $\mu g/m^3$ ($\mu g/m^3$) | -11 | -10 | -5 | -13 | -4 | -13 | -15 | -10 | |
| $PM_{10}$ change between estimated average 5-days $PM_{10}$ and baseline value at 20 $\mu g/m^3$ ($\mu g/m^3$) | 19 | 20 | 25 | 17 | 26 | 17 | 15 | 20 | |
| Estimated deaths from $PM_{10}$ change | | | | | | | | | |
| Actually natural mortality rate (per 1,000 persons per year) | 7.5 | 6.7 | 4.5 | 8.1 | 8.2 | 6.0 | 7.4 | 8.4 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 50 $\mu g/m^3$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 20 $\mu g/m^3$ | 2.48 | 2.62 | 3.28 | 2.22 | 3.42 | 2.22 | 1.96 | 2.62 | |
| Estimated deaths from 5-days impacts of $PM_{10}$ change (baseline value 50 $\mu g/m^3$) (persons) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Estimated deaths from 5-days impacts of $PM_{10}$ change (baseline value 20 $\mu g/m^3$) (persons) | 4 | 3 | - | 2 | 2 | 1 | 1 | 1 | 14 |
| Estimated hospital admissions of cardiovascular illness from $PM_{10}$ change | | | | | | | | | |
| Actually cardiovascular hospital admission rate (per 1,000 persons per year) | 36.0 | 28.0 | 16.0 | 38.4 | 27.6 | 44.3 | 33.2 | 36.4 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 50 $\mu g/m^3$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 20 $\mu g/m^3$ | 1.74 | 1.83 | 2.29 | 1.55 | 2.38 | 1.55 | 2.37 | 1.83 | |
| Estimated admissions from 5-days impacts of $PM_{10}$ change (baseline value 50 $\mu g/m^3$) (admissions) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Estimated admissions from 5-days impacts of $PM_{10}$ change (baseline value 20 $\mu g/m^3$) (admissions) | 14 | 8 | 1 | 6 | 4 | 4 | 3 | 4 | 44 |
| Estimated hospital admissions of respiratory illness from $PM_{10}$ change | | | | | | | | | |
| Actually all respiratory hospital admission rate (per 1,000 persons per year) | 31.2 | 25.3 | 26.7 | 29.6 | 25.4 | 33.7 | 28.0 | 25.6 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 50 $\mu g/m^3$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 20 $\mu g/m^3$ | 2.37 | 2.5 | 3.13 | 2.12 | 3.26 | 2.12 | 1.87 | 2.5 | |
| Estimated admissions from 5-days impacts of $PM_{10}$ change (baseline value 50 $\mu g/m^3$) (admissions) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Estimated admissions from 5-days impacts of $PM_{10}$ change (baseline value 20 $\mu g/m^3$) (admissions) | 17 | 10 | 3 | 6 | 5 | 4 | 3 | 4 | 52 |
| Estimated outpatient visits of respiratory illness from $PM_{10}$ change | | | | | | | | | |
| Actually all respiratory outpatient visit rate (per 1,000 persons per year) | 543.1 | 524.9 | 710.5 | 486.1 | 623.6 | 258.1 | 535.9 | 472.9 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 50 $\mu g/m^3$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| % increased risk from estimated $PM_{10}$ change and baseline value at 20 $\mu g/m^3$ | 2.48 | 2.62 | 3.28 | 2.22 | 3.42 | 2.22 | 1.96 | 2.62 | |
| Estimated visits from 5-days impacts of $PM_{10}$ change (baseline value 50 $\mu g/m^3$) (visits) | 0 | 0 | 0 | 0 | 0 | 35 | 0 | 0 | 35 |
| Estimated visits from 5-days impacts of $PM_{10}$ change (baseline value 20 $\mu g/m^3$) (visits) | 306 | 226 | 78 | 112 | 118 | 35 | 70 | 78 | 1,023 |

Generally, $PM_{10}$ from fires affected people's health through the fire season, February to April. Then death and illness numbers from fire impacts were estimated through this period. However, with the limitation of schedule of study time, regression line equations as shown in equation 4.9 and 4.10 (Wilks, 2006) were used to calculate the averaged $PM_{10}$ of every grid area in each province in the north of Thailand from 1 February to 30 April 2012. Equations were generated by using the relationship between 2 variables including hotspot numbers and simulated $PM_{10}$ concentrations during 26 February and 1 March 2012 which $PM_{10}$ concentration values were varied by X or numbers of hotspots.

$$y = a + bx, \tag{4.9}$$

Where X is the independent variable (or numbers of hotspots) and Y is the dependent variable (or $PM_{10}$ concentration), b is the slope of the line, and a is the intercept (see equation 4.10).

$$b = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sum(x - \bar{x})^2} \quad , a = \bar{y} - b\bar{x} \tag{4.10}$$

Data of hotspot numbers and $PM_{10}$ concentrations for high, medium and low number of hotspots condition were taken from input data of hotspot numbers and output data of $PM_{10}$ concentrations from three scenarios; actual fire events; fires controlled in agricultural area and forest areas within a range of 1 and fires controlled in agricultural area and forest areas within a range of 4 kilometres in the air quality model. Background $PM_{10}$ (around 25 $\mu g/m^3$ for rural and 50 $\mu g/m^3$ for urban area) and nearby pollutants from other countries and provinces were included in $PM_{10}$ concentrations for all scenarios and hotspot conditions. These values also were taken into account for $PM_{10}$ concentration for fire events from 1 February to 30 April 2012. Results of regression line equations for each province are shown in Table 4.8 and Table 4.2.

The coefficient of determination ($R^2$) is a parameter for testing the goodness of fit of the regression linier. $R^2$ results of hotspots and $PM_{10}$ concentration of all provinces are more than 0.5 except Mae Hon Son province. This is acceptable for the strength of the relationship between $PM_{10}$ concentrations and hotspots numbers that were more than 50%. In addition, the significance of the model can be determined by F-test. The model is significant when P-value in F-test is smaller than an alpha value(or the common significance F) at 0.05 (University of Tennessee Knoxville, 2016). The P-value less than 0.05 means the difference of hotspots numbers (x variable) influencing $PM_{10}$ concentration values (y variable) with the linear relationship. Results of every regression analysis in this study (see Table 4.8) had the P-value less than 0.05.

**Table 4.8** Regression line equations for estimating $PM_{10}$ concentration for fire events from 1 February to 30 April 2012 generated by using 2 variables including hotspot numbers and simulated $PM_{10}$ concentrations during 26 February and 1 March 2012

| Province | Date | Number of hotspots/ Averaged $PM_{10}$ concentration ($\mu g/m^3$) from all grid area by air quality model | | | Regression line equation (y = $PM_{10}$ concentration ($\mu g/m^3$), x = number of hotspots) | Regression analysis | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | High numbers of hotspots condition | Medium numbers of hotspots condition | Low numbers of hotspots condition | | Coefficient of determination ( $R^2$ ) | t-Stat | F-test | Significance F (P –value) |
| Chiang Mai | 26/02/2012 | 51/ 98.29 | 17/ 58.61 | 3/ 39.73 | y = 0.3848x + 43.1 | 0.7940 | 7.078 | 50.099 | 0.000 |
| | 27/02/2012 | 105/ 85.94 | 26/ 50.31 | 3/ 38.91 | | | | | |
| | 28/02/2012 | 202/ 124.92 | 52/ 39.76 | 6/ 39.76 | | | | | |
| | 29/02/2012 | 43/ 65.85 | 8/ 62.74 | 1/ 34.86 | | | | | |
| | 01/03/2012 | 220/ 121.54 | 41/ 42.93 | 0/ 42.93 | | | | | |
| Chiang Rai | 26/02/2012 | 16/ 88.31 | 3/ 52.13 | 0/ 37.62 | y = 0.638x + 44.625 | 0.8141 | 7.545 | 56.927 | 0.000 |
| | 27/02/2012 | 75/ 82.12 | 14/ 47.19 | 0/ 36.34 | | | | | |
| | 28/02/2012 | 95/ 106.36 | 10/ 43.1 | 0/ 43.1 | | | | | |
| | 29/02/2012 | 56/ 95.77 | 11/ 58.53 | 0/ 41.81 | | | | | |
| | 01/03/2012 | 117/ 115.53 | 17/ 42.81 | 0/ 42.81 | | | | | |
| Lampang | 26/02/2012 | 36/ 98.98 | 19/ 64.33 | 1/ 35.04 | y = 0.9564x + 38.493 | 0.7112 | 5.658 | 32.008 | 0.000 |
| | 27/02/2012 | 44/ 61.55 | 12/ 41.98 | 3/ 31.55 | | | | | |
| | 28/02/2012 | 110/ 139.8 | 33/ 40.44 | 4/ 40.44 | | | | | |
| | 29/02/2012 | 23/ 99.16 | 11/ 72.59 | 0/ 37.45 | | | | | |
| | 01/03/2012 | 87/ 135.99 | 35/ 40.85 | 4/ 40.85 | | | | | |
| Lamphun | 26/02/2012 | 12/ 85.78 | 4/ 56.56 | 0/ 41.4 | y = 1.4636x + 46.364 | 0.5825 | 4.259 | 18.139 | 0.001 |
| | 27/02/2012 | 31/ 59.68 | 11/ 46.86 | 4/ 36.92 | | | | | |
| | 28/02/2012 | 43/ 127.53 | 14/ 55.29 | 4/ 55.29 | | | | | |
| | 29/02/2012 | 0/ 52.35 | 0/ 79.35 | 0/ 34.8 | | | | | |
| | 01/03/2012 | 34/ 109.14 | 16/ 62.63 | 12/ 62.63 | | | | | |

| Province | Date | Number of hotspots/ Averaged $PM_{10}$ concentration ($\mu g/m^3$) from all grid area by air quality model | | | Regression line equation (y = $PM_{10}$ concentration ($\mu g/m^3$), x = number of hotspots) | Regression analysis | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | High numbers of hotspots condition | Medium numbers of hotspots condition | Low numbers of hotspots condition | | Coefficient of determination ( $R^2$ ) | t-Stat | F-test | Significance F (P –value) |
| Mae Hong Son | 26/02/2012 | 47/ 109.91 | 24/ 73.53 | 4/ 56.61 | y = 0.3558x + 48.726 | 0.4521 | 3.275 | 10.726 | 0.006 |
| | 27/02/2012 | 31/ 72.8 | 18/ 50.37 | 4/ 39.8 | | | | | |
| | 28/02/2012 | 132/ 94.65 | 57/ 42.64 | 5/ 42.64 | | | | | |
| | 29/02/2012 | 18/ 39.56 | 7/ 71.14 | 3/ 32.36 | | | | | |
| | 01/03/2012 | 152/ 105.34 | 69/ 54.74 | 19/ 54.74 | | | | | |
| Nan | 26/02/2012 | 24/ 80.53 | 8/ 45.81 | 0/ 34.3 | y = 0.804x + 35.917 | 0.7190 | 5.767 | 33.256 | 0.000 |
| | 27/02/2012 | 60/ 62.49 | 15/ 36.42 | 0/ 28.15 | | | | | |
| | 28/02/2012 | 92/ 83.89 | 22/ 32.71 | 1/ 32.71 | | | | | |
| | 29/02/2012 | 67/ 132.35 | 21/ 75.34 | 0/ 46.09 | | | | | |
| | 01/03/2012 | 132/ 150.75 | 36/ 42.77 | 5/ 42.77 | | | | | |
| Phayao | 26/02/2012 | 7/ 82.17 | 2/ 44.4 | 0/ 32.36 | y = 2.0147x + 35.799 | 0.7774 | 6.739 | 45.413 | 0.000 |
| | 27/02/2012 | 22/ 72.1 | 4/ 38.45 | 0/ 31.43 | | | | | |
| | 28/02/2012 | 45/ 109.75 | 8/ 35.67 | 0/ 35.67 | | | | | |
| | 29/02/2012 | 26/ 119.07 | 11/ 53.6 | 1/ 40.63 | | | | | |
| | 01/03/2012 | 31/ 105.62 | 8/ 34.26 | 0/ 34.26 | | | | | |
| Phrae | 26/02/2012 | 14/ 96.03 | 9/ 58.09 | 1/ 33.17 | y = 2.5434x + 35.618 | 0.7750 | 6.691 | 44.775 | 0.000 |
| | 27/02/2012 | 32/ 104.4 | 18/ 69.46 | 3/ 32.51 | | | | | |
| | 28/02/2012 | 32/ 90.95 | 6/ 36.85 | 1/ 36.85 | | | | | |
| | 29/02/2012 | 26/ 132.08 | 8/ 72.98 | 1/ 50.12 | | | | | |
| | 01/03/2012 | 34/ 137.17 | 12/ 47.42 | 4/ 47.42 | | | | | |

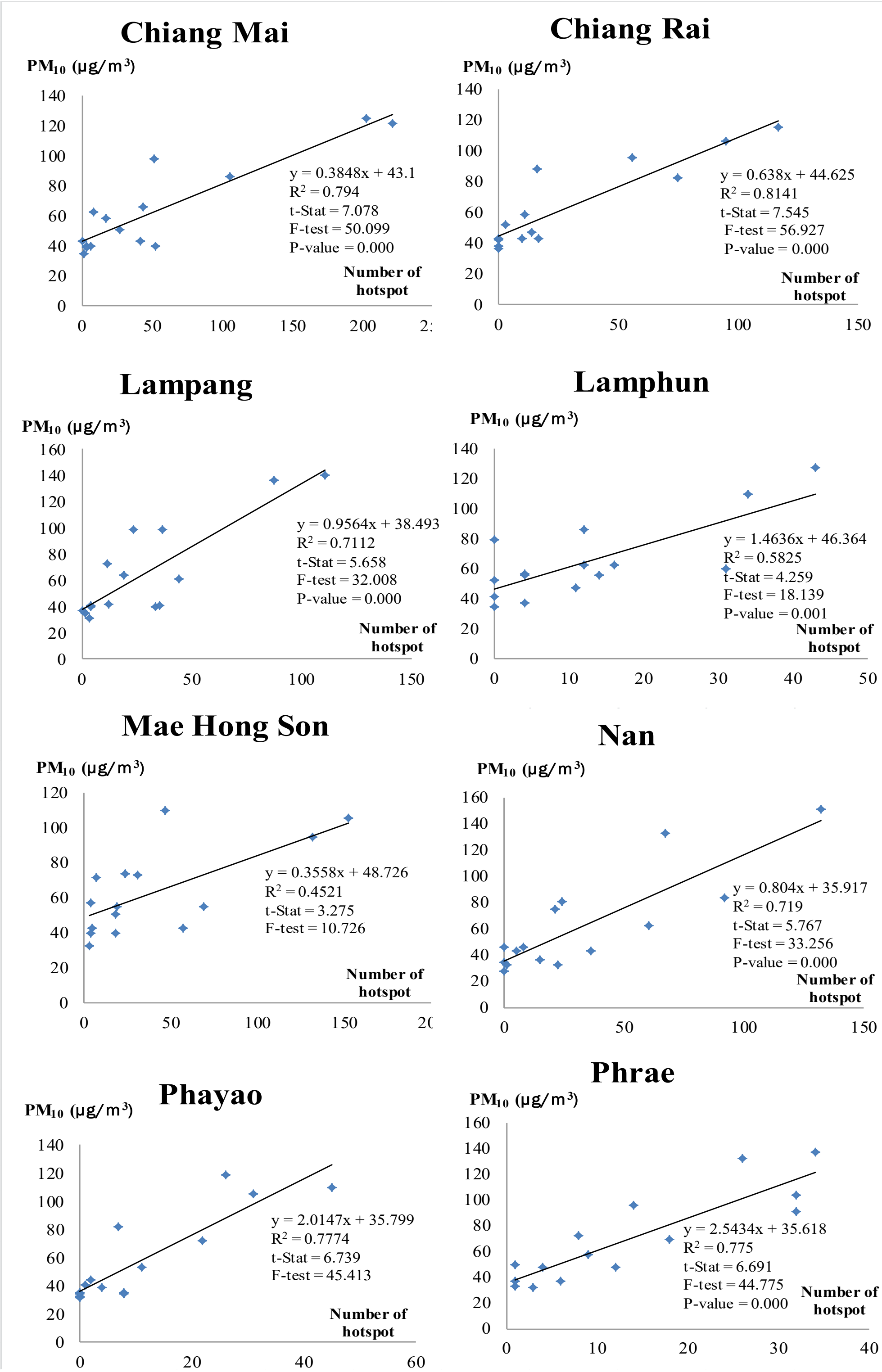



**Figure 4.2** Scatterplot graphs with trend line showing the relationship between hotspot numbers and simulated $PM_{10}$ concentrations during 26 February and 1 March 2012 and the square of the coefficient of determination ($R^2$), t-stat, F-test, and P-value

To estimate health impacts from fires, all $PM_{10}$ concentration values of provinces during 1 February to 30 April 2012 generated from regression equations were catalogued to the different range of pollutant levels; low, moderate, and very high by using Air Quality Index (AQI) (see Table 4.9). Generally, $PM_{10}$ concentrations of AQI related the health impacts and activity suggestions as follows.

- Low and good: enjoy your usual outdoor activities,
- Moderate: enjoy your usual outdoor activities but some sensitive groups should consider not to do outdoor activities,
- High, very high and unhealthy: some groups should consider reducing activity, particularly outdoors

**Table 4.9** The list of $PM_{10}$ concentrations range of Daily Air Quality Index **(**AQI**)** from Thailand, United Kingdom and United States including low, moderate, high and very high concentrations and people's health impacts **(**Pollution Control Department, 2016, Department for Environment Food & Rural Affairs, 2016, US EPA, 2016**).**

| Level of Air Quality Index | Thailand $PM_{10}$ (μg/m$^3$) | United Kingdom $PM_{10}$ (μg/m$^3$) | United States $PM_{10}$ (μg/m$^3$) | This study $PM_{10}$ (μg/m$^3$) |
|---|---|---|---|---|
| Low/ good | 0-40 | 0-50 | 0-54 | 0-20 and 0-50 |
| Moderate | 41-120 | 51-75 | 55-154 | 21-75 and 51-75 |
| High/ unhealthy | 121-350 | 76-100 | 155-254 | 76-100 |
| Very high/ unhealthy | | >101 | 255-354 | 101-120 and >121 |
| Very unhealthy | 351-420 | | 305-604 | |
| Hazardous | >421 | | >605 | |

The ranges of pollutant levels for this study are shown in Table 4.9 by considering threshold values at 20 and 50 μg/m$^3$ for health impacts. The numbers of illness cases were estimated from the change of $PM_{10}$ concentration from base line value at 20 and 50 μg/m$^3$ to the average values of each range. The hotspots numbers were used to estimate the average values of $PM_{10}$ concentration during 1 February to 31 April 2016 via linear equations in Table 4.8. The actual hotspots in this period were taken from National Aeronautics and Space Administration (NASA) (2014). The numbers of hotspots in agricultural area and forest areas within a range of 1 and 4 kilometres were identified by the GIS program. There were 11,007 hotspots during 1 February to 30 April 2012. This includes hotspots in agricultural area at around 2,211 hotspots, forest area around agricultural area ranging 1 km of about 5,157 hotspots, forest area around agricultural area ranging 2-4 km of about 3,069 hotspots, and forest area around agricultural area ranging > 4 km of about 570 hotspots (see Figure 4.3). The example of GIS results in Samoeng and Maewang districts of Chiang Mai are shown in Figure 4.4.

The average values of $PM_{10}$ concentration and the numbers of days for daily $PM_{10}$ average concentrations were calculated for three situations; actual fire events, fires controlled in agricultural and forest areas within a range of 1 and 4 kilometres as shown in Table 4.10, Table 4.11 and Table 4.12. The $PM_{10}$ from actual-fire situation was used all 11,007 hotspots for calculating the concentration. For the second situation, hot spot numbers of 3,069 and 570 in the forest area around agricultural area ranging 2-4 km and >4 km will be used as sources of $PM_{10}$ concentrations after fires controlled in agricultural and forest areas within a range of 1 kilometre. The last situation, the hotspots number of 570 in the forest area around agricultural area ranging >4 km will be used as sources of $PM_{10}$ concentrations after fires controlled in agricultural and forest areas within a range of 4 kilometre.

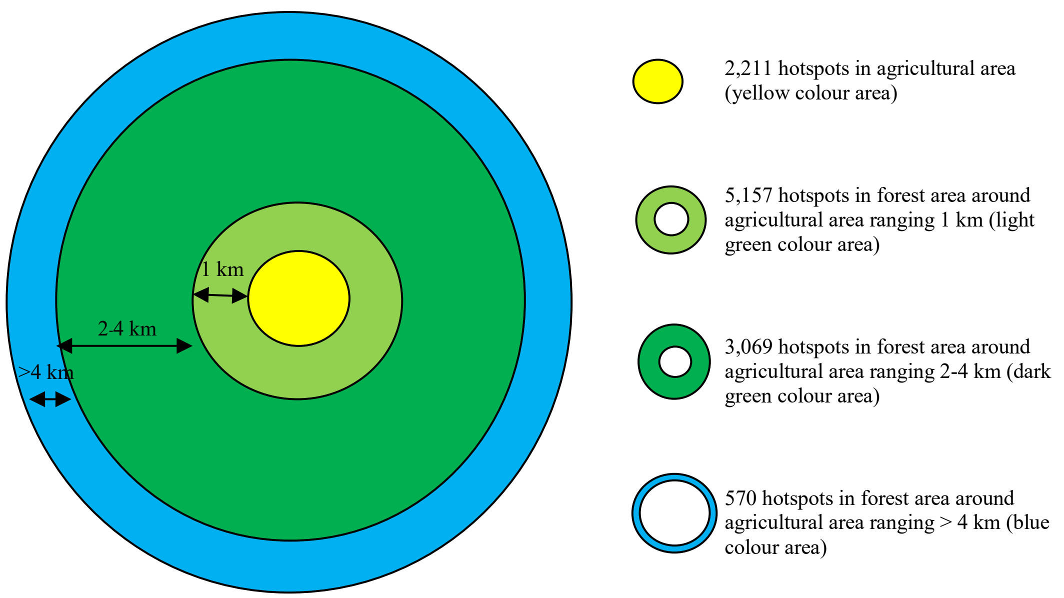
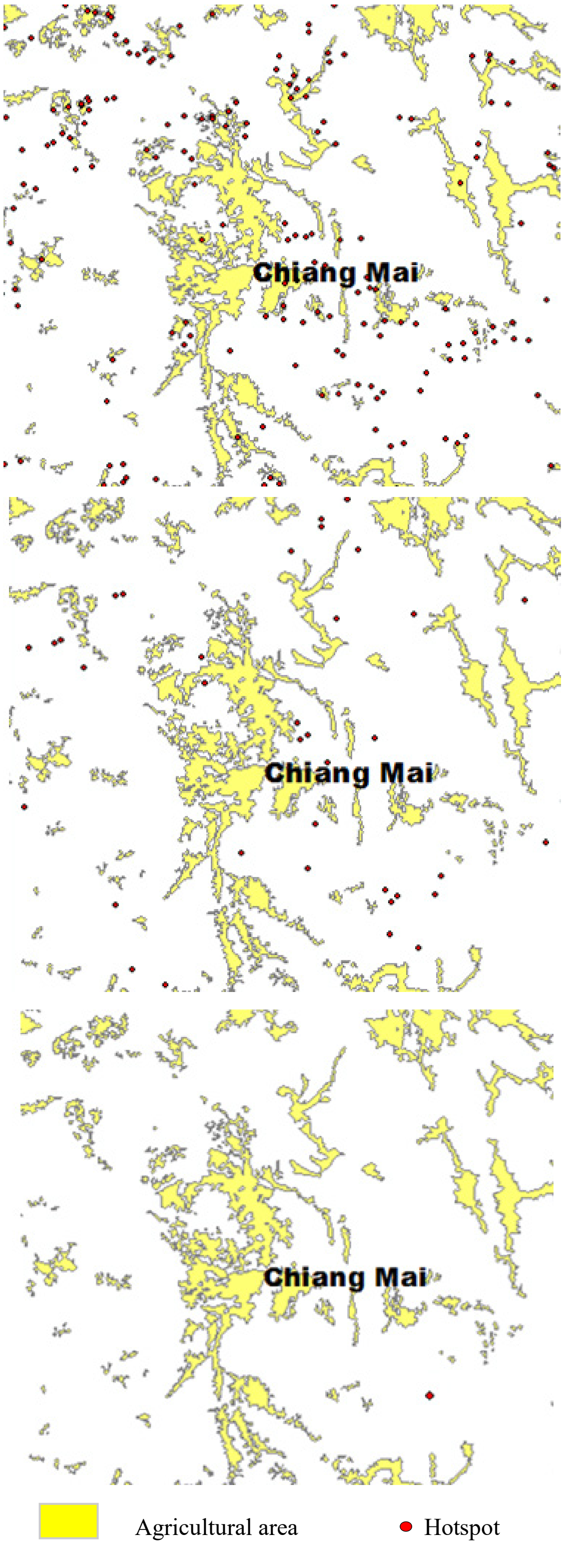



**Figure 4.3** The distribution of hotspots numbers in agricultural area, forest area around agricultural area ranging 1 km, 2-4 km and >4 km during 1 February to 30 April 2012**.**




(a) Actual fires

(b) Hotspot-locations after fires controlled in agricultural and forest areas within a range of 1 kilometre from agricultural area

(c) Hotspot-locations after fires controlled in agricultural and forest areas within a range of 4 kilometres from agricultural area

**Figure 4.4** The example of GIS results of hotspot-locations after fires controlled in agricultural area and forest areas within a range of 1 and 4 kilometres in Chiang Mai province during 1 February to 30 April 2012.

**Table 4.10** The average values of $PM_{10}$ concentration from actual fire events and number of days for daily $PM_{10}$ average concentrations in Chiang Mai, Chiang Rai, Lampang, Lamphun, Mae Hong Son, Nan, Phayao and Phrae during 1 February to 30 April 2012.

| Ranges of $PM_{10}$concentration ($\mu g/m^3$) | Averaged daily $PM_{10}$ concentration for each range ($\mu g/m^3$) / Number of days for daily $PM_{10}$ average concentrations | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Chiang Mai | Chiang Rai | Lampang | Lamphun | Mae Hong Son | Nan | Phayao | Phrae |
| 0-20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21-50 | 44/ 61 | 46/ 56 | 40/ 71 | 47/ 67 | 49/ 36 | 39/ 60 | 39/ 66 | 39/ 60 |
| 51-75 | 57/ 17 | 57/ 24 | 63/ 12 | 57/ 15 | 57/ 43 | 60/ 12 | 59/ 14 | 62/ 17 |
| 76-100 | 83/ 8 | 89/ 8 | 84/ 4 | 87/ 5 | 86/ 7 | 86/ 8 | 88/ 8 | 87/ 6 |
| 101-120 | 105/ 1 | 112/ 1 | 116/ 1 | 111/ 2 | 105/ 4 | 110/ 3 | 106/ 1 | 112/ 5 |
| >121 | 123/ 3 | 0/ 0 | 133/ 2 | 146/ 1 | 0/ 0 | 146/ 7 | 126/ 1 | 134/ 2 |
| Averaged $PM_{10}$/ Total (days) | 54/ 90 | 55/ 90 | 48/ 90 | 53/ 90 | 58/ 90 | 56/ 90 | 48/ 90 | 53/ 90 |

**Table 4.11** The average values of $PM_{10}$ concentration after fires controlled in agricultural and forest areas within a range of 1 kilometre and number of days for daily $PM_{10}$ average concentrations in Chiang Mai, Chiang Rai, Lampang, Lamphun, Mae Hong Son, Nan, Phayao and Phrae during 1 February to 30 April 2012.

| Ranges of $PM_{10}$ concentration ($\mu g/m^3$) | Averaged daily $PM_{10}$ concentration for each range ($\mu g/m^3$) / Number of days for daily $PM_{10}$ average concentrations | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Chiang Mai | Chiang Rai | Lampang | Lamphun | Mae Hong Son | Nan | Phayao | Phrae |
| 0-20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21-50 | 44/ 74 | 45/ 78 | 40/ 78 | 47/ 72 | 49/ 48 | 38/ 74 | 38/ 80 | 38/ 72 |
| 51-75 | 58/ 16 | 55/ 12 | 58/ 9 | 59/ 16 | 56/ 39 | 62/ 14 | 61/ 10 | 59/ 17 |
| 76-100 | 0/ 0 | 0/ 0 | 83/ 3 | 91/ 2 | 78/ 3 | 83/ 2 | 0/ 0 | 84/ 1 |
| 101-120 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 |
| >121 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 |
| Averaged $PM_{10}$/ Total (days) | 46/ 90 | 46/ 90 | 43/ 90 | 50/ 90 | 53/ 90 | 43/ 90 | 41/ 90 | 43/ 90 |

**Table 4.12** The average values of $PM_{10}$ concentration after fires controlled in agricultural and forest areas within a range of 4 kilometres and number of days for daily $PM_{10}$ average concentrations in Chiang Mai, Chiang Rai, Lampang, Lamphun, Mae Hong Son, Nan, Phayao and Phrae during 1 February to 30 April 2012**.**

| Ranges of $PM_{10}$ concentration (µg/m$^3$) | Averaged daily $PM_{10}$ concentration for each range (µg/m$^3$) / Number of days for daily $PM_{10}$ average concentrations | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Chiang Mai | Chiang Rai | Lampang | Lamphun | Mae Hong Son | Nan | Phayao | Phrae |
| 0-20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21-50 | 43/ 90 | 45/ 90 | 39/ 90 | 47/ 82 | 49/ 68 | 36/ 90 | 37/ 90 | 37/ 90 |
| 51-75 | 0/ 0 | 0/ 0 | 0/ 0 | 56/ 8 | 52/ 22 | 0/ 0 | 0/ 0 | 0/ 0 |
| 76-100 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 |
| 101-120 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 |
| >121 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 |
| Averaged $PM_{10}$/ Total (days) | 43/ 90 | 45/ 90 | 39/ 90 | 47/ 90 | 50/ 90 | 36/ 90 | 37/ 90 | 37/ 90 |

The average values of $PM_{10}$ concentration and number of days for daily $PM_{10}$ average from Table 4.10, Table 4.11 and Table 4.12 concentrations were used to estimate the mortality and illness cases. The actual fires during 1 February to 30 April 2012 may be causes of the mortality, respiratory and cardiovascular hospital admissions and respiratory outpatients as 100 persons, 331 and 382 admissions, and 7,689 outpatient visits for comparing with baseline value at 50 µg/m$^3$ and 435 persons, 1,401 and 1,645 admissions, and 31,039 outpatient visits for comparing with baseline value at 20 µg/m$^3$. The number of deaths and illnesses for each province are shown in Table 4.13. The total estimated number of mortality, respiratory and cardiovascular hospital admissions and respiratory outpatients before and after fire controlled are shown in Table 4.14 and Table 4.15.

After fire controlled in target areas including agricultural area and near agricultural areas within 1 km and 4 km, which were simulated as no fire areas by government measures, were calculated for the numbers of illness cases. The total estimated number of mortality, respiratory and cardiovascular hospital admissions and respiratory outpatients for 1 km fire controlled are 21 persons, 70 and 81 admissions, and 2,267 outpatient visits for comparing with baseline value at 50 µg/m$^3$ and 337 persons, 1,074 and 1,265 admissions, and 24,306 outpatient visits for comparing with baseline value at 20 µg/m$^3$. In addition, the total estimated number of mortality, respiratory and cardiovascular hospital admissions and respiratory outpatients for 4 km fire controlled are 1 persons, 2 and 3 admissions, and 664 outpatient visits for comparing with baseline value at 50 μg/m$^3$ and 290 persons, 916 and 1,086 admissions, and 21,185 outpatient visits for comparing with baseline value at 20 μg/m$^3$. Results showed that Chiang Mai province had the greatest mortality and illness numbers following by Chiang Rai province both before and after fire controlled. These are related to population numbers in each province, of which Chiang Mai had the greater.

However, in the situation without a fire (hotspot number = 0) in the north of Thailand, the number of deaths and illnesses still occur comparing with baseline value at 20 μg/m$^3$ as shown in Table 4.16. The background $PM_{10}$ (average value for all area ~21 μg/m$^3$), transboundary $PM_{10}$ from neighbouring countries and the lower part of Thailand are sources of $PM_{10}$ as the variable ‘a’ value at 35.618 to 48.726 in the regression line equation $y = a+bx$ (see Table 4.8).

**Table 4.13** Summary of estimated deaths, hospital admissions for respiratory and cardiovascular illness, and respiratory outpatient visits caused by $PM_{10}$ concentration increase from actual fires during 1 February to 30 April 2012 in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae provinces

| Province | Number of population | Averaged $PM_{10}$ in study area for each range ($\mu g/m^3$) | $PM_{10}$ increase ($\mu g/m^3$) from baseline | Number of days for daily $PM_{10}$ average concentrations | Actually natural mortality rate per 1,000 cases/year | New % increased risk from $PM_{10}$ change | Estimated death numbers from $PM_{10}$ change | Cardiovascular hospital admission rate per 1,000cases/ year | New % increased risk from $PM_{10}$ change | Estimated cardiovascular hospital admissions from $PM_{10}$ change | Respiratory hospital admission rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated respiratory hospital admissions from $PM_{10}$ change | Respiratory outpatient visit rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated outpatient visits from $PM_{10}$ change |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | |
| Chiang Mai | 1,655,640 | 44 | 24 | 61 | 7.5 | 3.15 | 65 | 35.8 | 2.20 | 217 | 31.2 | 3.00 | 259 | 543.1 | 3.15 | 4,728 |
| | | 57 | 37 | 17 | | 4.90 | 28 | | 3.41 | 94 | | 4.67 | 112 | | 4.90 | 2,049 |
| | | 83 | 63 | 8 | | 8.48 | 23 | | 5.87 | 76 | | 8.07 | 91 | | 8.48 | 1,669 |
| | | 105 | 85 | 1 | | 11.60 | 4 | | 8.00 | 13 | | 11.04 | 16 | | 11.60 | 286 |
| | | 123 | 103 | 3 | | 14.23 | 15 | | 9.78 | 48 | | 13.53 | 58 | | 14.23 | 1,051 |
| | | | | | Total | | 135 | | | 448 | | | 536 | | | 9,783 |
| | | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | |
| | | 57 | 7 | 17 | | 0.91 | 5 | | 0.64 | 18 | | 0.87 | 21 | | 0.91 | 380 |
| | | 83 | 33 | 8 | | 4.35 | 12 | | 3.03 | 40 | | 4.15 | 47 | | 4.35 | 858 |
| | | 105 | 55 | 1 | | 7.36 | 3 | | 5.11 | 8 | | 7.01 | 10 | | 7.36 | 181 |
| | | 123 | 73 | 3 | | 9.89 | 10 | | 6.84 | 33 | | 9.41 | 40 | | 9.89 | 730 |
| | | | | | Total | | 30 | | | 99 | | | 118 | | | 2,149 |
| | | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | |
| Chiang Rai | 1,200,423 | 46 | 26 | 56 | 6.7 | 3.42 | 42 | 28.1 | 2.38 | 123 | 25.3 | 3.26 | 152 | 524.9 | 3.42 | 3,2949 |
| | | 57 | 37 | 24 | | 4.90 | 26 | | 3.41 | 75 | | 4.67 | 93 | | 4.90 | 2,027 |
| | | 89 | 69 | 8 | | 9.32 | 16 | | 6.45 | 48 | | 8.88 | 59 | | 9.32 | 1,286 |
| | | 112 | 92 | 1 | | 12.62 | 3 | | 8.69 | 8 | | 12.01 | 10 | | 12.62 | 218 |
| | | | | | Total | | 87 | | | 254 | | | 314 | | | 6,830 |
| | | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | |
| | | 57 | 7 | 24 | | 0.91 | 5 | | 0.64 | 14 | | 0.87 | 17 | | 0.91 | 376 |
| | | 89 | 39 | 8 | | 5.17 | 9 | | 3.60 | 27 | | 4.92 | 33 | | 5.17 | 713 |
| | | 112 | 62 | 1 | | 8.34 | 2 | | 5.78 | 5 | | 7.94 | 7 | | 8.34 | 144 |
| | | | | | Total | | 16 | | | 46 | | | 57 | | | 1,233 |

| Province | Number of population | Averaged $PM_{10}$ in study area for each range ($\mu g/m^3$) | $PM_{10}$ increase ($\mu g/m^3$) from baseline | Number of days for daily $PM_{10}$ average concentrations | Actually natural mortality rate per 1,000 cases/year | New % increased risk from $PM_{10}$ change | Estimated death numbers from $PM_{10}$ change | Cardiovascular hospital admission rate per 1,000cases/ year | New % increased risk from $PM_{10}$ change | Estimated cardiovascular hospital admissions from $PM_{10}$ change | Respiratory hospital admission rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated respiratory hospital admissions from $PM_{10}$ change | Respiratory outpatient visit rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated outpatient visits from $PM_{10}$ change |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Lampang | 756,811 | 40 | 20 | 71 | 8.1 | 2.62 | 31 | 38.4 | 1.83 | 104 | 29.6 | 2.50 | 109 | 486.1 | 2.62 | 1,871 |
| | | 63 | 43 | 12 | | 5.71 | 12 | | 3.97 | 38 | | 5.44 | 40 | | 5.71 | 690 |
| | | 84 | 64 | 4 | | 8.62 | 6 | | 5.97 | 19 | | 8.21 | 20 | | 8.62 | 347 |
| | | 116 | 96 | 1 | | 13.20 | 2 | | 9.09 | 7 | | 12.56 | 8 | | 13.20 | 133 |
| | | 133 | 113 | 2 | | 15.71 | 5 | | 10.78 | 17 | | 14.94 | 18 | | 15.71 | 317 |
| | | | | | Total | | 56 | | | 185 | | | 195 | | | 3,358 |
| | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | | |
| | | 63 | 13 | 12 | | 1.69 | 3 | | 1.18 | 11 | | 1.61 | 12 | | 1.69 | 205 |
| | | 84 | 34 | 4 | | 4.49 | 3 | | 3.13 | 10 | | 4.28 | 11 | | 4.49 | 181 |
| | | 116 | 66 | 1 | | 8.90 | 2 | | 6.16 | 5 | | 8.47 | 5 | | 8.90 | 89 |
| | | 133 | 83 | 2 | | 11.32 | 4 | | 7.81 | 13 | | 10.77 | 13 | | 11.32 | 228 |
| | | | | | Total | | 12 | | | 39 | | | 41 | | | 703 |
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Lamphun | 404,673 | 47 | 27 | 67 | 8.2 | 3.55 | 21 | 27.6 | 2.48 | 51 | 25.4 | 3.38 | 64 | 623.6 | 3.55 | 1,643 |
| | | 57 | 37 | 15 | | 4.90 | 7 | | 3.41 | 16 | | 4.67 | 20 | | 4.90 | 507 |
| | | 87 | 67 | 5 | | 9.04 | 4 | | 6.26 | 9 | | 8.61 | 12 | | 9.04 | 312 |
| | | 111 | 91 | 2 | | 12.47 | 2 | | 8.59 | 5 | | 11.87 | 6 | | 12.47 | 173 |
| | | 146 | 126 | 1 | | 17.67 | 2 | | 12.09 | 4 | | 16.80 | 5 | | 17.67 | 122 |
| | | | | | Total | | 36 | | | 85 | | | 107 | | | 2,757 |
| | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | | |
| | | 57 | 7 | 15 | | 0.91 | 1 | | 0.64 | 3 | | 0.87 | 4 | | 0.91 | 94 |
| | | 87 | 37 | 5 | | 4.90 | 2 | | 3.41 | 5 | | 4.67 | 7 | | 4.90 | 169 |
| | | 111 | 61 | 2 | | 8.20 | 2 | | 5.68 | 3 | | 7.81 | 4 | | 8.20 | 114 |
| | | 146 | 96 | 1 | | 13.20 | 1 | | 9.09 | 3 | | 12.56 | 3 | | 13.20 | 91 |
| | | | | | Total | | 6 | | | 14 | | | 18 | | | 468 |

| Province | Number of population | Averaged $PM_{10}$ in study area for each range ($\mu g/m^3$) | $PM_{10}$ increase ($\mu g/m^3$) from baseline | Number of days for daily $PM_{10}$ average concentrations | Actually natural mortality rate per 1,000 cases/year | New % increased risk from $PM_{10}$ change | Estimated death numbers from $PM_{10}$ change | Cardiovascular hospital admission rate per 1,000cases/ year | New % increased risk from $PM_{10}$ change | Estimated cardiovascular hospital admissions from $PM_{10}$ change | Respiratory hospital admission rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated respiratory hospital admissions from $PM_{10}$ change | Respiratory outpatient visit rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated outpatient visits from $PM_{10}$ change |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Mae Hong Son | 244,356 | 49 | 29 | 36 | 4.5 | 3.82 | 4 | 16.1 | 2.66 | 10 | 26.7 | 3.64 | 23 | 710.5 | 3.82 | 653 |
| | | 57 | 37 | 43 | | 4.90 | 6 | | 3.41 | 16 | | 4.67 | 36 | | 4.90 | 1,000 |
| | | 86 | 66 | 7 | | 8.90 | 2 | | 6.16 | 5 | | 8.47 | 11 | | 8.90 | 296 |
| | | 105 | 85 | 4 | | 11.60 | 2 | | 8.00 | 3 | | 11.04 | 8 | | 11.60 | 221 |
| | | | | | Total | | 14 | | | 34 | | | 78 | | | 2,170 |
| | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | | |
| | | 57 | 7 | 43 | | 0.91 | 1 | | 0.64 | 3 | | 0.87 | 6 | | 0.91 | 186 |
| | | 86 | 36 | 7 | | 4.76 | 1 | | 3.31 | 3 | | 4.54 | 6 | | 4.76 | 158 |
| | | 105 | 55 | 4 | | 7.36 | 1 | | 5.11 | 2 | | 7.01 | 5 | | 7.36 | 140 |
| | | | | | Total | | 3 | | | 8 | | | 17 | | | 484 |
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Nan | 447,193 | 39 | 19 | 60 | 6.0 | 2.48 | 11 | 44.3 | 1.74 | 56 | 33.7 | 2.37 | 59 | 258.1 | 2.48 | 471 |
| | | 60 | 40 | 12 | | 5.30 | 5 | | 3.69 | 24 | | 5.05 | 25 | | 5.30 | 201 |
| | | 86 | 66 | 8 | | 8.90 | 5 | | 6.16 | 27 | | 8.47 | 28 | | 8.90 | 225 |
| | | 110 | 90 | 3 | | 12.33 | 3 | | 8.49 | 14 | | 11.73 | 15 | | 12.33 | 117 |
| | | 146 | 126 | 7 | | 17.67 | 9 | | 12.09 | 46 | | 16.80 | 48 | | 17.67 | 391 |
| | | | | | Total | | 33 | | | 167 | | | 175 | | | 1,405 |
| | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | | |
| | | 60 | 10 | 12 | | 1.30 | 1 | | 0.91 | 6 | | 1.24 | 6 | | 1.30 | 49 |
| | | 86 | 36 | 8 | | 4.76 | 3 | | 3.31 | 14 | | 4.54 | 15 | | 4.76 | 120 |
| | | 110 | 60 | 3 | | 8.06 | 2 | | 5.59 | 9 | | 7.67 | 10 | | 8.06 | 77 |
| | | 146 | 96 | 7 | | 13.20 | 7 | | 9.09 | 35 | | 12.56 | 36 | | 13.20 | 292 |
| | | | | | Total | | 13 | | | 64 | | | 67 | | | 538 |

| Province | Number of population | Averaged $PM_{10}$ in study area for each range ($\mu g/m^3$) | $PM_{10}$ increase ($\mu g/m^3$) from baseline | Number of days for daily $PM_{10}$ average concentrations | Actually natural mortality rate per 1,000 cases/year | New % increased risk from $PM_{10}$ change | Estimated death numbers from $PM_{10}$ change | Cardiovascular hospital admission rate per 1,000cases/ year | New % increased risk from $PM_{10}$ change | Estimated cardiovascular hospital admissions from $PM_{10}$ change | Respiratory hospital admission rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated respiratory hospital admissions from $PM_{10}$ change | Respiratory outpatient visit rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated outpatient visits from $PM_{10}$ change |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Phayao | 488,120 | 39 | 19 | 66 | 7.4 | 2.48 | 16 | 33.2 | 1.74 | 51 | 28 | 2.37 | 59 | 535.9 | 2.48 | 1,175 |
| | | 59 | 39 | 14 | | 5.17 | 7 | | 3.60 | 22 | | 4.92 | 26 | | 5.17 | 518 |
| | | 88 | 68 | 8 | | 9.18 | 7 | | 6.35 | 23 | | 8.74 | 26 | | 9.18 | 526 |
| | | 106 | 86 | 1 | | 11.75 | 1 | | 8.10 | 4 | | 11.18 | 4 | | 11.75 | 84 |
| | | 126 | 106 | 1 | | 14.67 | 1 | | 10.08 | 4 | | 13.95 | 5 | | 14.67 | 105 |
| | | | | | Total | | 33 | | | 104 | | | 120 | | | 2,408 |
| | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | | |
| | | 59 | 9 | 14 | | 1.17 | 1 | | 0.82 | 5 | | 1.12 | 6 | | 1.17 | 117 |
| | | 88 | 38 | 8 | | 5.03 | 4 | | 3.50 | 13 | | 4.79 | 14 | | 5.03 | 288 |
| | | 106 | 56 | 1 | | 7.50 | 1 | | 5.20 | 2 | | 7.15 | 3 | | 7.50 | 54 |
| | | 126 | 76 | 1 | | 10.31 | | | 7.13 | 3 | | 9.82 | 4 | | 10.31 | 74 |
| | | | | | Total | | 7 | | | 23 | | | 27 | | | 533 |
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Phrae | 457,607 | 39 | 19 | 60 | 8.4 | 2.48 | 15 | 36.4 | 1.74 | 47 | 25.6 | 2.37 | 46 | 472.9 | 2.48 | 883 |
| | | 62 | 42 | 17 | | 5.57 | 10 | | 3.88 | 30 | | 5.31 | 29 | | 5.57 | 562 |
| | | 87 | 67 | 6 | | 9.04 | 6 | | 6.26 | 17 | | 8.61 | 16 | | 9.04 | 321 |
| | | 112 | 92 | 5 | | 12.62 | 7 | | 8.69 | 20 | | 12.01 | 19 | | 12.62 | 374 |
| | | 134 | 114 | 2 | | 15.86 | 3 | | 10.88 | 10 | | 15.08 | 10 | | 15.86 | 188 |
| | | | | | Total | | 41 | | | 124 | | | 120 | | | 2,328 |
| | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | | |
| | | 62 | 12 | 17 | | 1.56 | 3 | | 1.09 | 9 | | 1.49 | 8 | | 1.56 | 157 |
| | | 87 | 37 | 6 | | 4.90 | 3 | | 3.41 | 9 | | 4.67 | 9 | | 4.90 | 174 |
| | | 112 | 62 | 5 | | 8.34 | 4 | | 5.78 | 13 | | 7.94 | 13 | | 8.34 | 247 |
| | | 134 | 84 | 2 | | 11.46 | 3 | | 7.91 | 7 | | 10.91 | 7 | | 11.46 | 136 |
| | | | | | Total | | 13 | | | 38 | | | 37 | | | 714 |

**Table 4.14** Summary of estimated deaths, hospital admissions for respiratory and cardiovascular illness, and respiratory outpatient visits caused by $PM_{10}$ concentration increase after government intervention by fires controlled in agricultural and forest areas within a range of 1 km during 1 February to 30 April 2012 in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae provinces

| Province | Number of population | Averaged $PM_{10}$ in study area for each range ($\mu g/m^3$) | $PM_{10}$ increase ($\mu g/m^3$) from baseline | Number of days for daily $PM_{10}$ average concentrations | Actually natural mortality rate per 1,000 cases/year | New % increased risk from $PM_{10}$ change | Estimated death numbers from $PM_{10}$ change | Cardiovascular hospital admission rate per 1,000cases/ year | New % increased risk from $PM_{10}$ change | Estimated cardiovascular hospital admissions from $PM_{10}$ change | Respiratory hospital admission rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated respiratory hospital admissions from $PM_{10}$ change | Respiratory outpatient visit rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated outpatient visits from $PM_{10}$ change |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Chiang Mai | 1,655,640 | 44 | 24 | 74 | 7.5 | 3.15 | 79 | 35.8 | 2.20 | 264 | 31.2 | 3.00 | 314 | 543.1 | 3.15 | 5,736 |
| | | 58 | 38 | 16 | | 5.03 | 28 | | 3.50 | 91 | | 4.79 | 109 | | 5.03 | 1,981 |
| | | | | | Total | | 107 | | | 355 | | | 423 | | | 7,717 |
| | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | | |
| | | 58 | 8 | 16 | | 1.04 | 6 | | 0.73 | 19 | | 0.99 | 22 | | 1.04 | 409 |
| | | | | | Total | | 6 | | | 19 | | | 22 | | | 409 |
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Chiang Rai | 1,200,423 | 45 | 25 | 78 | 6.7 | 3.28 | 57 | 28.1 | 2.29 | 165 | 25.3 | 3.13 | 203 | 524.9 | 3.28 | 4,416 |
| | | 55 | 35 | 12 | | 4.62 | 12 | | 3.22 | 36 | | 4.41 | 44 | | 4.62 | 9567 |
| | | | | | Total | | 69 | | | 201 | | | 247 | | | 5,373 |
| | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | | |
| | | 55 | 5 | 12 | | 0.65 | 2 | | 0.45 | 5 | | 0.62 | 6 | | 0.65 | 134 |
| | | | | | Total | | 2 | | | 5 | | | 6 | | | 134 |
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Lampang | 756,811 | 40 | 20 | 78 | 8.1 | 2.62 | 34 | 38.4 | 1.83 | 114 | 29.6 | 2.50 | 119 | 486.1 | 2.62 | 2,056 |
| | | 58 | 38 | 9 | | 5.03 | 8 | | 3.50 | 25 | | 4.79 | 27 | | 5.03 | 456 |
| | | 83 | 63 | 3 | | 8.48 | 4 | | 5.87 | 14 | | 8.07 | 15 | | 8.48 | 256 |
| | | | | | Total | | 46 | | | 153 | | | 161 | | | 2,768 |
| | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | | |
| | | 58 | 8 | 9 | | 1.04 | 2 | | 0.73 | 5 | | 0.99 | 5 | | 1.04 | 94 |
| | | 83 | 33 | 3 | | 4.35 | 2 | | 3.03 | 7 | | 4.15 | 8 | | 4.35 | 132 |
| | | | | | Total | | 4 | | | 12 | | | 13 | | | 226 |

| Province | Number of population | Averaged $PM_{10}$ in study area for each range ($\mu g/m^3$) | $PM_{10}$ increase ($\mu g/m^3$) from baseline | Number of days for daily $PM_{10}$ average concentrations | Actually natural mortality rate per 1,000 cases/year | New % increased risk from $PM_{10}$ change | Estimated death numbers from $PM_{10}$ change | Cardiovascular hospital admission rate per 1,000cases/ year | New % increased risk from $PM_{10}$ change | Estimated cardiovascular hospital admissions from $PM_{10}$ change | Respiratory hospital admission rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated respiratory hospital admissions from $PM_{10}$ change | Respiratory outpatient visit rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated outpatient visits from $PM_{10}$ change |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Lamphun | 404,673 | 47 | 27 | 72 | 8.2 | 3.55 | 23 | 27.6 | 2.48 | 54 | 25.4 | 3.38 | 69 | 623.6 | 3.55 | 1,765 |
| | | 59 | 39 | 16 | | 5.17 | 7 | | 3.60 | 18 | | 4.92 | 22 | | 5.17 | 571 |
| | | 91 | 71 | 2 | | 9.60 | 2 | | 6.64 | 4 | | 9.14 | 5 | | 9.60 | 133 |
| | | | | | Total | | 32 | | | 76 | | | 36 | | | 2,469 |
| | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | | |
| | | 59 | 9 | 16 | | 1.17 | 2 | | 0.82 | 4 | | 1.12 | 5 | | 1.17 | 129 |
| | | 91 | 41 | 2 | | 5.44 | 1 | | 3.78 | 2 | | 5.18 | 3 | | 5.44 | 75 |
| | | | | | Total | | 3 | | | 6 | | | 8 | | | 204 |
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Mae Hong Son | 244,356 | 49 | 29 | 48 | 4.5 | 3.82 | 5 | 16.1 | 2.66 | 13 | 26.7 | 3.64 | 31 | 710.5 | 3.82 | 871 |
| | | 56 | 36 | 39 | | 4.76 | 6 | | 3.31 | 14 | | 4.54 | 32 | | 4.76 | 882 |
| | | 78 | 58 | 3 | | 7.78 | 1 | | 5.39 | 2 | | 7.41 | 4 | | 7.78 | 111 |
| | | | | | Total | | 12 | | | 29 | | | 67 | | | 1,814 |
| | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | | |
| | | 56 | 6 | 39 | | 0.78 | 1 | | 0.55 | 0 | | 0.74 | 5 | | 0.78 | 144 |
| | | 78 | 28 | 3 | | 3.68 | 0 | | 2.57 | 0 | | 3.51 | 2 | | 3.68 | 53 |
| | | | | | Total | | 1 | | | 0 | | | 7 | | | 197 |
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Nan | 447,193 | 38 | 18 | 74 | 6.0 | 2.35 | 13 | 44.3 | 1.64 | 66 | 33.7 | 2.24 | 68 | 258.1 | 2.35 | 550 |
| | | 62 | 42 | 14 | | 5.57 | 6 | | 3.88 | 30 | | 5.31 | 31 | | 5.57 | 247 |
| | | 83 | 63 | 2 | | 8.48 | 1 | | 5.87 | 6 | | 8.07 | 7 | | 8.48 | 53 |
| | | | | | Total | | 20 | | | 102 | | | 106 | | | 850 |
| | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | | |
| | | 62 | 12 | 14 | | 1.56 | 1 | | 1.09 | 9 | | 1.49 | 9 | | 1.56 | 69 |
| | | 83 | 33 | 2 | | 4.35 | 1 | | 3.03 | 3 | | 4.15 | 3 | | 4.35 | 28 |
| | | | | | Total | | 2 | | | 12 | | | 12 | | | 97 |

| Province | Number of population | Averaged $PM_{10}$ in study area for each range ($\mu g/m^3$) | $PM_{10}$ increase ($\mu g/m^3$) from baseline | Number of days for daily $PM_{10}$ average concentrations | Actually natural mortality rate per 1,000 cases/year | New % increased risk from $PM_{10}$ change | Estimated death numbers from $PM_{10}$ change | Cardiovascular hospital admission rate per 1,000cases/ year | New % increased risk from $PM_{10}$ change | Estimated cardiovascular hospital admissions from $PM_{10}$ change | Respiratory hospital admission rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated respiratory hospital admissions from $PM_{10}$ change | Respiratory outpatient visit rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated outpatient visits from $PM_{10}$ change |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Phayao | 488,120 | 38 | 18 | 80 | 7.4 | 2.35 | 19 | 33.2 | 1.64 | 58 | 28.0 | 2.24 | 67 | 535.9 | 2.35 | 1,348 |
| | | 61 | 41 | 10 | | 5.44 | 5 | | 3.78 | 17 | | 5.18 | 20 | | 5.44 | 389 |
| | | | | | Total | | 24 | | | 75 | | | 87 | | | 1,737 |
| | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | | |
| | | 61 | 11 | 10 | | 1.43 | 1 | | 1.00 | 4 | | 1.36 | 5 | | 1.43 | 102 |
| | | | | | Total | | 1 | | | 4 | | | 5 | | | 102 |
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Phrae | 457,607 | 38 | 18 | 72 | 8.4 | 2.35 | 18 | 36.4 | 1.64 | 54 | 25.6 | 2.24 | 52 | 472.9 | 2.35 | 1,004 |
| | | 59 | 39 | 17 | | 5.17 | 9 | | 3.60 | 28 | | 4.92 | 27 | | 5.17 | 520 |
| | | 84 | 64 | 1 | | 8.62 | 1 | | 5.97 | 3 | | 8.21 | 2 | | 8.62 | 51 |
| | | | | | Total | | 28 | | | 85 | | | 81 | | | 1,575 |
| | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | | |
| | | 59 | 9 | 17 | | 1.17 | 2 | | 0.82 | 6 | | 1.12 | 6 | | 1.17 | 118 |
| | | 84 | 34 | 1 | | 4.49 | 1 | | 3.13 | 2 | | 4.28 | 1 | | 4.49 | 26 |
| | | | | | Total | | 3 | | | 8 | | | 7 | | | 144 |

**Table 4.15** Summary of estimated deaths, hospital admissions for respiratory and cardiovascular illness, and respiratory outpatient visits caused by $PM_{10}$ concentration increase after government intervention by fires controlled in agricultural and forest areas within a range of 4 km from actual fires during 1 February to 30 April 2012 in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae provinces

| Province | Number of population | Averaged $PM_{10}$ in study area for each range ($\mu g/m^3$) | $PM_{10}$ increase ($\mu g/m^3$) from baseline | Number of days for daily $PM_{10}$ average concentrations | Actually natural mortality rate per 1,000 cases/year | New % increased risk from $PM_{10}$ change | Estimated death numbers from $PM_{10}$ change | Cardiovascular hospital admission rate per 1,000cases/ year | New % increased risk from $PM_{10}$ change | Estimated cardiovascular hospital admissions from $PM_{10}$ change | Respiratory hospital admission rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated respiratory hospital admissions from $PM_{10}$ change | Respiratory outpatient visit rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated outpatient visits from $PM_{10}$ change |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Chiang Mai | 1,655,640 | 43 | 23 | 90 | 7.5 | 3.02 | 92 | 35.8 | 2.11 | 307 | 31.2 | 2.88 | 366 | 543.1 | 3.02 | 6,681 |
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Chiang Rai | 1,200,423 | 45 | 25 | 90 | 6.7 | 3.28 | 65 | 28.1 | 2.29 | 190 | 25.3 | 3.13 | 234 | 524.9 | 3.28 | 5,095 |
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Lampang | 756,811 | 39 | 19 | 90 | 8.1 | 2.48 | 38 | 38.4 | 1.74 | 124 | 29.6 | 2.37 | 131 | 486.1 | 2.48 | 2,252 |
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Lamphun | 404,673 | 47 | 27 | 82 | 8.2 | 3.55 | 26 | 27.6 | 2.48 | 62 | 25.4 | 3.38 | 78 | 623.6 | 3.55 | 2,011 |
| | | 56 | 36 | 8 | | 4.76 | 4 | | 3.31 | 8 | | 4.54 | 10 | | 4.76 | 263 |
| | | | | | Total | | 30 | | | 70 | | | 88 | | | 2,274 |
| | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | | |
| | | 56 | 6 | 8 | | 0.78 | 1 | | 0.55 | 1 | | 0.74 | 2 | | 0.78 | 43 |
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Mae Hong Son | 244,356 | 49 | 29 | 68 | 4.5 | 3.82 | 8 | 16.1 | 2.66 | 19 | 26.7 | 3.64 | 44 | 710.5 | 3.82 | 1,234 |
| | | 52 | 32 | 22 | | 4.22 | 3 | | 2.94 | 7 | | 4.02 | 16 | | 4.22 | 441 |
| | | | | | Total | | 11 | | | 26 | | | 60 | | | 1,675 |
| | | | $PM_{10}$ increase from baseline at 50 $\mu g/m^3$ | | | | | | | | | | | | | |
| | | 52 | 2 | 22 | | 0.26 | 0 | | 0.18 | 0 | | 0.25 | 1 | | 0.26 | 27 |
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Nan | 447,193 | 36 | 16 | 90 | 6.0 | 2.09 | 14 | 44.3 | 1.46 | 71 | 33.7 | 1.99 | 74 | 258.1 | 2.09 | 594 |
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Phayao | 488,120 | 37 | 17 | 90 | 7.4 | 2.22 | 20 | 33.2 | 1.55 | 62 | 28.0 | 2.12 | 71 | 535.9 | 2.22 | 1,431 |
| | | | $PM_{10}$ increase from baseline at 20 $\mu g/m^3$ | | | | | | | | | | | | | |
| Phrae | 457,607 | 37 | 17 | 90 | 8.4 | 2.22 | 21 | 36.4 | 1.55 | 64 | 25.6 | 2.12 | 61 | 472.9 | 2.22 | 1,184 |

**Table 4.16** Summary of estimated deaths, hospital admissions for respiratory and cardiovascular illness, and respiratory outpatient visits caused by $PM_{10}$ concentration increase for the no-fire situation during 1 February to 30 April 2012 in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae provinces

| Province | Number of population | Averaged $PM_{10}$ in study area for each range (µg/m$^3$) | $PM_{10}$ increase (µg/m$^3$) from baseline | Number of days for daily $PM_{10}$ average concentrations | Actually natural mortality rate per 1,000 cases/year | New % increased risk from $PM_{10}$ change | Estimated death numbers from $PM_{10}$ change | Cardiovascular hospital admission rate per 1,000cases/ year | New % increased risk from $PM_{10}$ change | Estimated cardiovascular hospital admissions from $PM_{10}$ change | Respiratory hospital admission rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated respiratory hospital admissions from $PM_{10}$ change | Respiratory outpatient visit rate per 1,000 cases/ year | New % increased risk from $PM_{10}$ change | Estimated outpatient visits from $PM_{10}$ change |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $PM_{10}$ increase from baseline at 20 µg/m$^3$ | | | | | | | | | | | | | |
| Chiang Mai | 1,655,640 | 43.1 | 23.1 | 90 | 7.5 | 3.02 | 92 | 35.8 | 2.11 | 307 | 31.2 | 2.88 | 366 | 543.1 | 3.02 | 6,681 |
| Chiang Rai | 1,200,423 | 44.6 | 24.6 | 90 | 6.7 | 3.23 | 64 | 28.1 | 2.25 | 187 | 25.3 | 3.08 | 230 | 524.9 | 3.23 | 5,012 |
| Lampang | 756,811 | 38.5 | 18.5 | 90 | 8.1 | 2.42 | 37 | 38.4 | 1.69 | 121 | 29.6 | 2.31 | 127 | 486.1 | 2.42 | 2,192 |
| Lamphun | 404,673 | 46.4 | 26.4 | 90 | 8.2 | 3.47 | 26 | 27.6 | 2.42 | 61 | 25.4 | 3.31 | 76 | 623.6 | 3.47 | 1,965 |
| Mae Hong Son | 244,356 | 48.7 | 28.7 | 90 | 4.5 | 3.78 | 8 | 16.1 | 2.63 | 19 | 26.7 | 3.60 | 44 | 710.5 | 3.78 | 1,221 |
| Nan | 447,193 | 35.9 | 15.9 | 90 | 6.0 | 2.07 | 14 | 44.3 | 1.45 | 71 | 33.7 | 1.98 | 73 | 258.1 | 2.07 | 590 |
| Phayao | 488,120 | 35.8 | 15.8 | 90 | 7.4 | 2.06 | 18 | 33.2 | 1.44 | 58 | 28.0 | 1.97 | 66 | 535.9 | 2.06 | 1,329 |
| Phrae | 457,607 | 35.6 | 15.6 | 90 | 8.4 | 2.04 | 19 | 36.4 | 1.42 | 58 | 25.6 | 1.94 | 56 | 472.9 | 2.04 | 1,085 |

### 4.2.2 The values of health effects from $PM_{10}$

Economic valuation methods for health impacts from fires can be estimated in terms of mortality and morbidity. The most practical method for the valuation of mortality is the Value of Statistical Life (VSL). VSL is based on willingness-to-pay (WTP) to reduce the risk of mortality. The benefit transfer value from other countries could be applied for Thailand study area by an equation (Reinhardt et al., 2010). The different year of the reference country was adjusted by the PPP increased per year.

$$\text{Value}_{(\text{Thailand})} = \text{Value}_{(\text{Reference country})} \times ((\text{PPP}_{\text{Thailand}}/\text{PPP}_{\text{Reference country}})^{\gamma}) \qquad (4.11)$$

Where PPP is the gross national income (GNI) per capita adjusted for purchasing power parity, and $\gamma$ is the income elasticity, = 1.0 for the central and low estimation.

Vassanadumrongdee and Matsuoka (2005) have shown the average value of WTP to reduce mortality risk arising from air pollution by contingent valuation (CV) surveys in Bangkok at \$1.03 million (\$ 0.74 to \$1.32 million) in year 2003. This value can be adjusted for year 2012 at around \$2.55 million by using Thai GDP. The value is similar to that estimated by Kochi (2010) of \$2.21 million. Therefore, the cost of mortality and morbidity as shown in Table 4.17, adjusted from US EPA study by Kochi (2010), were used to estimate the health impact costs. All cost values by Kochi (2010) were based on WTP. The per-unit cost of premature mortality by US EPA is measured by VSL, which based on willingness to pay to save lives. For the estimated per-unit cost of morbidity, the US EPA used the contingent valuation (CV) or conventional cost of illness (COI) method. The CV method is based on WTP to prevent an adverse health outcome while the individual COI was converted to WTP using a WTP/COI ratio. However, these values were based on the United States economy. The Gross Domestic Product (GDP) per capita and GDP per capita based on purchasing power parity (PPP) are used to convert the value from the reference country for Thai study area. The PPP GDP per capita of Thai people in year 2012 are 13,983.4 US\$ whereas the United States is 51,495.9 The ratio value, 0.2715 is used to estimate for the base year costs including the value 1.56 of the averaged inflation per year between 2007 to 2012 (World Bank, 2015).

**Table 4.17** The per-unit cost of mortality and morbidity by the US EPA (1999) adjusted to year 2007 level by Kochi et al. (2010) and applied to Thai people values by using GDP.

| | US EPA value (US$ 2007) | US EPA value (US$ 2012) | Thai value in US$ 2012 (by PPP GDP and inflation, 2007 prices) | Thai value (by GDP PPP) (US$ 2012) |
|---|---|---|---|---|
| Mortality | $7,600,000 | $ 8,143,400 | $2,046,134 | $2,210,933 |
| Hospital admissions | | | | |
| All respiratory | $10,971 | $ 11,755 | $2,954 | $3,192 |
| All cardiovascular | $15,105 | $ 16,185 | $4,066 | $4,394 |
| Emergency department visits for asthma | $308 | $330 | $83 | $90 |
| Respiratory illness and symptoms (outpatients) | | | | |
| Acute bronchitis | $71 | $76 | $19 | $21 |
| Asthma attack or moderate or worse asthma day | $50 | $54 | $14 | $15 |
| Acute respiratory symptoms | $28 | $30 | $7 | $8 |
| Upper respiratory symptoms | $30 | $32 | $8 | $9 |
| Lower respiratory symptoms | $19 | $20 | $5.6 | $6 |
| Shortness of breath, chest tightness or wheeze | $8 | $9 | $2.1 | $2.3 |
| The average of Respiratory illness and symptoms cost | $34 | $37 | $9 | $10 |
| Work days loss | $131 | $140 | $35 | $38 |
| Mild restricted-activity days | $60 | $64 | $16 | $17 |

### 4.2.3 The economic losses of health effects from $PM_{10}$

The mortality and hospital admissions of all respiratory and cardiovascular diseases, respiratory outpatients, and loss of work days were taken into account for health impact values in this study. Respiratory outpatients including acute bronchitis, asthma attack, acute respiratory symptoms, upper and lower respiratory symptoms, shortness of breath, and chest tightness or wheeze were accounted by using the values from the emergency department (ED) and the average cost for respiratory illness and symptoms. The health impact costs by $PM_{10}$ change in each area were calculated as follows:

Value of health impact from $PM_{10}$ change = (Number of mortalities x \$2,210,933) + (Number of respiratory hospital admissions x \$3,192) + (Number of cardiovascular hospital admissions x \$4,394) + (Number of respiratory outpatient visits x \$10) + (Number of respiratory and cardiovascular hospital admissions, and outpatient visits x \$38)

If the $PM_{10}$ concentration average in Chiang Mai reached 102 µg/m$^3$ during 26$^{th}$ February to 1$^{st}$ March 2012, health impacts caused by $PM_{10}$ increase from base line at 50 µg/m$^3$ including mortalities, respiratory and cardiovascular hospital admissions, and respiratory outpatient visits will be 12 persons, 39 and 47 admissions, and 855 visits (see Table 4.5). The value of health impacts with $PM_{10}$ base line at 50 µg/m$^3$ are estimated from equation (4.12) as (12 x \$2,210,933) + (47 x \$3,192) + (39 x \$4,394) + (855 x \$10) + ((39+47+855) x 38)) = \$26,896,894 for 5-days impact value or \$26,896,894/5 = \$5,379,379 for averaged 1-day value in Chiang Mai province. For $PM_{10}$ base line at 20 µg/m$^3$, the values of health impacts are estimated as (19 x \$2,210,933) + (75 x \$3,192) + (63 x \$4,394) + (1,375 x \$10) + ((19 + 75 + 1,375) x 38)) = \$42,595,193 for 5-days impact value or \$42,595,193/5 = \$8,519,038 for averaged 1-day value. In summary, the total estimated cost of mortality, respiratory and cardiovascular hospital admissions and respiratory outpatients from 5-days impact in the study area are \$85,152,104 by the baseline value at 50 µg/m$^3$ and \$138,918,404 by the baseline value at 20 µg/m$^3$ (see Table 4.18).

The economic losses from health impacts of 5-days fire impacts were \$85,152,104 by the baseline value at 50 µg/m$^3$ and \$138,918,404 by the baseline value 20 µg/m$^3$. The values of health impact after controlling fires both agricultural and forests around agricultural area were calculated (see Table 4.19 and Table 4.20). After controlling fires both agricultural and forests around agricultural area 1 km, the total estimated cost of mortality, respiratory and cardiovascular hospital admissions and respiratory outpatients from 5-days impact in the study area were \$2,256,815 by the baseline value at 50 µg/m$^3$ and \$51,533,109 by the baseline value at 20 µg/m$^3$. For 4-km fire-controlled area, the value of 5-days impacts in the study area were \$1,681 by the baseline value at 50 µg/m$^3$ and \$31,365,210 by the baseline value at 20 µg/m$^3$.

**Table 4.18** Summary of costs for deaths, hospital admissions for respiratory and cardiovascular illness, and respiratory outpatient visits caused by average 5-days $PM_{10}$ increase from fires during 26 February to 1 March 2012 in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae provinces

| | Chiang Mai | Chiang Rai | Mae Hong Son | Lampang | Lamphun | Nan | Phayao | Phrae | Total |
|---|---|---|---|---|---|---|---|---|---|
| **Cost from $PM_{10}$ change compared with $PM_{10}$ base line at 50 µg/m$^3$** | | | | | | | | | |
| - Estimated deaths from 5-days impacts of $PM_{10}$ change (persons) | 12 | 7 | 1 | 5 | 2 | 3 | 3 | 5 | 38 |
| Statistic value of life (per person = US$ 2,210,933) (US$) | 26,531,196 | 15,476,531 | 2,210,933 | 11,054,665 | 4,421,866 | 6,632,799 | 6,632,799 | 11,054,665 | 84,015,454 |
| - Estimated cardiovascular hospital admissions from 5-days impacts of $PM_{10}$ change (admissions) | 39 | 21 | 3 | 17 | 5 | 13 | 10 | 15 | 123 |
| Cost of cardiovascular hospital admission (per admission = US$ 4,394) (US$) | 171,366 | 92,274 | 13,182 | 74,698 | 21,970 | 57,122 | 43,940 | 65,910 | 540,462 |
| - Estimated respiratory hospital admissions from 5-days impacts of $PM_{10}$ change (admissions) | 47 | 26 | 7 | 17 | 6 | 14 | 11 | 14 | 142 |
| Cost of respiratory hospital admission (per admission = US$ 3,192) (US$) | 150,024 | 82,992 | 22,344 | 54,264 | 19,152 | 44,688 | 35,112 | 44,688 | 453,264 |
| - Estimated outpatient visits from 5-days impacts of $PM_{10}$ change (visits) | 855 | 575 | 195 | 301 | 164 | 177 | 224 | 276 | 2,767 |
| Cost of outpatient visits for respiratory illness (per visit = US$ 10) (US$) | 8,550 | 5,750 | 1,950 | 3,010 | 1,640 | 1,770 | 2,240 | 2,760 | 27,670 |
| - Estimated number of respiratory and cardiovascular hospital admission, and outpatient visits | 941 | 623 | 205 | 335 | 176 | 203 | 245 | 305 | 3,033 |
| Cost of work days loss (per illness case = US$ 38) (US$) | 35,758 | 23,674 | 7,790 | 12,730 | 6,688 | 7,714 | 9,310 | 11,590 | 115,254 |
| Total cost (US$) | 26,896,894 | 15,681,221 | 2,256,199 | 11,199,367 | 4,471,316 | 6,744,093 | 6,723,401 | 11,179,613 | 85,152,104 |
| **Cost $PM_{10}$ change compared with $PM_{10}$ base line at 20 µg/m$^3$** | | | | | | | | | |
| - Estimated deaths from 5-days impacts of $PM_{10}$ change (persons) | 19 | 12 | 2 | 9 | 4 | 4 | 5 | 7 | 62 |
| Statistic value of life (per person = US$ 2,210,933) (US$) | 42,007,727 | 26,531,196 | 4,421,866 | 19,898,397 | 8,843,732 | 8,843,732 | 11,054,665 | 15,476,531 | 137,077,846 |
| - Estimated cardiovascular hospital admissions from 5-days impacts of $PM_{10}$ change (admissions) | 63 | 35 | 5 | 28 | 9 | 21 | 16 | 21 | 198 |
| Cost of cardiovascular hospital admission (per admission = US$ 4,394) (US$) | 276,822 | 153,790 | 21,970 | 123,032 | 39,546 | 92,274 | 70,304 | 92,274 | 870,012 |
| - Estimated respiratory hospital admissions from 5-days impacts of $PM_{10}$ change (admissions) | 75 | 43 | 11 | 30 | 12 | 22 | 19 | 21 | 233 |
| Cost of respiratory hospital admission (per admission = US$ 3,192) (US$) | 239,400 | 137,256 | 35,112 | 95,760 | 38,304 | 70,224 | 60,648 | 67,032 | 743,736 |
| - Estimated outpatient visits from 5-days impacts of $PM_{10}$ change (visits) | 1,375 | 939 | 296 | 512 | 307 | 177 | 374 | 404 | 4,384 |
| Cost of outpatient visits for respiratory illness (per visit = US$ 10) (US$) | 13,750 | 9,390 | 2,960 | 5,120 | 3,070 | 1,770 | 3,740 | 4,040 | 43,840 |
| - Estimated number of respiratory and cardiovascular hospital admission, and outpatient visits | 1,513 | 1,017 | 312 | 570 | 329 | 219 | 409 | 446 | 4,815 |
| Cost of work days loss (per illness case = US$ 38) (US$) | 57,494 | 38,646 | 11,856 | 21,660 | 12,502 | 8,322 | 15,542 | 16,948 | 182,970 |
| Total cost (US$) | 42,595,193 | 26,870,278 | 4,493,764 | 20,143,969 | 8,937,154 | 9,016,322 | 11,204,899 | 15,656,825 | 138,918,404 |

**Table 4.19** Summary of costs for deaths, hospital admissions for respiratory and cardiovascular illness, and respiratory outpatient visits caused by average 5-days PM10 increase from after fires controlled both agricultural and forest around agricultural area 1 km to be no fire areas during 26 February to 1 March 2012 in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae provinces

| | Chiang Mai | Chiang Rai | Mae Hong Son | Lampang | Lamphun | Nan | Phayao | Phrae | Total |
|---|---|---|---|---|---|---|---|---|---|
| **Cost from $PM_{10}$ change compared with $PM_{10}$ base line at 50 µg/m$^3$** | | | | | | | | | |
| - Estimated deaths from 5-days impacts of $PM_{10}$ change (persons) | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Statistic value of life (per person = US$ 2,210,933) (US$) | 0 | 0 | 0 | 0 | 2,210,933 | 0 | 0 | 0 | 2,210,933 |
| - Estimated cardiovascular hospital admissions from 50days impacts of $PM_{10}$ change (admissions) | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 4 |
| Cost of cardiovascular hospital admission (per admission = US$ 4,394) (US$) | 4,394 | 0 | 0 | 4,394 | 4,394 | 0 | 0 | 4,394 | 17,576 |
| - Estimated respiratory hospital admissions from 50days impacts of $PM_{10}$ change (admissions) | 1 | 0 | 1 | 1 | 2 | 0 | 0 | 1 | 6 |
| Cost of respiratory hospital admission (per admission = US$ 3,192) (US$) | 3,192 | 0 | 3,192 | 3,192 | 6,384 | 0 | 0 | 3,192 | 19,152 |
| - Estimated outpatient visits from 50days impacts of $PM_{10}$ change (visits) | 16 | 0 | 25 | 13 | 45 | 56 | 0 | 27 | 182 |
| Cost of outpatient visits for respiratory illness (per visit = US$ 10) (US$) | 160 | 0 | 250 | 130 | 450 | 560 | 0 | 270 | 1,820 |
| - Estimated number of respiratory and cardiovascular hospital admission, and outpatient visits | 18 | 0 | 26 | 15 | 48 | 56 | 0 | 30 | 193 |
| Cost of work days loss (per illness case = US$ 38) (US$) | 684 | 0 | 988 | 570 | 1,824 | 2,128 | 0 | 1,140 | 7,334 |
| Total cost (US$) | 8,430 | 0 | 4,430 | 8,286 | 2,223,985 | 2,688 | 0 | 8,996 | 2,256,815 |
| **Cost $PM_{10}$ change compared with $PM_{10}$ base line at 20 µg/m$^3$** | | | | | | | | | |
| - Estimated deaths from 50days impacts of $PM_{10}$ change (persons) | 7 | 4 | 1 | 4 | 2 | 1 | 1 | 3 | 23 |
| Statistic value of life (per person = US$ 2,210,933) (US$) | 15,476,531 | 8,843,732 | 2,210,933 | 8,843,732 | 4,421,866 | 2,210,933 | 2,210,933 | 6,632,799 | 50,851,459 |
| - Estimated cardiovascular hospital admissions from 50days impacts of $PM_{10}$ change (admissions) | 23 | 12 | 2 | 12 | 6 | 7 | 4 | 8 | 74 |
| Cost of cardiovascular hospital admission (per admission = US$ 4,394) (US$) | 101,062 | 52,728 | 8,788 | 52,728 | 26,364 | 30,758 | 17,576 | 35,152 | 325,156 |
| - Estimated respiratory hospital admissions from 50days impacts of $PM_{10}$ change (admissions) | 28 | 15 | 4 | 12 | 7 | 7 | 5 | 7 | 85 |
| Cost of respiratory hospital admission (per admission = US$ 3,192) (US$) | 89,376 | 47,880 | 12,768 | 38,304 | 22,344 | 22,344 | 15,960 | 22,344 | 271,320 |
| - Estimated outpatient visits from 50days impacts of $PM_{10}$ change (visits) | 503 | 329 | 120 | 213 | 183 | 56 | 98 | 145 | 1,647 |
| Cost of outpatient visits for respiratory illness (per visit = US$ 10) (US$) | 5,030 | 3,290 | 1,200 | 2,130 | 1,830 | 560 | 980 | 1,450 | 16,470 |
| - Estimated number of respiratory and cardiovascular hospital admission, and outpatient visits | 554 | 357 | 126 | 237 | 196 | 70 | 108 | 160 | 1,808 |
| Cost of work days loss (per illness case = US$ 38) (US$) | 21,052 | 13,566 | 4,788 | 9,006 | 7,448 | 2,660 | 4,104 | 6,080 | 68,704 |
| Total cost (US$) | 15,693,051 | 8,961,196 | 2,238,477 | 8,945,900 | 4,479,852 | 2,267,255 | 2,249,553 | 6,697,825 | 51,533,109 |

**Table 4.20** Summary of costs for hospital admissions for respiratory and cardiovascular illness, and respiratory outpatient visits caused by average 5-days $PM_{10}$ increase from after fires controlled both agricultural and forest around agricultural area 4 km to be no fire areas during 26 February to 1 March 2012 in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae provinces

| | Chiang Mai | Chiang Rai | Mae Hong Son | Lampang | Lamphun | Nan | Phayao | Phrae | Total |
|---|---|---|---|---|---|---|---|---|---|
| **Cost from $PM_{10}$ change compared with $PM_{10}$ base line at 50 μg/m$^3$** | | | | | | | | | |
| - Estimated deaths from 50days impacts of $PM_{10}$ change (persons) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Statistic value of life (per person = US$ 2,210,933) (US$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - Estimated cardiovascular hospital admissions from 50days impacts of $PM_{10}$ change (admissions) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cost of cardiovascular hospital admission (per admission = US$ 4,394) (US$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - Estimated respiratory hospital admissions from 50days impacts of $PM_{10}$ change (admissions) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cost of respiratory hospital admission (per admission = US$ 3,192) (US$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - Estimated outpatient visits from 50days impacts of $PM_{10}$ change (visits) | 0 | 0 | 0 | 0 | 0 | 35 | 0 | 0 | 35 |
| Cost of outpatient visits for respiratory illness (per visit = US$ 10) (US$) | 0 | 0 | 0 | 0 | 0 | 350 | 0 | 0 | 350 |
| - Estimated number of respiratory and cardiovascular hospital admission, and outpatient visits | 0 | 0 | 0 | 0 | 0 | 35 | 0 | 0 | 35 |
| Cost of work days loss (per illness case = US$ 38) (US$) | 0 | 0 | 0 | 0 | 0 | 1,330 | 0 | 0 | 1,330 |
| Total cost (US$) | 0 | 0 | 0 | 0 | 0 | 1,680 | 0 | 0 | 1,680 |
| **Cost $PM_{10}$ change compared with $PM_{10}$ base line at 20 μg/m$^3$** | | | | | | | | | |
| - Estimated deaths from 50days impacts of $PM_{10}$ change (persons) | 4 | 3 | 0 | 2 | 2 | 1 | 1 | 1 | 14 |
| Statistic value of life (per person = US$ 2,210,933) (US$) | 8,843,732 | 6,632,799 | 0 | 4,421,866 | 4,421,866 | 2,210,933 | 2,210,933 | 2,210,933 | 30,953,062 |
| - Estimated cardiovascular hospital admissions from 50days impacts of $PM_{10}$ change (admissions) | 14 | 8 | 1 | 6 | 4 | 4 | 3 | 4 | 44 |
| Cost of cardiovascular hospital admission (per admission = US$ 4,394) (US$) | 61,516 | 35,152 | 4,394 | 26,364 | 17,576 | 17,576 | 13,182 | 17,576 | 193,336 |
| - Estimated respiratory hospital admissions from 50days impacts of $PM_{10}$ change (admissions) | 17 | 10 | 3 | 6 | 5 | 4 | 3 | 4 | 52 |
| Cost of respiratory hospital admission (per admission = US$ 3,192) (US$) | 54,264 | 31,920 | 9,576 | 19,152 | 15,960 | 12,768 | 9,576 | 12,768 | 165,984 |
| - Estimated outpatient visits from 50days impacts of $PM_{10}$ change (visits) | 306 | 226 | 78 | 112 | 118 | 35 | 70 | 78 | 1,023 |
| Cost of outpatient visits for respiratory illness (per visit = US$ 10) (US$) | 3,060 | 2,260 | 780 | 1,120 | 1,180 | 350 | 700 | 780 | 10,230 |
| - Estimated number of respiratory and cardiovascular hospital admission, and outpatient visits | 337 | 245 | 82 | 124 | 126 | 44 | 77 | 86 | 1,121 |
| Cost of work days loss (per illness case = US$ 38) (US$) | 12,806 | 9,310 | 3,116 | 4,712 | 4,788 | 1,672 | 2,926 | 3,268 | 42,598 |
| Total cost (US$) | 8,975,378 | 6,711,441 | 17,866 | 4,473,214 | 4,461,370 | 2,243,299 | 2,237,317 | 2,245,325 | 31,365,210 |

The economic losses from health impacts through the fire season from 1 February to 30 April 2012 were \$224,163,186 by the baseline value at 50 μg/m$^3$ and \$974,768,271 by the baseline value 20 μg/m$^3$. After fires controlled both agricultural and forest around agricultural area 1 km, the economic losses have decreased to \$49,313,616 by the baseline value at 50 μg/m$^3$ and \$755,108,997 by the baseline value 20 μg/m$^3$. Moreover, these have more decreased to \$2,261,321 by the baseline value at 50 μg/m$^3$ and \$651,953,867 by the baseline value at 20 μg/m$^3$ when fires were controlled both agricultural and forest around agricultural area 4 km. The values of health impact before and after fire controlled through fire season are shown in Table 4.21, Table 4.22 and Table 4.23. Chiang Mai was more affected from $PM_{10}$ than other provinces due to the greater number of population at 1.66 million persons following by Chiang Rai and Lampang at 1.20 and 0.76 million, respectively.

At the base line 50 μg/m$^3$, the economic losses of health impacts decreased by \$174,849,570 or 78.00% from \$224,163,186 to \$49,313,616 from fire controlled ranged 1 km and decreased by \$221,901,865 or 98.99% from \$224,163,186 to \$2,261,321 from fire controlled ranged 4 km. However, percentage decrease of the economic loss of health impacts at the base line 20 μg/m$^3$ was less than the base line 50 μg/m$^3$. At the base line 20 μg/m$^3$, the economic losses of health impacts decreased by \$219,659,274 or 22.53% from \$974,768,271 to \$755,108,997 from fire controlled ranged 1 km and decreased by \$322,814,404 or 33.12% from \$974,768,271 to \$651,953,867 from fire controlled ranged 4 km. The economic loss from the mortality was more than 90% of the total value of health impacts.

**Table 4.21** Summary of costs for hospital admissions for respiratory and cardiovascular illness, and respiratory outpatient visits from actual fires during 1 February to 30 April 2012 in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae provinces

| | Chiang Mai | Chiang Rai | Mae Hong Son | Lampang | Lamphun | Nan | Phayao | Phrae | Total |
|---|---|---|---|---|---|---|---|---|---|
| **Cost from $PM_{10}$ change compared with $PM_{10}$ base line at 50 µg/m$^3$** | | | | | | | | | |
| - Estimated deaths from $PM_{10}$ change (persons) | 30 | 16 | 3 | 12 | 6 | 13 | 7 | 13 | 100 |
| Statistic value of life (per person = US$ 2,210,933) (US$) | 66,327,990 | 35,374,928 | 6,632,799 | 26,531,196 | 13,265,598 | 28,742,129 | 15,476,531 | 28,742,129 | 221,093,300 |
| - Estimated cardiovascular hospital admissions from $PM_{10}$ change (admissions) | 99 | 46 | 8 | 39 | 14 | 64 | 23 | 38 | 331 |
| Cost of cardiovascular hospital admission (per admission = US$ 4,394) (US$) | 435,006 | 202,124 | 35,152 | 171,366 | 61,516 | 281,216 | 101,062 | 166,972 | 1,454,414 |
| - Estimated respiratory hospital admissions from $PM_{10}$ change (admissions) | 118 | 57 | 17 | 41 | 18 | 67 | 27 | 37 | 382 |
| Cost of respiratory hospital admission (per admission = US$ 3,192) (US$) | 376,656 | 181,944 | 54,264 | 130,872 | 57,456 | 213,864 | 86,184 | 118,104 | 1,219,344 |
| - Estimated outpatient visits from $PM_{10}$ change (visits) | 2,149 | 1,233 | 484 | 703 | 468 | 1,405 | 533 | 714 | 7,689 |
| Cost of outpatient visits for respiratory illness (per visit = US$ 10) (US$) | 21,490 | 12,330 | 4,840 | 7,030 | 4,680 | 14,050 | 5,330 | 7,140 | 76,890 |
| - Estimated number of respiratory and cardiovascular hospital admission, and outpatient visits | 2,365 | 1,336 | 509 | 783 | 500 | 1,536 | 583 | 789 | 8,401 |
| Cost of work days loss (per illness case = US$ 38) (US$) | 89,870 | 50,768 | 19,342 | 29,754 | 19,000 | 58,368 | 22,154 | 29,982 | 319,238 |
| Total cost (US$) | 67,251,012 | 35,822,094 | 6,746,397 | 26,870,218 | 13,408,250 | 29,309,627 | 15,691,261 | 29,064,327 | 224,163,186 |
| **Cost $PM_{10}$ change compared with $PM_{10}$ base line at 20 µg/m$^3$** | | | | | | | | | |
| - Estimated deaths from $PM_{10}$ change (persons) | 135 | 87 | 14 | 56 | 36 | 33 | 33 | 41 | 435 |
| Statistic value of life (per person = US$ 2,210,933) (US$) | 298,475,955 | 192,351,171 | 30,953,062 | 123,812,248 | 79,593,588 | 72,960,789 | 72,960,789 | 90,648,253 | 961,755,855 |
| - Estimated cardiovascular hospital admissions from $PM_{10}$ change (admissions) | 448 | 254 | 34 | 185 | 85 | 167 | 104 | 124 | 1,401 |
| Cost of cardiovascular hospital admission (per admission = US$ 4,394) (US$) | 1,968,512 | 1,116,076 | 149,396 | 812,890 | 373,490 | 733,798 | 456,976 | 544,856 | 6,155,994 |
| - Estimated respiratory hospital admissions from $PM_{10}$ change (admissions) | 536 | 314 | 78 | 195 | 107 | 175 | 120 | 120 | 1,645 |
| Cost of respiratory hospital admission (per admission = US$ 3,192) (US$) | 1,710,912 | 1,002,288 | 248,976 | 622,440 | 341,544 | 558,600 | 383,040 | 383,040 | 5,250,840 |
| - Estimated outpatient visits from $PM_{10}$ change (visits) | 9,783 | 6,830 | 2,170 | 3,358 | 2,757 | 1,405 | 2,408 | 2,328 | 31,039 |
| Cost of outpatient visits for respiratory illness (per visit = US$ 10) (US$) | 97,830 | 68,300 | 21,700 | 33,580 | 27,570 | 14,050 | 24,080 | 23,280 | 310,390 |
| - Estimated number of respiratory and cardiovascular hospital admission, and outpatient visits | 10,767 | 7,398 | 2,282 | 3,738 | 2,949 | 1,747 | 2,631 | 2,572 | 34,084 |
| Cost of work days loss (per illness case = US$ 38) (US$) | 409,146 | 281,124 | 86,716 | 142,044 | 112,062 | 66,386 | 99,978 | 97,736 | 1,295,192 |
| Total cost (US$) | 302,662,355 | 194,818,959 | 31,459,850 | 125,423,202 | 80,448,254 | 74,333,623 | 73,924,863 | 91,697,165 | 974,768,271 |

**Table 4.22** Summary of costs for deaths, hospital admissions for respiratory and cardiovascular illness, and respiratory outpatient visits after fires controlled both agricultural and forest around agricultural area 1 km to be no fire areas during 1 February to 30 April 2012 in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae provinces

| | Chiang Mai | Chiang Rai | Mae Hong Son | Lampang | Lamphun | Nan | Phayao | Phrae | Total |
|---|---|---|---|---|---|---|---|---|---|
| **Cost from $PM_{10}$ change compared with $PM_{10}$ base line at 50 μg/m$^3$** | | | | | | | | | |
| - Estimated deaths from $PM_{10}$ change (persons) | 6 | 2 | 1 | 4 | 3 | 2 | 1 | 3 | 21 |
| Statistic value of life (per person = US$ 2,210,933) (US$) | 13,265,598 | 4,421,866 | 2,210,933 | 8,843,732 | 6,632,799 | 4,421,866 | 2,210,933 | 6,632,799 | 48,640,526 |
| - Estimated cardiovascular hospital admissions from $PM_{10}$ change (admissions) | 19 | 5 | 3 | 12 | 6 | 12 | 4 | 8 | 70 |
| Cost of cardiovascular hospital admission (per admission = US$ 4,394) (US$) | 83,486 | 21,970 | 13,182 | 52,728 | 26,364 | 52,728 | 17,576 | 35,152 | 303,186 |
| - Estimated respiratory hospital admissions from $PM_{10}$ change (admissions) | 22 | 6 | 7 | 13 | 8 | 12 | 5 | 7 | 81 |
| Cost of respiratory hospital admission (per admission = US$ 3,192) (US$) | 70,224 | 19,152 | 22,344 | 41,496 | 25,536 | 38,304 | 15,960 | 22,344 | 255,360 |
| - Estimated outpatient visits from $PM_{10}$ change (visits) | 409 | 134 | 197 | 226 | 204 | 850 | 102 | 144 | 2,267 |
| Cost of outpatient visits for respiratory illness (per visit = US$ 10) (US$) | 4,090 | 1,340 | 1,970 | 2,260 | 2,040 | 8,500 | 1,020 | 1,440 | 22,660 |
| - Estimated number of respiratory and cardiovascular hospital admission, and outpatient visits | 450 | 145 | 207 | 251 | 219 | 874 | 112 | 160 | 2,418 |
| Cost of work days loss (per illness case = US$ 38) (US$) | 17,100 | 5,510 | 7,866 | 9,538 | 8,322 | 33,212 | 4,256 | 6,080 | 91,884 |
| Total cost (US$) | 13,440,498 | 4,469,838 | 2,256,295 | 8,949,754 | 6,695,061 | 4,554,610 | 2,249,745 | 6,697,815 | 49,313,616 |
| **Cost $PM_{10}$ change compared with $PM_{10}$ base line at 20 μg/m$^3$** | | | | | | | | | |
| - Estimated deaths from $PM_{10}$ change (persons) | 107 | 69 | 11 | 46 | 32 | 20 | 24 | 28 | 337 |
| Statistic value of life (per person = US$ 2,210,933) (US$) | 236,569,831 | 152,554,377 | 24,320,263 | 101,702,918 | 70,749,856 | 44,218,660 | 53,062,392 | 61,906,124 | 745,084,421 |
| - Estimated cardiovascular hospital admissions from $PM_{10}$ change (admissions) | 355 | 201 | 29 | 153 | 76 | 102 | 75 | 85 | 1,074 |
| Cost of cardiovascular hospital admission (per admission = US$ 4,394) (US$) | 1,559,870 | 883,194 | 127,426 | 672,282 | 333,944 | 448,188 | 329,550 | 373,490 | 4,727,944 |
| - Estimated respiratory hospital admissions from $PM_{10}$ change (admissions) | 423 | 247 | 65 | 161 | 96 | 106 | 87 | 81 | 1,265 |
| Cost of respiratory hospital admission (per admission = US$ 3,192) (US$) | 1,350,216 | 788,424 | 207,480 | 513,912 | 306,432 | 338,352 | 277,704 | 258,552 | 4,041,072 |
| - Estimated outpatient visits from $PM_{10}$ change (visits) | 7,717 | 5,373 | 1,816 | 2,768 | 2,469 | 850 | 1,737 | 1,575 | 24,306 |
| Cost of outpatient visits for respiratory illness (per visit = US$ 10) (US$) | 77,170 | 53,730 | 18,160 | 27,680 | 24,690 | 8,500 | 17,370 | 15,750 | 243,050 |
| - Estimated number of respiratory and cardiovascular hospital admission, and outpatient visits | 8,495 | 5,821 | 1,909 | 3,081 | 2,641 | 1,058 | 1,899 | 1,741 | 26,645 |
| Cost of work days loss (per illness case = US$ 38) (US$) | 322,810 | 221,198 | 72,542 | 117,078 | 100,358 | 40,204 | 72,162 | 66,158 | 1,012,510 |
| Total cost (US$) | 239,879,897 | 154,500,923 | 24,745,871 | 103,033,870 | 71,515,280 | 45,053,904 | 53,759,178 | 62,620,074 | 755,108,997 |

**Table 4.23** Summary of costs for deaths, hospital admissions for respiratory and cardiovascular illness, and respiratory outpatient visits after fires controlled both agricultural and forest around agricultural area 4 km to be no fire areas during 1 February to 30 April 2012 in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae provinces

| | Chiang Mai | Chiang Rai | Mae Hong Son | Lampang | Lamphun | Nan | Phayao | Phrae | Total |
|---|---|---|---|---|---|---|---|---|---|
| **Cost from $PM_{10}$ change compared with $PM_{10}$ base line at 50 µg/m$^3$** | | | | | | | | | |
| - Estimated deaths from $PM_{10}$ change (persons) | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Statistic value of life (per person = US$ 2,210,933) (US$) | 0 | 0 | 0 | 0 | 2,210,933 | 0 | 0 | 0 | 2,210,933 |
| - Estimated cardiovascular hospital admissions from $PM_{10}$ change (admissions) | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 2 |
| Cost of cardiovascular hospital admission (per admission = US$ 4,394) (US$) | 0 | 0 | 4,394 | 0 | 4,394 | 0 | 0 | 0 | 8,788 |
| - Estimated respiratory hospital admissions from $PM_{10}$ change (admissions) | 0 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 3 |
| Cost of respiratory hospital admission (per admission = US$ 3,192) (US$) | 0 | 0 | 3,192 | 0 | 6,384 | 0 | 0 | 0 | 9,576 |
| - Estimated outpatient visits from $PM_{10}$ change (visits) | 0 | 0 | 27 | 0 | 43 | 594 | 0 | 0 | 664 |
| Cost of outpatient visits for respiratory illness (per visit = US$ 10) (US$) | 0 | 0 | 270 | 0 | 430 | 5,940 | 0 | 0 | 6,640 |
| - Estimated number of respiratory and cardiovascular hospital admission, and outpatient visits | 0 | 0 | 28 | 0 | 46 | 594 | 0 | 0 | 668 |
| Cost of work days loss (per illness case = US$ 38) (US$) | 0 | 0 | 1,064 | 0 | 1,748 | 22,572 | 0 | 0 | 25,384 |
| Total cost (US$) | 0 | 0 | 8,920 | 0 | 2,223,889 | 28,512 | 0 | 0 | 2,261,321 |
| **Cost $PM_{10}$ change compared with $PM_{10}$ base line at 20 µg/m$^3$** | | | | | | | | | |
| - Estimated deaths from $PM_{10}$ change (persons) | 92 | 65 | 11 | 38 | 30 | 14 | 20 | 21 | 290 |
| Statistic value of life (per person = US$ 2,210,933) (US$) | 203,405,836 | 143,710,645 | 24,320,263 | 84,015,454 | 66,327,990 | 30,953,062 | 44,218,660 | 46,429,593 | 643,381,503 |
| - Estimated cardiovascular hospital admissions from $PM_{10}$ change (admissions) | 307 | 190 | 26 | 124 | 70 | 71 | 62 | 64 | 916 |
| Cost of cardiovascular hospital admission (per admission = US$ 4,394) (US$) | 1,348,958 | 834,860 | 114,244 | 544,856 | 307,580 | 311,974 | 272,428 | 281,216 | 4,016,116 |
| - Estimated respiratory hospital admissions from $PM_{10}$ change (admissions) | 366 | 234 | 60 | 131 | 88 | 74 | 71 | 61 | 1,086 |
| Cost of respiratory hospital admission (per admission = US$ 3,192) (US$) | 1,168,272 | 746,928 | 191,520 | 418,152 | 280,896 | 236,208 | 226,632 | 194,712 | 3,463,320 |
| - Estimated outpatient visits from $PM_{10}$ change (visits) | 6,681 | 5,095 | 1,675 | 2,252 | 2,274 | 594 | 1,431 | 1,184 | 21,185 |
| Cost of outpatient visits for respiratory illness (per visit = US$ 10) (US$) | 66,810 | 50,950 | 16,750 | 22,520 | 22,740 | 5,940 | 14,310 | 11,840 | 211,860 |
| - Estimated number of respiratory and cardiovascular hospital admission, and outpatient visits | 7,354 | 5,520 | 1,761 | 2,507 | 2,432 | 739 | 1,564 | 1,309 | 23,187 |
| Cost of work days loss (per illness case = US$ 38) (US$) | 279,452 | 209,760 | 66,918 | 95,266 | 92,416 | 28,082 | 59,432 | 49,742 | 881,068 |
| Total cost (US$) | 206,269,328 | 145,553,143 | 24,709,695 | 85,096,248 | 67,031,622 | 31,535,266 | 44,791,462 | 46,967,103 | 651,953,867 |

**Table 4.24** Summary of costs for deaths, hospital admissions for respiratory and cardiovascular illness, and respiratory outpatient visits for the no-fire situation during 1 February to 30 April 2012 in Chiang Mai, Chiang Rai, Mae Hong Son, Lampang, Lamphun, Nan, Phayao and Phrae provinces

| | Chiang Mai | Chiang Rai | Mae Hong Son | Lampang | Lamphun | Nan | Phayao | Phrae | Total |
|---|---|---|---|---|---|---|---|---|---|
| **Cost from $PM_{10}$ change compared with $PM_{10}$ base line at 50 μg/m$^3$** | | | | | | | | | |
| - Estimated deaths from $PM_{10}$ change (persons) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Statistic value of life (per person = US$ 2,210,933) (US$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - Estimated cardiovascular hospital admissions from $PM_{10}$ change (admissions) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cost of cardiovascular hospital admission (per admission = US$ 4,394) (US$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - Estimated respiratory hospital admissions from $PM_{10}$ change (admissions) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cost of respiratory hospital admission (per admission = US$ 3,192) (US$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - Estimated outpatient visits from $PM_{10}$ change (visits) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cost of outpatient visits for respiratory illness (per visit = US$ 10) (US$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - Estimated number of respiratory and cardiovascular hospital admission, and outpatient visits | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cost of work days loss (per illness case = US$ 38) (US$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total cost (US$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Cost $PM_{10}$ change compared with $PM_{10}$ base line at 20 μg/m$^3$** | | | | | | | | | |
| - Estimated deaths from $PM_{10}$ change (persons) | 93 | 64 | 7.7 | 37 | 26 | 14 | 18 | 19 | 278 |
| Statistic value of life (per person = US$ 2,210,933) (US$) | 205,616,769 | 141,499,712 | 17,024,184.1 | 81,804,521 | 57,484,258 | 30,953,062 | 39,796,794 | 42,007,727 | 616,187,027 |
| - Estimated cardiovascular hospital admissions from $PM_{10}$ change (admissions) | 309 | 187 | 19.3 | 121 | 61 | 71 | 58 | 58 | 884 |
| Cost of cardiovascular hospital admission (per admission = US$ 4,394) (US$) | 1,357,746 | 821,678 | 84,804.2 | 531,674 | 268,034 | 311,974 | 254,852 | 254,852 | 3,885,614 |
| - Estimated respiratory hospital admissions from $PM_{10}$ change (admissions) | 368 | 230 | 43.7 | 127 | 76 | 73 | 66 | 56 | 1,041 |
| Cost of respiratory hospital admission (per admission = US$ 3,192) (US$) | 1,174,656 | 734,160 | 139,490.4 | 405,384 | 242,592 | 233,016 | 210,672 | 178,752 | 3,318,722 |
| - Estimated outpatient visits from $PM_{10}$ change (visits) | 6,710 | 5,012 | 1,220.7 | 2,192 | 1,965 | 590 | 1,329 | 1,085 | 20,105 |
| Cost of outpatient visits for respiratory illness (per visit = US$ 10) (US$) | 67,100 | 50,120 | 12,207.0 | 21,920 | 19,650 | 5,900 | 13,290 | 10,850 | 201,037 |
| - Estimated number of respiratory and cardiovascular hospital admission, and outpatient visits | 7,387 | 5,430 | 1,283.7 | 2,440 | 2,102 | 734 | 1,453 | 1,200 | 22,030 |
| Cost of work days loss (per illness case = US$ 38) (US$) | 280,706 | 206,340 | 48,780.6 | 92,720 | 79,876 | 27,892 | 55,214 | 45,600 | 837,129 |
| Total cost (US$) | 208,496,977 | 143,312,010 | 17,309,466.3 | 82,856,219 | 58,094,410 | 31,531,844 | 40,330,822 | 42,497,781 | 624,429,529 |

## 4.3 Socio-economic impact valuation.

Forest fires deplete forest areas which are important sources of goods and services for human well-being including foods, water supply, raw materials and recreation. The values of forested areas can be estimated by accounting forest goods and services (see Table 4.25). These consist of provisioning services such as food, fresh water, medical, wood and other raw materials; regulating services that affect climate, disease, floods, storm and water purification; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as nutrient cycling, soil formation, and photosynthesis. To estimate the ecosystem values, Fisher et al. (2008) have suggested that supporting and regulating services provide the same services. In addition, the supporting services are also crucial ecosystem functions underpinning the other services. In addition, for a cost–benefit analysis, counting all ecosystem services may lead to double counting because some ecosystem final services have included intermediate service processes. For example, food provision is a final service as a result from a pollination service that is an intermediate. The final services include water regulation, clean-water and food provision. Generally, final services are direct benefits to humans and should be accounted. Then, intermediate services, including soil formation, nutrient cycling and pollination, were not included in the forest valuation part. It is because this may lead to the double counting and these services are weak linkages to socioeconomic factors and human well-being. This is different from provision and regulating service which have strong linkages in terms of socioeconomic factors and human well-being while the others have the weak ones (MEA, 2005).

### 4.3.1 The benefit transfer values of ecosystem goods and services

The criteria for selecting transfer values are the ecosystem and economic status of the reference study; these should be similar to the studied area. The tropical forest is the most common vegetation type in the study area as shown in section 4.1 and developing country with the upper-middle income economy is the economic status of Thailand as defined by the World Bank (2016). More than 50% of the north of Thailand area are forests and are important sources of water flow to both the north and central areas of Thailand. The total economic value of the north is small compared with other regions and industrial and agriculture are the main sectors contributing to the country's gross domestic product (Office of the National Economic and Social Development Board, 2011). However, there are limitations such as the lack of some forest goods and services values from a similar reference area or they may be from a similar area but have very high values compared with the global value. Hence, reference values from different countries were used. The transfer values from different studies and periods were converted to the monetary values for year 2012 same as this study period by the equation (4.13).

$$P_{2012} = Pi(1+r)^{n} \qquad (4.13)$$

Where $P_{2012}$ = the value of goods or services in year 2012, Pi = the value of goods or services from the reference study in year i, r = the average inflation rate per year, and n = number of years (2012 - i)

**Table 4.25** The economic transfer values per hectare of each ecosystem goods and services in tropical forests from various studies.

| Service/ Product | Source | Study area | Values (US Dollar) | Method | Reference | Remark |
|---|---|---|---|---|---|---|
| **Provision services** | | | | | | |
| 1. Timber | | | | | | |
| | Rosales et al. (2005) | Laos in year 2003 | $10.5 /ha/yr | Using direct market pricing method | van der Ploeg et al. (2010) | Used in this study, the value in year 2012 = 12.75 /ha/yr |
| | CBD (2001) | World in year 2001 | $148-$230 /ha/yr | Using benefit transfer method | van der Ploeg et al. (2010) | |
| 2. Non-timber products | | | | | | |
| - Food and raw materials | Subanaseree et al. (1992) | Thailand in year 2005 | 76.1/ha/yr | 306,750 Baht/km$^2$ = 3,067.5 Baht/ha/yr (avg. rate in year 2005 THB1 = USD0.0248) | Chulalongkorn University (2010) | Used in this study, the value in year 2012 = 87 /ha/yr |
| – Fuel wood and charcoal | Lescuyer (2007) | Cameroon in year 2001 | $61 /ha/yr | Using benefit transfer method | van der Ploeg et al. (2010) | |
| – Food only | Rosales et al. (2005) | Laos in year 2003 | $9.3 /ha/yr<br>$12.8 /ha/yr | Using direct market pricing method for $9.3 and group valuation method for $12.8 | van der Ploeg et al. (2010) | |
| 3. Water | | | | | | |
| - Water supply | Estimated from various studies | Tropical forests, year 2007 | $ 200 /ha/yr | Adjusted by using GDP PPP and inflation to standardize to 2007 monetary year value, average value from previous studies. | de Groot et al. (2012) | Used in this study, the value in year 2012 = 216 /ha/yr |

| Service/ Product | Source | Study area | Values (US Dollar) | Method | Reference | Remark |
|---|---|---|---|---|---|---|
| – Water for irrigation | Lele et al. (2008) | India | $107 /household /yr | Using change in productivity method by estimating expected annual income related with reduction of changes in forest cover | Ferraro et al. (2011) | |
| – Water supply | Li et al. (2008) | China in year 2004 | $374.5 /ha/yr | Using benefit transfer method, CNY3,097.90 per hectare per year (avg. rate in year 2004 CNY1 = USD0.1209) | van der Ploeg et al. (2010) | |
| 4. Medical resources | | | | | | |
| - Biochemical | Rosales et al. (2005) | Laos in year 2003 | $0.33 /ha/yr | Using benefit transfer method | van der Ploeg et al. (2010) | Used in this study, the value in year 2012 = 0.38 /ha/yr |
| **Cultural services** | | | | | | |
| 5. Recreation and tourism | | | | | | |
| | Sombat et al. (1998) | Northern Thailand in year 2005 | $9.92/ha/yr | Using travel cost method, 40,000 Baht/km$^2$ = 400 Baht/ha/yr (avg. rate in year 2005 THB1 = USD0.0248) | Chulalongkorn University (2010) | Used in this study, the value in year 2012 = 11.35 /ha/yr |
| | Li et al. (2008) | China in year 2004 | $150 /ha/yr | Using benefit transfer method, CNY1,239.20 per hectare per year (avg. rate in year 2004 CNY1 = USD0.1209) | van der Ploeg et al. (2010) | |
| | Verweij et al. (2009) | Ecuador in year 2007 | $6.65 /ha/yr | Using benefit transfer method for estimating ecotourism value | van der Ploeg et al. (2010) | |
| **Regulating services** | | | | | | |
| 6. Climate regulation | | | | | | |
| | Nauleurai (2005) | Thailand in year 2005 | $769/ha/yr | 3,100,790 Baht/km$^2$ = 31,007.9 Baht/ha/yr (avg. rate in year 2005 THB1 = USD0.0248) | Chulalongkorn University (2010) | Used in this study, the value in year 2012 = 880 /ha/yr |

| Service/ Product | Source | Study area | Values (US Dollar) | Method | Reference | Remark |
|---|---|---|---|---|---|---|
| | Rosales et al. (2005) | Laos in year 2003 | $1,284 /ha/yr | Using benefit transfer method for estimating carbon sequestration value | van der Ploeg et al. (2010) | |
| 7. Water quality | | | | | | |
| | Curtis (2004) | Australia in year 2002 | $ 7.54/ha/yr | Using direct market pricing method, AUS 13.61 per hectare per year (avg. rate in year 2004 AUD1= USD0.5440) | van der Ploeg et al. (2010) | Used in this study, the value in year 2012 = 9.33 /ha/yr |
| | Li et al. (2008) | China in year 2004 | $153.33 /ha/yr | Using benefit transfer method, CNY1,268.20 per hectare per year (avg. rate in year 2004 CNY1 = USD0.1209) | van der Ploeg et al. (2010) | |
| 8. Flood prevention | | | | | | |
| | Rosales et al. (2005) | Laos in year 2003 | $92.3 /ha/yr | Using avoided Cost method for estimating carbon sequestration value | van der Ploeg et al. (2010) | Used in this study, the value in year 2012 = 105.6 /ha/yr |
| 9. Biodiversity protection | | | | | | |
| | Curtis (2004) | Australia in year 2002 | $12.64 /ha/yr | Using direct market pricing method, AUS 23.24 per hectare per year (avg. rate in year 2004 AUD1 = USD0.5440) | van der Ploeg et al. (2010) | Used in this study, the value in year 2012 = 13.13 /ha/yr |
| | Verma (2000) | India in year 2000 | $435 /ha/yr | Using benefit transfer method | van der Ploeg et al. (2010) | |
| | Verweij et al. (2009) | Brazil in year 2007 | $18 /ha/yr | Using benefit transfer method | van der Ploeg et al. (2010) | |

### 4.3.2 The economic losses of ecosystem goods and services from forest fires

Forest fire can be a natural process to maintain or damage forest ecosystems or cause deforestation depending on fire intensity and frequency. Generally, most of the fires in Thailand were low to moderate intensity levels. Fire intensity in the mixed deciduous forest is low level with flame length 0.84 m and dry deciduous forest have low to moderate fires with flame length 0.5 – 8 m (Wiriya, 2010). Baker et al. (2008) also showed that tropical forests are often low-intensity surface fires with flame lengths ranging from 5 to 50 cm and appeared to affect only trees <2m tall. Smaller trees are more vulnerable to death from fires, but are also more likely to quickly resprout, within months of a fire. Moreover, this study also suggested that fires in the forest mosaic of continental South-east Asia may not be particularly disastrous for tree species and biodiversity effects. However, some studies showed that the dominant tree might die months or years after low-intensity surface fires. This could affect the forest type which is sensitive to fires such as an evergreen forest, and may lead to the transformation of evergreen forest to deciduous forest and savanna and consequently to a significant loss of biodiversity (Cochrane, 2009). The Global Fire Monitoring Center (2002) showed that fires can cause very severe damage to evergreen forests by killing more than 50% of mature trees, completely destroying all saplings and undergrowth, and destroying food and habitat for wildlife.

Forest fires in the north of Thailand tend to occur in the same area every 1-3 years (Dontee et al., 2011, Department of National Parks Wildlife and Plant Conservation, 2016). The main types of vegetation burned have been mixed deciduous forest, hill evergreen forest, dry evergreen forest, and dry dipterocarp forest. The natural fire regime for the deciduous dipterocarp was 1-3 years whereas there were no data for other types (Kodandapani et al., 2008). However, deciduous forests in the north of Thailand have faced annual burn by surface fire and become relatively fire-resistant. Therefore mature trees did not die from fires (Global Fire Monitoring Center, 2002). Consequently, the values for timber products and biodiversity impacts have not been estimated for fire impact losses of deciduous forests but will be calculated for evergreen forests with 50% losses of mature trees for timber products. For the biodiversity losses, Global Fire Monitoring Center (2006) showed fire protection had more tree density and contained more individual trees than burnt area by around 25%. Hence a value of 25% was used to estimate the change of biodiversity for evergreen forests.

The fire season in the north of Thailand occurs annually in the dry season and ends in April; after that, the monsoon rain season goes from May to October. Fires have changed the soil characteristics and destroyed aboveground small trees. This affects the ecosystem by increasing soil erosion and surface runoff in every type of forest but is more intensive in evergreen forests. Most tree species in evergreen forest are sensitive to fire (Cochrane, 2009) and fires can cause very severe damage by completely destroying all sapling and killing 50% of mature trees (Global Fire Monitoring Center, 2002). These caused an increase of water supply (Scott, 1993, White et al., 2006) and increase the chance of flood events. However, fires will decrease water yield in the long term (White et al., 2006). As most mature and dominant trees in deciduous and evergreen forests were still alive after fires, only small trees were destroyed. Thus, the value of water supply and water quality were not estimated, but the flood prevention was accounted.

Fires have burnt only small trees in every forest type and killed some dominant trees in evergreen forests. Then the carbon consequence value will include the combustion completeness value 0.25 for deciduous forest value (Michel et al., 2005) and 50% of mature tree deaths or 0.50 for evergreen forests value (Global Fire Monitoring Center, 2002) in the estimation of the impact value.

In Thailand, collecting forest products for a living is permitted without asking for permission in all types of the forest including the national park and the national reserved forest, provided it does not destroy the forest ecosystem. However, any activities that may damage a forest area such as mining, livestock and agricultural activities can be operated in the national reserved forest but has to have legal permission for the specific time period from a competent officer of each national reserved forest. Therefore, the people could get benefits from the non-timber forest products for every forest type.

To estimate the value of the forest damage, not only was the value of goods and services per hectare used, but the sizes of areas burned were also taken into account. The estimation of the values of the ecosystem goods and services can use equation 4.14:

$$\text{Total value of goods or services per year (US\$)} = \text{Timber products value} + \text{Non-timber products value} + \text{Medical resources value} + \text{Recreation and tourism value} + \text{Climate regulation value} + \text{Flood prevention value} + \text{Biodiversity protection value} \quad (4.14)$$

Where each value of good or service can be calculated by equation 4.15

$$\text{Value of goods or Services per year (US\$)} = \text{Value}_{\text{in year 2012}} \text{ of goods or services per ha per year (\$)} \times \text{area burned (ha)} \times \text{damage (\%)} \quad (4.15)$$

As outlined in Chapter 3, the estimated area burned of one hotspot was 12,750 $m^2$ or 1.275 ha. There were 498 hotspots in mixed deciduous forest, hill evergreen forest, dry evergreen forest, and dry dipterocarp forest during 26th February to 1st March 2012 in Chiang Mai. The forest goods and services losses by fire events were calculated by using the value from Table 4.25. However, fire intensities in different types of forest cause the different impacts of ecosystem goods and services. The percent damages of different forest types were considered to estimate the total value of ecosystem goods and services as equation (4.14). The value of the impacts to mixed deciduous forest, hill evergreen forest, dry evergreen forest, and dry dipterocarp forest are shown in Table 4.26.

**Table 4.26** The impact values of forest fires to ecosystem goods and services of mixed deciduous forest, hill evergreen forest, dry evergreen forest, and dry dipterocarp forest in Chiang Mai during 26th February to 1st March 2012.

| Details | Mixed deciduous forest | Dry dipterocarp forest | Hill evergreen forest | Dry evergreen forest | Total |
|---|---|---|---|---|---|
| Numbers of hotspots | 321 | 41 | 71 | 65 | 498 hotspots |
| Area burned (ha) | 321x1.275 = 409.3 | 41x1.275 = 52.3 | 71x1.275 = 90 | 65x1.275 = 83 | 635.1 ha |
| Value of timber ($12.75/ha) | No effect | No effect | No effect to 90 x 12.75 x 0.5 = $577 | No effect to 83 x 12.75 x 0.5 = $529 | $0 to $1,106 |
| Non-timber products ($87/ha) | 409.3 x 87= $35,609 | 52.3 x 87= $4,550 | 90 x 87 = $7,830 | 83 x 87 = $7,221 | $55,210 |
| Medical resources ($0.33/ha) | 409.3 x 0.33= $135.1 | 52.3 x 0.33= $17.3 | 90 x 0.33= $29.7 | 83 x 0.33= $27.4 | $209.5 |
| Recreation and tourism ($11.35/ha) | 409.3 x 11.35= $4,645.6 | 52.3 x 11.35= $593.6 | 90 x 11.35= $1,021.5 | 83 x 11.35= $942.1 | $7,202.8 |
| Climate regulation ($880/ha) | 409.3 x 880 x 0.25= $90,046 | 52.3 x 880 x 0.25= $11,506 | 90 x 880 x 0.5= $39,600 | 83 x 880 x 0.5= $36,520 | $177,672 |
| Flood prevention ($105.6/ha) | 409.3 x 105.6= $43,222 | 52.3 x 105.6= $5,523 | 90 x 105.6= $9,504 | 83 x 105.6= $8,765 | $67,014 |
| Biodiversity protection ($13.13/ha) | No effect | No effect | No effect to 90 x 13.13 x 0.25= $295.4 | No effect to 83 x 13.13 x 0.25= $272.4 | $0 to $567.8 |
| | | Total | | | $307,308 to $308,982 |

The estimated total value of forest losses from 5-day fires in Chiang Mai province will be $307,308 to $308,982, or $307,308 / 5 and $308,982 / 5 = $61,461.6 to $61,796.4 for averaged 1-day value. This loss is a small amount compared with the health impact value at $4,519,326 for 5-days impact value or $903,865.2 for averaged 1-day value. The estimated total value of ecosystem goods and services losses in the study, 8 provinces were $1,063,001.47 to $1,066,018.23. Details of the rest of the areas' values are shown in Table 4.27. After fire controlled, the estimated total value of ecosystem goods and services losses were $440,359.44 to $441,713.91 for controlled fires both agricultural and forest around agricultural area 1 km, and $36,644.87 to $36,804.95 for controlled fires both agricultural and forest around agricultural area 4 km (see Table 4.28 and Table 4.29).

**Table 4.27** Summary of impact values from forest fires to ecosystem goods and services of mixed deciduous forest, hill evergreen forest, dry evergreen forest, and dry dipterocarp forest in Chiang Mai, Mae Hong Son, Nan, Chiang Rai, Lampang, Phrae, Phayao and Lamphun during 26 February to 1 March 2012**.**

| Land use type | Chiang Mai | Mae Hong Son | Nan | Chiang Rai | Lampang | Phrae | Phayao | Lamphun | Total |
|---|---|---|---|---|---|---|---|---|---|
| Number of hotspots in mixed deciduous forest / area burned (ha) | 321/ 409.275 | 287/ 365.925 | 260/ 331.5 | 207/ 263.925 | 197/ 251.175 | 77/ 98.175 | 58/ 73.95 | 74/ 94.35 | 1,481/ 1,888.275 |
| Number of hotspots in dry dipterocarp forest / area burned (ha) | 41/ 52.275 | 9/ 11.475 | 16/ 20.4 | 1/ 1.275 | 8/ 10.2 | 13/ 16.575 | 8/ 10.2 | 16/ 20.4 | 112/ 142.8 |
| Number of hotspots in hill evergreen forest / area burned (ha) | 71/ 90.525 | 25/ 31.875 | 7/ 8.925 | 2/ 2.55 | 6/ 7.65 | 3/ 3.825 | 18/ 22.95 | 1/ 1.275 | 133/ 169.575 |
| Number of hotspots in dry evergreen forest / area burned (ha) | 65/ 82.875 | 8/ 10.2 | 0/ 0 | 14/ 17.85 | 18/ 22.95 | 4/ 5.1 | 3/ 3.825 | 0/ 0 | 112/ 142.8 |
| Value of timber (US$12.75/ha) (US$) | 0 to1,105.43 | 0 to 268.23 | 0 to 56.90 | 0 to 130.05 | 0 to 195.08 | 0 to 56.90 | 0 to 170.69 | 0 to 8.13 | 0 to 1,991.39 |
| Non-timber products (US$87/ha) (US$) | 55,240.65 | 36,494.33 | 31,391.78 | 24,847.20 | 25,401.83 | 10,759.73 | 9,650.48 | 10,094.18 | 203,880.15 |
| Medical resources (US$0.33/ha) (US$) | 209.53 | 138.43 | 119.07 | 94.25 | 96.35 | 40.81 | 36.61 | 38.29 | 773.34 |
| Recreation and tourism (US$11.35/ha) (US$) | 7,206.68 | 4,761.04 | 4,095.36 | 3,241.56 | 3,313.92 | 1,403.71 | 1,259.00 | 1,316.88 | 26,598.16 |
| Climate regulation (US$880/ha) (US$) | 177,837.00 | 101,541.00 | 81,345.00 | 67,320.00 | 70,966.50 | 29,172.00 | 30,294.00 | 25,806.00 | 584,281.50 |
| Flood prevention (US$105.6/ha) (US$) | 67,050.72 | 44,296.56 | 38,103.12 | 30,159.36 | 30,832.56 | 13,060.08 | 11,713.68 | 12,252.24 | 247,468.32 |
| Biodiversity protection (US$13.13/ha) (US$) | 0 to 569.19 | 0 to 138.11 | 0 to 29.30 | 0 to 66.96 | 0 to 100.44 | 0 to 29.30 | 0 to 87.89 | 0 to 4.19 | 0 to 1,025.37 |
| Total value US$ | 307,544.59 to 309,219.20 | 187,231.35 to 187,637.69 | 155,054.33 to 155,140.52 | 125,662.37 to 125,859.38 | 130,611.15 to 130,906.67 | 54,436.33 to 54,522.52 | 52,953.76 to 53,212.34 | 49,507.59 to 49,519.90 | 1,063,001.47 to 1,066,018.23 |

**Table 4.28** Summary of impact values from forest fires to ecosystem goods and services after fires controlled both agricultural and forest around agricultural area 1 km for mixed deciduous forest, hill evergreen forest, dry evergreen forest, and dry dipterocarp forest in Chiang Mai, Mae Hong Son, Nan, Chiang Rai, Lampang, Phrae, Phayao and Lamphun during 26 February to 1 March 2012

| Land use type | Chiang Mai | Mae Hong Son | Nan | Chiang Rai | Lampang | Phrae | Phayao | Lamphun | Total |
|---|---|---|---|---|---|---|---|---|---|
| Number of hotspots in mixed deciduous forest / area burned (ha) | 113/ 144.075 | 151/ 192.525 | 101/ 128.775 | 42/ 53.55 | 91/ 116.025 | 37/ 47.175 | 15/ 19.125 | 50/ 63.75 | 600/ 765 |
| Number of hotspots in dry dipterocarp forest / area burned (ha) | 25/ 31.875 | 10/ 12.75 | 3/ 3.825 | 0 | 1/ 1.275 | 5/ 6.375 | 0 | 3/ 3.825 | 47/ 59.925 |
| Number of hotspots in hill evergreen forest / area burned (ha) | 11/ 14.025 | 4/ 5.1 | 0 | 7/ 8.925 | 10/ 12.75 | 5/ 6.375 | 3/ 3.825 | 0 | 40/ 51 |
| Number of hotspots in dry evergreen forest / area burned (ha) | 25/ 31.875 | 15/ 19.125 | 7/ 8.925 | 2/ 2.55 | 4/ 5.1 | 1/ 1.275 | 15/ 19.125 | 1/ 1.275 | 70/ 89.25 |
| Value of timber (US$ 12.75/ha) (US$) | 0 to 292.61 | 0 to 154.43 | 0 to 56.90 | 0 to 73.15 | 0 to 113.79 | 0 to 48.77 | 0 to 146.31 | 0 to 8.13 | 0 to 894.09 |
| Non-timber products (US$ 87/ha) (US$) | 19,300.95 | 19,966.50 | 12,312.68 | 5,657.18 | 11,758.05 | 5,324.40 | 3,660.53 | 5,989.95 | 83,970.23 |
| Medical resources (US$ 0.33/ha) (US$) | 73.21 | 75.74 | 46.70 | 21.46 | 44.60 | 20.20 | 13.88 | 22.72 | 318.51 |
| Recreation and tourism (US$ 11.35/ha) (US$) | 2,518.00 | 2,604.83 | 1,606.31 | 738.03 | 1,533.95 | 694.62 | 477.55 | 781.45 | 10,954.74 |
| Climate regulation (US$ 880/ha) (US$) | 58,905.00 | 55,819.50 | 33,099.00 | 16,830.00 | 33,660.00 | 15,147.00 | 14,305.50 | 15,427.50 | 243,193.50 |
| Flood prevention (US$ 105.6/ha) (US$) | 23,427.36 | 24,235.20 | 14,945.04 | 6,866.64 | 14,271.84 | 6,462.72 | 4,443.12 | 7,270.56 | 101,922.48 |
| Biodiversity protection (US$ 13.13/ha) (US$) | 0 to 150.67 | 0 to 79.52 | 0 to 29.30 | 0 to 37.67 | 0 to 58.59 | 0 to 25.11 | 0 to 75.33 | 0 to 4.19 | 0 to 460.37 |
| Total value US$ | 104,224.51 to 104,667.80 | 102,701.76 to 102,935.71 | 62,009.72 to 62,095.92 | 30,113.30 to 30,224.12 | 61,268.44 to 61,440.82 | 27,648.93 to 27,722.81 | 22,900.58 to 23,122.22 | 29,492.17 to 29,504.49 | 440,359.44 to 441,713.91 |

**Table 4.29** Summary of impact values from forest fires to ecosystem goods and services after fires controlled both agricultural and forest around agricultural area 4 km for mixed deciduous forest, hill evergreen forest, dry evergreen forest, and dry dipterocarp forest in Chiang Mai, Mae Hong Son, Nan, Chiang Rai, Lampang, Phrae, Phayao and Lamphun during 26 February to 1 March 2012

| Land use type | Chiang Mai | Mae Hong Son | Nan | Chiang Rai | Lampang | Phrae | Phayao | Lamphun | Total |
|---|---|---|---|---|---|---|---|---|---|
| Number of hotspots in mixed deciduous forest / area burned (ha) | 6/ 7.65 | 14/ 17.85 | 3/ 3.825 | 0 | 1/ 1.275 | 1/ 1.275 | 0 | 12/ 15.3 | 37/ 47.175 |
| Number of hotspots in dry dipterocarp forest / area burned (ha) | 4/ 5.1 | 4/ 5.1 | 0 | 0 | 1/ 1.275 | 2/ 2.55 | 0 | 0 | 11/ 14.025 |
| Number of hotspots in hill evergreen forest / area burned (ha) | 1/ 1.275 | 5/ 6.375 | 1/ 1.275 | 0 | 0 | 0 | 0 | 1/ 1.275 | 8/ 10.2 |
| Number of hotspots in dry evergreen forest / area burned (ha) | 0 | 0 | 0 | 0 | 1/ 1.275 | 4/ 5.1 | 0 | 0 | 5/ 6.375 |
| Value of timber (US$ 12.75/ha) (US$) | 0 to 8.13 | 0 to 40.64 | 0 to 8.13 | 0 | 0 to 8.13 | 0 to 32.51 | 0 | 0 to 8.13 | 0 to 105.67 |
| Non-timber products (US$ 87/ha) (US$) | 1,220.18 | 2,551.28 | 443.70 | 0 | 332.78 | 776.48 | 0 | 1,442.03 | 6,766.43 |
| Medical resources (US$ 0.33/ha) (US$) | 4.63 | 9.68 | 1.68 | 0 | 1.26 | 2.95 | 0 | 5.47 | 25.67 |
| Recreation and tourism (US$ 11.35/ha) (US$) | 159.18 | 332.84 | 57.89 | 0 | 43.41 | 101.30 | 0 | 188.13 | 882.75 |
| Climate regulation (US$ 880/ha) (US$) | 3,366.00 | 7,854.00 | 1,402.50 | 0 | 1,122.00 | 3,085.50 | 0 | 3,927.00 | 20,757.00 |
| Flood prevention (US$ 105.6/ha) (US$) | 1,481.04 | 3,096.72 | 538.56 | 0 | 403.92 | 942.48 | 0 | 1,750.32 | 8,213.04 |
| Biodiversity protection (US$ 13.13/ha) (US$) | 0 to 4.19 | 0 to 20.93 | 0 to 4.19 | 0 | 0 to 4.19 | 0 to 16.74 | 0 | 0 to 4.19 | 0 to 54.41 |
| Total value US$ | 6,231.02 to 6,243.34 | 13,844.51 to 13,906.07 | 2,444.32 to 2,456.64 | 0 | 1,903.37 to 1,915.68 | 4,908.69 to 4,957.95 | 0 | 7,312.94 to 7,325.25 | 36,644.87 to 36,804.95 |

**Table 4.30** Summary of impact values from forest fires to ecosystem goods and services of mixed deciduous forest, hill evergreen forest, dry evergreen forest, and dry dipterocarp forest in Chiang Mai, Mae Hong Son, Nan, Chiang Rai, Lampang, Phrae, Phayao and Lamphun during 1 February to 30 April 2012**.**

| Land use type | Chiang Mai | Mae Hong Son | Nan | Chiang Rai | Lampang | Phrae | Phayao | Lamphun | Total |
|---|---|---|---|---|---|---|---|---|---|
| Number of hotspots in mixed deciduous forest / area burned (ha) | 1,077/ 1,373 | 1,580/ 2,015 | 1,514/ 1,930 | 787/ 1,003 | 506/ 645 | 321/ 409 | 198/ 252 | 251/ 320 | 6,234/ 7,948 |
| Number of hotspots in dry dipterocarp forest / area burned (ha) | 214/ 273 | 77/ 98 | 77/ 98 | 6/ 8 | 42/ 54 | 38/ 48 | 30/ 38 | 72/ 92 | 556/ 709 |
| Number of hotspots in hill evergreen forest / area burned (ha) | 413/ 527 | 388/ 495 | 75/ 96 | 2/ 3 | 11/ 14 | 11/ 14 | 135/ 172 | 5/ 6 | 1,040/ 1,326 |
| Number of hotspots in dry evergreen forest / area burned (ha) | 206/ 263 | 60/ 77 | 13/ 17 | 37/ 47 | 49/ 62 | 29/ 37 | 5/ 6 | 0/ 0 | 399/ 509 |
| Value of timber (US$ 12.75/ha) (US$) | 0 to 5,031 | 0 to 3,641 | 0 to 715 | 0 to 317 | 0 to 488 | 0 to 325 | 0 to 1,138 | 0 to 41 | 0 to 11,696 |
| Non-timber products (US$ 87/ha) (US$) | 211,867 | 233,497 | 186,243 | 92,290 | 67,442 | 44,259 | 40,820 | 36,383 | 912,802 |
| Medical resources (US$ 0.33/ha) (US$) | 804 | 886 | 706 | 350 | 256 | 168 | 155 | 138 | 3,462 |
| Recreation and tourism (US$ 11.35/ha) (US$) | 27,640 | 30,462 | 24,297 | 12,040 | 8,799 | 5,774 | 5,325 | 4,747 | 119,084 |
| Climate regulation (US$ 880/ha) (US$) | 709,385 | 716,117 | 495,644 | 244,316 | 187,374 | 123,140 | 142,494 | 93,407 | 2,711,874 |
| Flood prevention (US$ 105.6/ha) (US$) | 257,162 | 283,417 | 226,061 | 112,020 | 81,861 | 53,721 | 49,548 | 44,162 | 1,107,953 |
| Biodiversity protection (US$ 13.13/ha) (US$) | 0 to 2,591 | 0 to 1,875 | 0 to 368 | 0 to 163 | 0 to 251 | 0 to 167 | 0 to 586 | 0 to 21 | 0 to 6,022 |
| Total value US$ | 1,206,857 to 1,214,479 | 1,264,378 to 1,269,895 | 932,951 to 934,034 | 461,016 to 461,496 | 345,732 to 346,471 | 227,062 to 227,554 | 238342 to 240066 | 178,836 to 178,898 | 4,855,175 to 4,872,894 |

**Table 4.31** Summary of impact values from forest fires to ecosystem goods and services after fires controlled both agricultural and forest around agricultural area 1 km for mixed deciduous forest, hill evergreen forest, dry evergreen forest, and dry dipterocarp forest in Chiang Mai, Mae Hong Son, Nan, Chiang Rai, Lampang, Phrae, Phayao and Lamphun during 1 February to 30 April 2012**.**

| Land use type | Chiang Mai | Mae Hong Son | Nan | Chiang Rai | Lampang | Phrae | Phayao | Lamphun | Total |
|---|---|---|---|---|---|---|---|---|---|
| Number of hotspots in mixed deciduous forest / area burned (ha) | 381/ 486 | 823/ 1,049 | 599/ 764 | 192/ 245 | 285/ 363 | 165/ 210 | 81/ 103 | 169/ 215 | 2,695/ 3,436 |
| Number of hotspots in dry dipterocarp forest / area burned (ha) | 140/ 179 | 52/ 66 | 54/ 69 | 3/ 4 | 26/ 33 | 15/ 19 | 21/ 27 | 36/ 46 | 347/ 442 |
| Number of hotspots in hill evergreen forest / area burned (ha) | 143/ 182 | 149/ 190 | 36/ 46 | 2/ 3 | 8/ 10 | 5/ 6 | 100/ 128 | 5/ 6 | 448/ 571 |
| Number of hotspots in dry evergreen forest / area burned (ha) | 39/ 50 | 21/ 27 | 4/ 5 | 17/ 22 | 35/ 45 | 29/ 37 | 4/ 5 | 0/ 0 | 149/ 190 |
| Value of timber (US$ 12.75/ha) (US$) | 0 to 1,479 | 0 to 1,382 | 0 to 325 | 0 to 154 | 0 to 350 | 0 to 276 | 0 to 845 | 0 to 41 | 0 to 4,852 |
| Non-timber products (US$ 87/ha) (US$) | 77,980 | 115,917 | 76,871 | 23,738 | 39,267 | 23,738 | 22,851 | 23,294 | 403,656 |
| Medical resources (US$ 0.33/ha) (US$) | 296 | 440 | 292 | 90 | 149 | 90 | 87 | 88 | 1,531 |
| Recreation and tourism (US$ 11.35/ha) (US$) | 10,173 | 15,122 | 10,029 | 3,097 | 5,123 | 3,097 | 2,981 | 3,039 | 52,661 |
| Climate regulation (US$ 880/ha) (US$) | 248,243 | 340,808 | 205,607 | 65,357 | 111,359 | 69,564 | 86,955 | 60,308 | 1,188,198 |
| Flood prevention (US$ 105.6/ha) (US$) | 94,652 | 140,699 | 93,306 | 28,813 | 47,663 | 28,813 | 27,736 | 28,274 | 489,955 |
| Biodiversity protection (US$ 13.13/ha) (US$) | 0 to 762 | 0 to 711 | 0 to 167 | 0 to 80 | 0 to 180 | 0 to 142 | 0 to 435 | 0 to 21 | 0 to 2,499 |
| Total value US$ | 431,344 to 433,585 | 612,985 to 615,078 | 386,103 to 386,596 | 121,094 to 121,328 | 203,560 to 204,090 | 125,302 to 125,720 | 140,609 to 141,890 | 115,003 to 115,065 | 2,136,001 to 2,143,352 |

**Table 4.32** Summary of impact values from forest fires to ecosystem goods and services after fires controlled both agricultural and forest around agricultural area 4 km for mixed deciduous forest, hill evergreen forest, dry evergreen forest, and dry dipterocarp forest in Chiang Mai, Mae Hong Son, Nan, Chiang Rai, Lampang, Phrae, Phayao and Lamphun during 1 February to 30 April 2012**.**

| Land use type | Chiang Mai | Mae Hong Son | Nan | Chiang Rai | Lampang | Phrae | Phayao | Lamphun | Total |
|---|---|---|---|---|---|---|---|---|---|
| Number of hotspots in mixed deciduous forest / area burned (ha) | 24/ 31 | 193/ 246 | 48/ 61 | 1/ 1 | 56/ 71 | 21/ 27 | 4/ 5 | 58/ 74 | 405/ 516 |
| Number of hotspots in dry dipterocarp forest / area burned (ha) | 27/ 34 | 17/ 22 | 0/ 0 | 0/ 0 | 3/ 4 | 5/ 6 | 4/ 5 | 4/ 5 | 60/ 77 |
| Number of hotspots in hill evergreen forest / area burned (ha) | 9/ 11 | 19/ 24 | 11/ 14 | 1/ 1 | 1/ 1 | 0/ 0 | 31/ 40 | 2/ 3 | 74/ 94 |
| Number of hotspots in dry evergreen forest / area burned (ha) | 0/ 0 | 0/ 0 | 0/ 0 | 0/ 0 | 12/ 15 | 19/ 24 | 0/ 0 | 0/ 0 | 31/ 40 |
| Value of timber (US$ 12.75/ha) (US$) | 0 to 73 | 0 to 154 | 0 to 89 | 0 to 8 | 0 to 106 | 0 to 154 | 0 to 252 | 0 to 16 | 0 to 853 |
| Non-timber products (US$ 87/ha) (US$) | 6,656 | 25,402 | 6,545 | 222 | 7,987 | 4,992 | 4,326 | 7,099 | 63,227 |
| Medical resources (US$ 0.33/ha) (US$) | 25 | 96 | 25 | 1 | 30 | 19 | 16 | 27 | 240 |
| Recreation and tourism (US$ 11.35/ha) (US$) | 868 | 3,314 | 854 | 29 | 1,042 | 651 | 564 | 926 | 8,249 |
| Climate regulation (US$ 880/ha) (US$) | 19,355 | 69,564 | 19,635 | 842 | 23,843 | 17,952 | 19,635 | 18,513 | 189,338 |
| Flood prevention (US$ 105.6/ha) (US$) | 8,078 | 30,833 | 7,944 | 269 | 9,694 | 6,059 | 5,251 | 8,617 | 76,745 |
| Biodiversity protection (US$ 13.13/ha) (US$) | 0 to 38 | 0 to 80 | 0 to 46 | 0 to 4 | 0 to 54 | 0 to 80 | 0 to 130 | 0 to 8 | 0 to 439 |
| Total value US$ | 34,982 to 35,093 | 129,209 to 129,443 | 35,002 to 35,137 | 1,362 to 1,375 | 42,595 to 42,755 | 29,673 to 29,907 | 29,793 to 30,175 | 35,182 to 35,207 | 337,798 to 339,091 |

The estimated total value of ecosystem goods and services losses in Chiang Mai, Mae Hong Son, Nan, Chiang Rai, Lampang, Phrae, Phayao and Lamphun during 1 February to 30 April 2012 were $4,855,175 to $4,872,894 (see Table 4.30). After fire controlled, the estimated total value of ecosystem goods and services losses were $2,136,001 to $2,143,352 for controlled fires both agricultural and forest around agricultural area 1 km, and $337,798 to $339,091 for controlled fires both agricultural and forest around agricultural area 4 km (see Table 4.31 and Table 4.32). However, the total ecosystem goods and services loss is a small amount compared with the health impact value at $224,163,186 and $974,768,271 through fire season.

The economic losses decreased by $2,729,541 or 56% from $4,872,894 to $2,143,352 from fire controlled ranged 1 km and decreased by $4,533,803 or 93% from $2,729,541 to $339,091 from fire controlled ranged 4 km. The economic loss from climate regulation was more than 50% of the total value of ecosystem goods and services.

### 4.4 Cost-benefit analysis module

To evaluate the government budget for fire management, cost-benefit analysis was used to find suitable policies for solving the forest fire problems. The value of the impacts(s) of vegetation fires both health and ecosystems were set as the benefits from fires managements and the government budgets were set as costs. The comparison costs and benefits are shown in Figure 4.5. The net values of each case are compared to choose the most suitable budget.

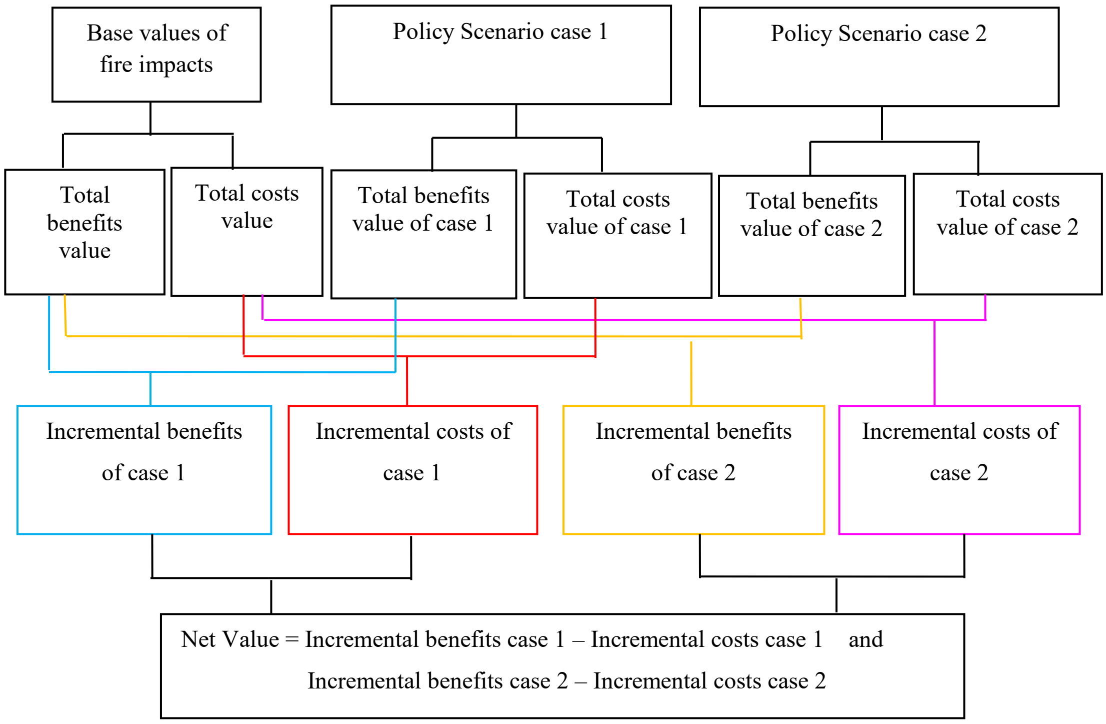



**Figure 4.5** A schematic of comparing costs and benefits from policy scenarios in a cost-benefit analysis

The economic valuation of forest management by the government would cover all main stakeholders. Variables for weighting costs and benefits of policy interventions are listed in Table 4.33.

**Table 4.33** Summary of costs and benefits from forest fires interventions by the government.

| Party affected | Costs | Benefits | Sources of data /value of forest good and services |
|---|---|---|---|
| 1. Government | | | |
| 1.1 Central government | Cost for vegetation fire management | | - Government departments in Thailand (Royal forest department, Department of national parks, wildlife and plant conservation, and Pollution control department) and study reports<br>- Prescribe burning cost = 25.38 US$/ha/day (5,000 Bath/rai/day) (Dontee et al., 2011) 1 Bath= US$0.03173 (in year 2011)<br>- Building fire buffer cost = 108 US$/km (Dontee et al., 2011)<br>- Promoting and giving knowledge about vegetation fire impacts and control to northern people in 8 provinces = US$ 4.94 million |
| 2. Industry | | | |
| 2.1 Tourism | | - Income from tourism | - Tourism and recreation value |
| 2.2 Transportation | | - Decreased cancellations of flights | - 1 flight = 3,630 US$ (66 seats, price ~55 US$/seat) cancelled due to visibility at runway area less than 1,500 m. http://www2.manager.co.th/Daily/ViewNews.aspx?NewsID=9550000027867 |
| 3. Householders | | | |
| 3.1 People's health (loss of life, illness from air pollution) | | - Value of human life<br>- Illness treatment cost | -The estimation of morbidity, mortality impact value caused by air pollution from fires |
| 3.2 Property | | - Reduced damage to property | - There was no property damaged from forest fires (Department of National Parks Wildlife and Plant Conservation 2012). |
| 3.3 Local people/ Farmers | | -Forest goods and services | - Timber and non-timber products value<br>- Water supply value |
| 4. Ecosystem | | | |
| 4.1 Watershed Protection | | - Water regulation<br>- Flood protection | - Flood prevention value |
| 4.2 Carbon sequestration | | - Carbon credits | - Climate regulation by considering carbon sequestration value |
| 4.3 Biodiversity | | - Increase biodiversity | - Biodiversity value |

Land-use types in study area include national parks at around 3,392,670 ha, forest parks (excluding agricultural area) of about 2,682,170 ha, and agricultural area at around 1,690,045 ha (Ministry of Nataural Resources and Environment, 2015, OFFICE OF NATURAL RESOURCES AND ENVIRONMENTAL POLICY AND PLANNING (ONEP), 2009). The differences between national parks and forest parks relate to people's rights to use and manage forests. The people are not allowed to live permanently in national parks, while in forest parks people can settle including managing forest areas (Royal Forest Department, 2016a). Most areas burned were in forest parks in every province except Mae Hong Son, which were dominant in national parks. Generally, national parks have fewer disturbances from fires and timber harvest compared with forest parks. Forest parks consist of many secondary forests where trees have been lost by timber harvest, shifting cultivation systems of agriculture and fires. The main government organizations for fire management in agricultural, national parks and national forests area are Ministry of Natural Resources and Environment: Department of National Parks, Wildlife and Plant Conservation (DNP) and Royal Forest Department (RFD), and Ministry of Agriculture and Cooperatives. To compare the net value of government options for fire management (see Figure 4.5), incremental costs are the additional costs from the current budget for controlling fires in the target area including agricultural and forest nearby 1-4 km to have no fire. The government measures for each land-use type are considered.

In the agricultural area, fires are used in processes of agricultural residue management and field preparation. The use of fires in this area not only is the cause of fire events in agricultural area, but also is the cause of fires spreading to forest areas by 15% of all cause of forest fires (Department of National Parks Wildlife and Plant Conservation, 2012). Most of farmers in the north of Thailand are poor and cannot get technologies and machines for these processes. The government may support technologies and machines for fires controlled in these agricultural areas. To prevent fires spreading to forest areas, building fire buffer between agricultural areas and forests is also considered for the budget. The costs for these areas are shown in Table 4.34.

For fires in forest areas nearby agricultural areas ranged 1 to 4 km, forest goods collecting is the main cause at around 51% of all cause of forest fires (Department of National Parks Wildlife and Plant Conservation, 2012). The measures, which the government can use for fire control in this area, are hiring more officers to keep guarding the forest area nearby agricultural areas ranged 1km and 4 km in the fire season during February to April every year.

The government budget for fire control and fire impact values were identified and shown in Table 4.34. There are two main landuse types for fire managements: agricultural and forest areas. Generally, there are agricultural areas both inside and outside forests areas. There are 1,601 villages in forest parks (Royal Forest Department, 2016a) and 418 villages close to national parks (Ministry of Nataural Resources and Environment, 2015) which have agricultural activities and use forest goods and services. A budget of 3,218 US$ per village (Ministry of Nataural Resources and Environment, 2015) was set for fire management in agricultural area and forest area nearby the village. There are around 1,690,045 ha of agricultural areas outside forest area (Ministry of Nataural Resources and Environment, 2015). Ministry of Agriculture and Cooperatives has set the budget in a 10-year plan for supporting knowledge, technology and building motivation to farmers to manage agriculture areas without fire use by spending at around18,252,486 US$ for all agricultural areas in the study area (or at around 10.80 US$/ha) (Ministry of Nataural Resources and Environment, 2015).

Forest area size per one forest guard was estimated from( Ministry of Nataural Resources and Environment, 2015). This plan required 25 volunteers from each village for protecting forests area around their villages. FromRoyal Forest Department (2016a), there were 1,601 villages covering area 172,700 ha in the national forest, then 1 village cover area 108 ha or 1.08 $km^2$. The estimated area of forest around village ranging 1 to 1.5 km from village was around 4.16 to 6.3 $km^2$ (420 to 630 ha) per village. The total area for all villages is around 670,000 ha. Therefore, 25 volunteers respond the forest area 416 to 630 ha or 1 volunteer per 17 to 25 ha. This study chose 1 forest guard per a corresponding forest area of 25 ha.

**Table 4.34** The cost of fire management for agricultural area, forest areas nearby agricultural ranging 1 to 4 km and all forest area by government measures

| | Number of target units | Cost per unit (US$) | Total costs (US$) | Annual budget (US$) | Main government organization |
|---|---|---|---|---|---|
| **Agricultural area:** | | | | | |
| Agricultural area (outside national park areas) | | | | | |
| - Supporting knowledge , technology and building motivation to farmers in 8 provinces for managing agriculture area without fire use | 1,690,045 ha | 10.80 US$ per ha | 18,252,486 | 18,252,486 | Ministry of Agriculture and Cooperatives |
| Agricultural area and villages near forest parks | | | | | |
| - Supporting knowledge , technology and building motivation to farmers in 8 provinces for managing agriculture area without fire use<br>- Supporting fund for preventing and suppressing forest fires | 1,601 villages (~172,700 ha) | 3,218 US$ per village | 4,733,678 | 4,733,678 | Ministry of Natural Resources and Environment |

| | Number of target units | Cost per unit (US$) | Total costs (US$) | Annual budget (US$) | Main government organization |
|---|---|---|---|---|---|
| **Border between agricultural area and forests:** | | | | | |
| Building Fire buffer (National Park 5,700 km, Forest Park 6,700 km) | 12,400 km | 108 US$ per km | 1,339,200 | 1,339,200 (December to February) | Ministry of Natural Resources and Environment |
| **Forest areas:** | | | | | |
| Forest areas nearby agricultural ranging 1 km covering area 670,000 ha for forest parks | | | | | |
| - Number of guard/firefighter officers (1 officers per 25 ha) | 26,800 officers | 10 US$ per day | 268,000 (per day) | 24,120,000 (90 days) | Ministry of Natural Resources and Environment |
| Forest areas nearby agricultural ranging 1 km covering area 570,000 ha for national parks | | | | | |
| - Number of guard/firefighter officers (1 officers per 25 ha) | 28,500 officers | 10 US$ per day | 228,000 (per day) | 20,520,000 (90 days) | Ministry of Natural Resources and Environment |
| Forest areas nearby agricultural ranging 4 km covering area 2,660,000 ha for forest parks | | | | | |
| - Number of guard/ firefighter officers (1 officer per 25 ha) | 133,000 officers | 10 US$ per day | 1,064,000 (per day) | 95,760,000 (90 days) | Ministry of Natural Resources and Environment |
| Forest areas nearby agricultural ranging 4 km covering area 2,280,000 ha for national parks | | | | | |
| - Number of guard/ firefighter officers (1 officer per 25 ha) | 114,000 officers | 10 US$ per day | 912,000 (per day) | 82,080,000 (90 days) | Ministry of Natural Resources and Environment |
| Forest areas nearby agricultural ranging 204 km covering area 1,990,000 ha for forest parks | | | | | |
| - Number of guard/ firefighter officers (1 officer per 25 ha) | 99,500 officers | 10 US$ per day | 796,000 (per day) | 71,640,000 (90 days) | Ministry of Natural Resources and Environment |
| All forest areas covering area 2,682,170 ha for forest parks | | | | | |
| - Number of guard/ firefighter officers (1 officer per 25 ha) | 134,109 officers | 10 US$ per day | 10,728,680( per day) | 965,581,200 (90 days) | Ministry of Natural Resources and Environment |
| All forest areas covering area 3,392,670 ha for national parks | | | | | |
| - Number of guard/ firefighter officers (1 officer per 25 ha) | 169,634 officers | 10 US$ per day | 13,570,680 (per day) | 1,221,361,200 (90 days) | Ministry of Natural Resources and Environment |
| Prescribe burning | | | | | |
| - For dipterocarp forest area 136,400 ha in National parks | 136,400 ha | 25.4 US$ per ha | 3,464,560 | 3,464,560 | Ministry of Natural Resources and Environment |

From the health impacts and ecosystem goods and services valuation part, the estimated total losses in eight provinces in the north of Thailand during 1 February to 30 April 2012 from vegetation fires were $229 million to $980 million. These values consist of ecosystem goods and services at around $4.9 million and health impact value of about $224 million to $975 million. The economic losses decreased by $178 million or 77.5% from $229 million to 51 million by the baseline value at 50 μg/m$^3$, and by \$223 million or 22.8% from \$980 million to \$757 million by the baseline value at 20 μg/m$^3$ from fire controlled ranged 1 km. After from fire controlled ranged 4 km, economic losses decreased by \$227 million or 98.9 % from \$229million to 2.5 million by the baseline value at 50 μg/m$^3$, and by \$328 million or 33.5 % from \$980 million to \$652 million by the baseline value at 20 μg/m$^3$. However, the government budget for fire management has to be considered for the worthwhile investment. The detail of the cost of government option budgets and fire impacts values are shown in Table 4.35.

The government budget for short-term fire management of the main ministries; Ministry of Agriculture and Cooperatives and Ministry of Natural Resources and Environment, in year 2012 was about 12,659,562 US\$ (Miriam et al., 2015, Pollution Control Department, 2008, Bureau of the Budget, 2012). This budget excluded the public communication cost for giving awareness and community engagement from other organizations such as Office of Prime Minister, Government Public Relations, Department and Ministry of Education and controlling burning of weed along the road by Ministry of Transportation. The budget allocation for fire management did not cover for all fire areas. The budget for Ministry of Agriculture and Cooperatives for fire management in agricultural areas was 1,532,847 US\$ for the target area at 800 ha (Bureau of the Budget, 2012). The budget of Ministry of Natural Resources and Environment was focused on giving knowledge to people, building fire buffers, prescribe burning and fire suppression but it was less emphasized on hiring fire guards (Bureau of the Budget, 2012, Department of National Parks Wildlife and Plant Conservation, 2012). There were about 2,500 officers (consist of 1,500 firefighters and other duties) responding to forest fires in national park areas 3,392,670 ha (Department of National Parks Wildlife and Plant Conservation, 2012). This number was not covering all forest area for preventing and detecting fire occurrences from the local people and cannot suppress fires efficiently in the fire season with fire frequencies more than 300 events per day (hotspots) in the peak period. According to the Food and Agriculture Organization (FAO) of the United Nations (2007), the limited fund for fire management in Southeast Asia affects the fire management to be ineffective. In Russia and many countries in South America, have laws for fire management but lack enforcement. These problems also occur in Thailand. A fund for enforcing laws should be considered for Thailand. Then hiring more employees such as forest guards in the fire season is focused in this study.

Compared with actual fire events, additional costs of fire controlled at 1 and 4 km are budgets for employing fireguards and firefighters. From Table 4.35, the estimation of the government budget costs of fire controlled 1 km for forest and national parks area are different in terms of the people's right to use and manage forests. People can settle including managing forest areas in forest parks. The government budget for villages in forest parks to manage their agricultural and forest area ranging 1 km was 4,733,678 US\$. This budget was supported to people in villages to manage their agriculture areas without the use of fire, do prescribe burning in forests, prevent and fight forest fires occurred close to villages (Royal Forest Department, 2016a). For national park, the people are not allowed to live permanently in this forest type. Budgets for managing the national park were spent by the government. Fire controlled by hiring guards/ firefighters for the national park in the range of 1 km was 20,520,000 US$. For building fire buffer between villages and forests, the government was the main party both forest and national parks with the budget at around 1,339,200 US$. The summary of the total cost for agricultural and forest area ranging 1 km was 48,309,924 US$. In addition, the government budget costs of fire controlled both agricultural and forest around agricultural area 4 km was 216,475,364 US$ which includes the fire control in agricultural area inside and outside forest area, building fire buffer, hiring guards/ firefighters for forest park areas nearby agricultural ranging 204 km and national park areas nearby agricultural ranging 4 km.

**Table 4.35** Lists of costs and benefits of fire impacts and government budgets for fire management in agricultural and forest area ranging 1and 4 km **(**US$ millions**)**

| Base value from actual fire events (US$ millions) | | | | | Estimated values from fires controls both agricultural and forest around agricultural area 1 km (US$ millions) | | | | | Estimated values from fires controls both agricultural and forest around agricultural area 4 km (US$ millions) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Impact value | Lower value | Higher value | Fires controlled areas/ measures | Budget cost value | Impact value | Lower value | Higher value | Fires controlled areas/ measures | Budget cost value | Impact value | Lower value | Higher value | Fires controlled areas/ measures | Budget cost value |
| - Health values | 224.16 | 974.77 | - Agricultural area (outside forest area) | 1.53 | - Health values | 49.31 | 755.11 | - Agricultural area (outside forest area) | 18.25 | - Health values | 2.26 | 651.95 | - Agricultural area (outside forest area) | 18.25 |
| - Ecosystem goods and services values | 4.86 | 4.87 | -Agricultural area and in forest park areas and -Forest parks areas | 2.16 | - Ecosystem goods and services values | 2.14 | 2.14 | - Agricultural area and villages in forest areas | 4.73 | - Ecosystem goods and services values | 0.34 | 0.34 | - Agricultural area and villages in forest areas | 4.73 |
| | | | -National parks areas | 8.97 | | | | - Building Fire buffer (National Park 5,700 km, Forest Park 6,700 km) | 1.34 | | | | - Building Fire buffer (National Park 5,700 km, Forest Park 6,700 km) | 1.34 |
| | | | | | | | | - Hiring guard/ fire-fighters for national park areas nearby agricultural ranging 1 km (570,000 ha) | 25.65 | | | | - Hiring guards/ fire-fighters for forest park areas nearby agricultural ranging 204 km (1,990,000 ha) | 89.55 |
| | | | | | | | | - Prescribe burning in national parks | 3.46 | | | | - Hiring guard/ fire-fighters for national park areas nearby agricultural ranging 4 km (570,000 ha ) | 102.60 |
| | | | | | | | | | | | | | - Prescribe burning in national parks | 3.46 |
| Total | 229.02 | 979.64 | Total | 12.66 | Total | 51.45 | 757.25 | Total | 48.31 | Total | 2.60 | 652.29 | Total | 216.8 |
| Midpoint between low and high value | | 604.33 | | | Midpoint between low and high value | | 404.35 | | | Midpoint between low and high value | | 327.45 | | |

**Table 4.36** Summary of cost-benefit analysis including cost and benefit values, incremental cost and benefit values, and net values for fire management in agricultural and forest around agricultural area with the range of 1and 4 km

| Impact value and government's budget (US$ millions) | | Increment of benefit (or decreased value of impacts) and cost (or government's budget) (US$ millions) | | | Net value (US$ millions) | | |
|---|---|---|---|---|---|---|---|
| - Impact value of health and ecosystem goods and services from fires controls both agricultural and forest around agricultural area 1 km | | - Comparing between fires controls with the range of 1 km and actual fires | | | - Net value of fires controls ranging1 km | | |
| | | • Incremental benefit | | | | | |
| Lower value | 51.45 | At lower value | = 229.02 - 51.45= | 177.57 | At lower value | = 177.57 - 35.65 = | 141.92 |
| Higher value | 757.25 | At higher value | = 979.64 - 757.25 = | 222.39 | At higher value | = 222.39 - 35.65 = | 186.74 |
| Midpoint between low and high value | 404.35 | At midpoint value | = 604.33 - 404.35 = | 199.98 | At midpoint value | = 199.98 - 35.65 = | 164.33 |
| Government's budget cost value | 48.31 | • Incremental budget cost | = 48.31 - 12.66 = | 35.65 | | | |
| - Impact value of health and ecosystem goods and services from fires controls both agricultural and forest around agricultural area 4 km | | - Comparing between fires controls with the range of 4 km and actual fires<br>• Incremental benefit | | | - Net value of fires controls ranging 4 km | | |
| Lower value | 2.60 | At lower value | = 229.02 - 2.6 = | 226.42 | At lower value | = 226.42 - 204.14 = | 22.28 |
| Higher value | 652.29 | At higher value | = 979.64 - 652.29 = | 327.35 | At higher value | = 327.35 - 204.14 = | 123.21 |
| Midpoint between low and high value | 327.45 | At midpoint value | = 604.33 - 327.45 = | 276.88 | At midpoint value | = 276.88 - 204.14 = | 72.74 |
| Government's budget value | 216.8 | • Incremental budget cost | = 216.8 –12.66 = | 204.14 | | | |
| - Impact value of health and ecosystem goods and services from actual fire events (or base values) | | - Comparing between no-fire situation in the north of Thailand and actual fires, fires controls with the range of 1 km and 4 km | | | - Comparing between net value of fires controls with the range of 4 km and 1 km | | |
| Lower value | 229.02 | • Actual value of impacts from fire generated in the north of Thailand area, not included other sources or costs from transboundary pollutants from fires in other area) | | | Incremental net value | | |
| Higher value | 979.64 | | | | At midpoint value | =164.33-72.74 = | 91.59 |
| Midpoint between low and high value | 604.33 | | | | | | |
| Government's budget cost value | 12.66 | At baseline 20 $\mu g/m^3$ | = 979.64 – 624.43= | 355.21 | | | |
| | | • For fires controls with the range of 4 km | | | | | |
| - Impact value of health and ecosystem goods and services from no-fire situation in the north of Thailand | | Actual value of impacts from only fires generated in the north of Thailand area after controls fire ranging 4 km, at baseline 20 $\mu g/m^3$ | | | | | |
| Higher value (at baseline 20 $\mu g/m^3$) | 624.43 | | = 652.29 -624.43 = | 27.86 | | | |
| | | Incremental benefit | = 355.21-27.86 = | 327.35 | | | |
| | | • For fires controls with the range of 1 km | | | | | |
| | | Actual value of impacts from only fires generated in the north of Thailand area after controls fire ranging 1 km, at baseline 20 $\mu g/m^3$ | | | | | |
| | | | = 757.25 – 624.43 = | 132.82 | | | |
| | | Incremental benefit | = 355.21-132.82 = | 222.39 | | | |

The net values of government options were shown in Table 4.36. These values were calculated from Figure 4.5 and Table 4.35. The actual government budget for fire controls in year 2012 and the impacts values of actual fire event were set as base values. The impact value of health and ecosystem goods and services after fire-controls options in the area both agricultural and forest around agricultural area 1 km and 4 km from results of air quality models which were estimated in the part of economic losses of health effects, ecosystem goods and services, were also shown in Table 4.35. The amount costs of the government budget for each fire-controls option were calculated based on the budget required by ministries for mitigation fire problems. From the Table 4.36, the midpoint value of incremental benefit of the fires controls 1 km from the base value is \$199.98 million and the incremental cost is \$35.65 million. Then the net value at the midpoint is \$164.33 million. For the fires controls 4 km, the midpoint value of incremental benefit of is \$276.88 million and the incremental cost is \$204.14 million. The net value at the midpoint is \$72.74 million.

## 4.5 Conclusion and discussion

Five-days vegetation fires from 26th February to 1st March 2012 impacted socio-economic losses at around \$86.22 million to \$139.98 million, or around \$17.24 million to \$27.99 million per day. The value of health impacts from $PM_{10}$ was 99.24% of the total loss, which was greater than ecosystem goods and services losses by around 129 times. However, the comparison between costs and benefits of fire impacts and management need the whole year estimation. The estimated total losses in the north of Thailand during 1 February to 30 April 2012 from vegetation fires were \$229.02 million to \$979.64 million, which consist of ecosystem goods and services at around \$4.86 million to \$4.87 million and health impact value of about \$224.16 million to \$974.77 million. The value of health impacts from $PM_{10}$ was 97.88 to 99.50% of the total loss, which was greater than ecosystem goods and services losses by around 45 to 199 times.

This significant value of health impacts is important information for the government to emphasize on air pollutant by setting the air quality goal for the fire management. Health effects are more easily understood by policy-makers than values associated with many ecosystem services. The reason of health impacts was greater value than the ecosystem good and services value because it affected the large area and large amount of people whereas the depletion of ecosystem goods and services from fires occurred in the smaller area, only the value of climate regulation may affect the global area. From the air quality model, $PM_{10}$ could transport more than 1,000 km from source areas, although the relative contribution to global climate regulation may not be large. However, the value of health is calculated for people in the north of Thailand, not including other areas for this study. The large amount of health impact value will increase for calculating all area affected.

Results from air quality focus on simulating scenarios of all study to meet the Thai air quality standard by controlling fires both agricultural and forest around agricultural area 1 and 4 km. For fire controls in agricultural and forest around agricultural area 1 km, this scenario could not solve the air quality in all area grids, size 27x27 km, in the north of Thailand to meet Thai $PM_{10}$- daily standard compared with controlling fires in agricultural area and forest around agricultural area within 4 km, which it could. This scenario almost is the zero burning which may be difficult in reality. However, in air quality part, the peak period of hotspots and $PM_{10}$ concentrations from 26 February to 1 March 2012 were selected for simulating the optimum option for solving the problem (see for example the Chiang Mai situation in Figure 4.4). Then it may be assumed that $PM_{10}$ concentrations of each grid in rest periods were less than simulating results and the most concentrations met the air quality standard after fire controls ranged 1 km. For the whole area of every single province, there was no daily $PM_{10}$ value exceeding Thai daily standard after fire controls ranged 1 km.

Considering all year estimating value (see Table 4.36), the economic losses at the midpoint value from fire controls ranged 1 km decreased by \$199.98 million or 33.09% from \$604.33 million to \$404.35 million and decreased by \$276.88 million or 45.82% from \$604.33 million to \$327.45 million from fire controls ranged 4 km. The economic losses decreased, or incremental benefit of 4-km fire controls is more than 1-km fire controls (\$276.88 million >\$199.98 million). The hotspot numbers controls in the 4-km option, which is more than the 1-km option (10,437 > 7,368 hotspots), is the factor of the higher incremental benefit of the 4-km option. For the budget cost, the highest cost is from the fireguard employment due to the focus on regulation enforcement. Costs will increase by area based on an area equation of $\pi r^2$.This should be a factor of 16 from the base cost value at \$12.66 million to \$216.8 million for the cost of 4-km fire controls. The cost of 1-km fire controls is \$48.31 million. This cost is less than 4-km fire controls (\$48.31 million < \$216.8million) while the incremental benefit of 4-km fire controls is higher the 1-km option. Then the net value is used for weighting the fire-control options between 1 and 4 km.

The government budget for fire management was considered as a worthwhile investment by cost-benefit analysis. The net value result of the fires controls 1 km at the midpoint is \$164.33 million and \$72.74 million for the fires controls 4 km. The net value of the 1-km fire controls is more than 4-km fire controls. The 1-km fire controls should be more considered in a term of the worthwhile. However, the net value of the 4-km fire controls is also the positive value. Then, the focus of the fire controlled in agricultural area and forest around agricultural area ranging both 1 km and 4 km are the suggested options for the short-term plan. In addition, the rest of budgets of $72.74 million and $164.33 million after employing the short-term plan can be used for a long-term plan. The long-term plan of the fire management is necessary for the sustainable policy. This was discussed in the next chapter.

Considering the study's possible limitations, the measurement error in the input data sets and the lack of representativeness of the available data for study can be a cause of uncertainty (WHO, 2008). A further limitation of this study is assessment based on inconsistent, fragmented and partial data from different studies from various countries due to the lack of mortality and morbidity studies caused by vegetation fires in Thailand. The chosen increased risks of morbidity from difference general background issues and different countries may cause uncertainty in the estimation of death and illness from vegetation fires in the north of Thailand. To provide the best match, this study chose mortality caused by $PM_{10}$ from vehicles emissions in Thailand and used the morbidity risks of $PM_{10}$ from the developed countries as shown in the section 4.2.1.

Beside the uncertainty of health impacts, there are uncertainties related to fire management costs in agricultural and forest areas with the range of 1-4 km as shown in Table 4.35 and 4.36. The sizes of all landuses including agricultural areas, Forest and National Parks were estimated using formulars. The formulars were also applied for area-burned sizes and government budgets. The fire impacts were estimated based on the assumptions that each fire event (or hotspot) has the same size of area burned and the same health impacts. These criteria could not reveal actual-impact values in affected areas. For ecosystem goods and services values, types of vegetations are the important variables to estimate impacts values of each fire event. However, it was also based on the assumption that every area burned was the same size. Therefore, there were uncertainties in all costs and benefits as shown Table 4.35, because these values were calculated by formulas generated with area sizes of landuse and area burned. However, the uncertainty also occurs from the use of benefit transfer method for valuing ecosystem goods and services which may be not good representatives in the study area.

In this study, the area burned size per 1 hotspot was low compared to other studies. This study used 12,750 $m^2$ (or 1.275 ha) per 1 hotspot, while other studies applied up to 1-1.8 $km^2$ (or 100-180 ha) as shown in Section 2.4.2 (Areas burned). The large amount of ecosystem goods and services losses will occur when the higher values of area burned size are used. For the health impacts, the economic losses may be not very different due to the validation process in air quality models. The modelled results have been adjusted to the mornitoring values.

# Chapter 5

## Vegetation Fire Policy

The work presented shows that vegetation fires in the north of Thailand are mainly caused by human activities (see section 3.2). There was a relationship between the forest fire locations that occurred near human communities, especially agricultural and nearby areas. The Government measures can control fires in the short period but need a large budget. Then the middle and long-term fire management is needed for fire management. The strategy options such as fire regulatory, education, physical protection and economic mechanisms are the widespread policy instruments throughout the world. Then these options also should be applied and set to the action plan for Thailand.

In the United States 2012, Wildland Fire Leadership Council (WiFLC) showed quantitative models which each region used for risk analysis and prioritizing landscapes for fuel treatment or prescribed burning (Cook and O'Laughlin, 2014). This study also applied the air quality models to investigate the factors of high pollution levels in the fire season and the suitable number of areas burned to maintain air quality. Results showed that the weather condition is the most important factor for the air pollution occurrences. A few hotspot events affected the air quality and exceeded the air quality standard. Then the zero burning is the main policy option for the fire season. Fires are needed for some vegetation ecosystems and are used to decrease the severity of forest fires in Thailand as in other countries. The reduction of hazardous fuel accumulations appeared in many of the United States' national fire plan's recommendations, especially on lands at the wildland-urban interface (WUI) - the area where houses meet or intermingle with the undeveloped wildland vegetation (Cook and O'Laughlin, 2014). Similarly, Australia has had the same patterns of fuel reduction as the United States (Adams, 2013). However, forest fires in Thailand are low to moderate fires. Prescribed burning is necessary for some forest types.

The integration between zero and quota burning is the suitable policy pattern for the north of Thailand. The policy is divided into two plans; during and outside the fire season. Policy options are shown in the schematic diagram in Figure 5.1. If zero burning can mitigate the air pollution problem, then it is set to the main policy. However, fire controls in agricultural and forest area ranging 1 km is also the suitable action plan to solve the problem effectively in a term of an economic return for the investment. Then, all agricultural area and villages in forest areas are the main target parties. In addition, important supported measures for all processes in this diagram are regulation and enforcement, awareness and engagement of the population, and knowledge and technology.

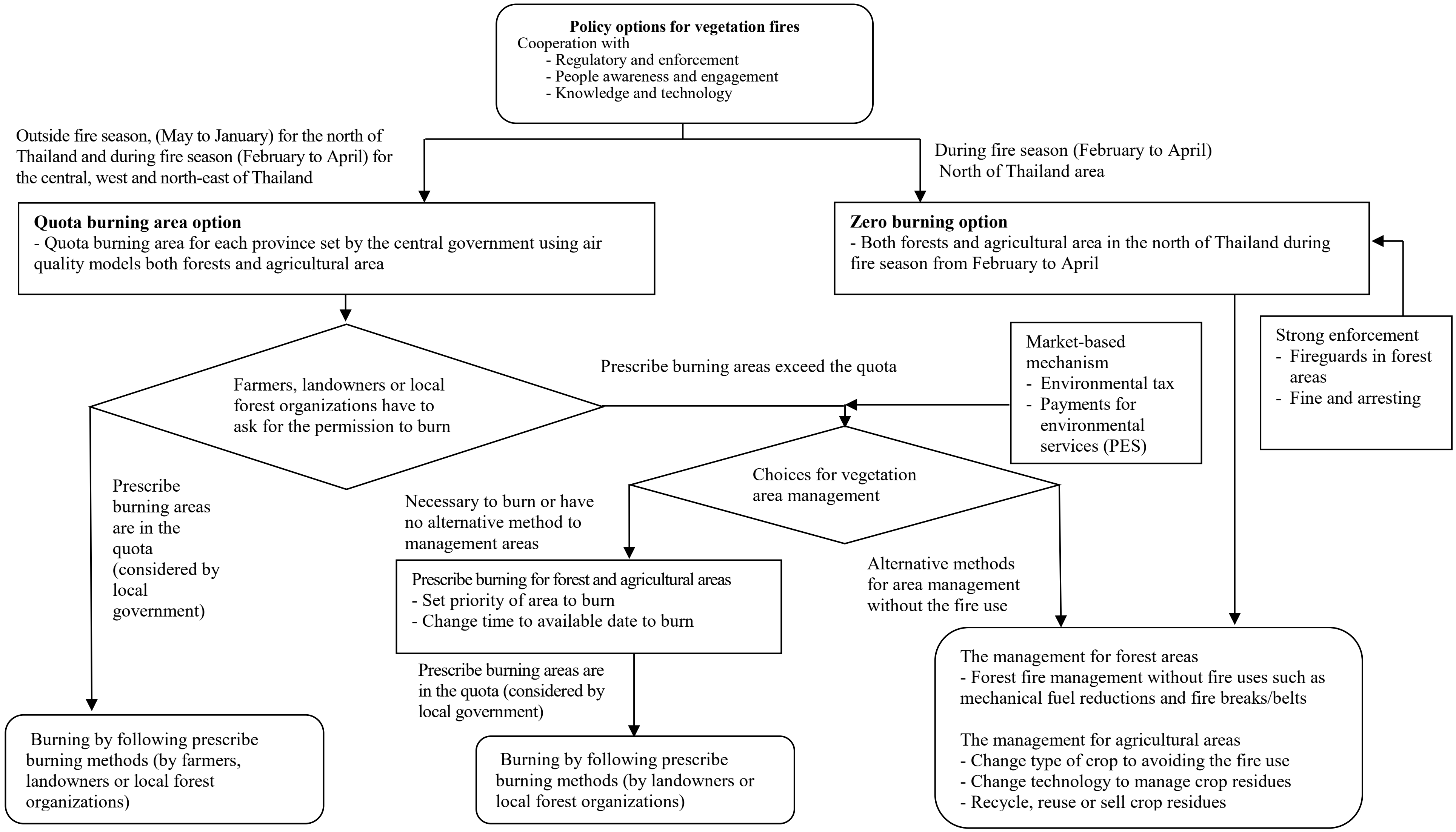



**Figure 5.1** Schematic diagram of policy options to control areas of vegetation burning generated from results of previous chapters; air quality simulations and CBA.

## 5.1 Regulatory measures for burning control

Generally, air pollution problems from fires can be managed by reducing the area burned, decreasing pollutant emissions by using the burning technique, and avoiding fire uses in the unsuitable weather conditions. The fire uses in the unsuitable weather conditions need the government regulatory measures to enforce the people to avoid this. A government regulation of setting the zero burning periods is an option for the policy in the fire season. The burning quota for all vegetation fire type and following the burning technique are the options for the rest of the period.

### 5.1.1 Zero burning in the fire season

The results from chapter 3 on air quality evaluation showed that meteorological condition from February until April 2012 may influence the accumulation of pollutant concentrations reaching the high level. Therefore, open burning should be not allowed in this condition. The main target areas are agricultural and forest area ranging 1 km and the main target people are farmers and local people living near forests.

In the agricultural area, the use of fires appeared in processes of removing agricultural residues and preparing fields for agriculture or pasture. Fires are used for removing crop residues, controlling pests, weeds and disease, improving goods yield (Pollution Control Department, 2009). However, many studies showed that leaving crop residues in fields after harvesting could increase soil quality and the crop yield more than removing agricultural residue from fields (Romero-Perezgrovas et al., 2014, Turmel et al., 2015, Pollution Control Department, 2009). For controlling weed, pest and disease, Williams et al. (2013) showed that burning was a more effective tool than retaining residues in fields. The crop residue can be managed by selling to supplement for producing animal feed or biofuel. In some areas, farmers use fires to remove crop residue because there is no market for supporting its use (Turmel et al., 2015). Beside these, fields without residue are easy to prepare for the next cultivation. These problems should be solved by the government employing a zero-burning policy in the fire season.

The zero-burning policy should include plans for before and during the fire season. Before fire season, fires are needed in the forest area. Fires are used for building fire resilience to forests by prescribed burning to remove fuel load on the forest ground. This not only builds the fire resilience to forests but also prevents the occurrence of forest fires in the fire season. In agricultural areas, the management of agricultural residue is the main issue to be focused for the zero-burning policy. Generally, the harvesting periods for the main crops; rice and corn, in the north of Thailand are November to December for rice and May to July or August to October and February to March for corn (Pollution Control Department, 2009, Land Development

Department, 2016). The burning activity started to prepare the new crop in the beginning of the monsoon season in May. Then the suitable time for the crop residue management is November to the beginning of January because farmers who need fires for managing their field can ask for the permission to use fires in this period. For the harvesting of corn in February to March, the crop residue should be not allowed to burn but be managed by other ways. Generally, agricultural residues can be managed by leaving in the field as the fertilizer, producing animal feed or other products. Government can give knowledge and technology and support the market systems for crop residues. The report by Pollution Control Department (2009) showed that most farmers required the government supporting the market for buying residues and higher prices of zero-burning crop products, followed by giving technology and knowledge.

For agricultural areas, a certain time for each year is needed to be set for farmers preparing their residue management. The strong enforcement by paying fine for being illegal should be concentrated by local administration. For the zero burning in the forest area, more officers to survey and arrest persons who break the law at least up to 1 km are needed for the first stage of the zero-burning policy. Results from the cost-benefit analysis showed that the net benefit of the agricultural area management by giving knowledge and technology and hiring forest guards is a positive value and should be considered by the government.

### 5.1.2 Prescribe burning in the rest period

Fires are necessary for some agricultural processes and fire-dependent ecosystem. Zero burning through the year may lead to severe fires due to the accumulation of fuel loads and severe damages to the ecosystem lacking fire resilience. The use of fires should be allowed outside the burning season period. The Pollution Control Department studied the approach of prescribed burning or controlled burning by setting the quota burning area for each province (Pollution Control Department, 2009). It is possible to set the quota burning regulation and the government should support the agricultural residues markets, technology and higher prices of fire free crops to farmers. The objective of this study was the mitigation of health impacts from high concentrations of $PM_{10}$ from fire emissions due to meteorological conditions and high burning activities in the crop-harvesting season. This approach showed that the farmer has to ask for permission for burning. It also appeared in the United States, England, Canada and Brazil that farmers have to ask for a permission to burn their agricultural residue from the government (Ministry of Nataural Resources and Environment, 2015).

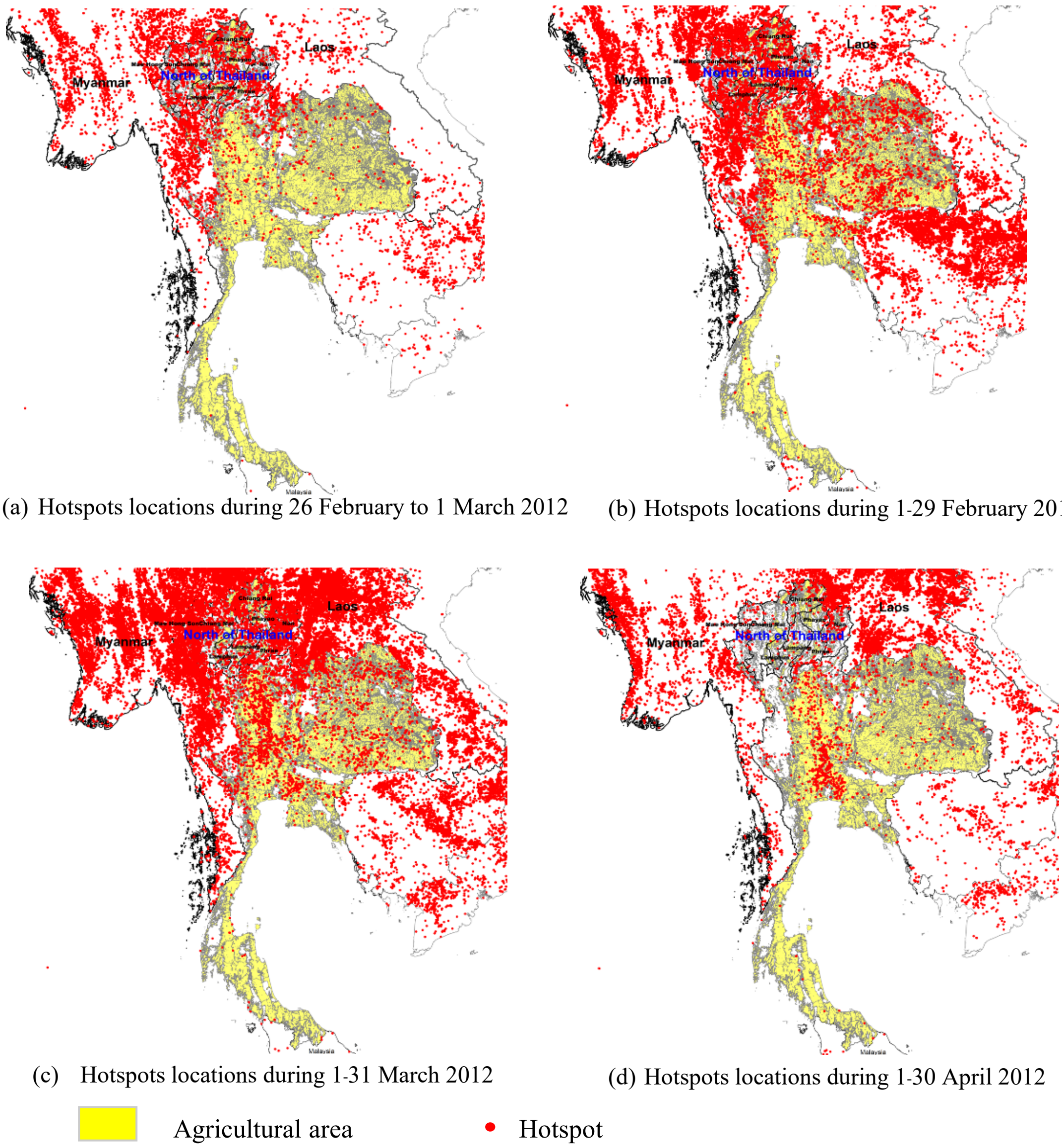
Results from the air quality part show that the hotspot numbers after fire controlled in agricultural and forest area ranging 1 and 4 km can be used to estimate area sizes to be allowed burning during the unsuitable weather condition influencing the accumulation of high concentrations of pollutants. With the target of $PM_{10}$ concentrations meeting Thai air quality standard (< 120 $\mu g/m^3$) for all district area or every small area, the daily quota of area burned for each province is not more than 3 hotspots (= 3.825 ha) (results from fire controlled ranging 4 km scenario). For average $PM_{10}$ of entire province area or large-scale area, the daily quota is not more than 16 hotspots (= 20.4 ha) (results from fire controlled ranging 1 km scenario). However, results from fire controls ranging to 1 km scenario showed that $PM_{10}$ concentrations exceeded Thai air quality standard in some districts. Thai national standard of $PM_{10}$ is higher than the WHO guidelines but it is accepted by Thai people and easier to achieve as the first step of air quality management by Thai government. The health impact valuation has shown high morbidity and mortality, and the associated economic losses from $PM_{10}$ concentrations more than the WHO guideline at 20 and 50 $\mu g/m^3$ but the government needs to balance costs and level of protection. Therefore, a methodology as CBA was applied to determine areas to control that bring about maximum benefits for least cost.

The use of fires should be applied for only necessary cases such as some agricultural processes and fire-dependent ecosystem. The government should consider alternative technology replacing fire use such as mechanical fuel reductions and wet fire breaks for the forest fire management and promoting farmers to change a type of crop depending on fire use in the fire season, and supporting harvesting mechanics and residue markets to manage crop residues in the agricultural area.

For the prescribed burning in agricultural areas, the burning quota process can be set as a regulatory framework by the local administration. The policy in Thailand was decentralized to the local level. All districts can set their own regulations for communities by being based on the main country law. According to Pollution Control Department (2009), the prescribed burning in agricultural areas should include two mains parts; quota for burning and burning methods. The central government sets the burning quota for each province by using air quality models. After that, each province will allocate the area burned to communities. The people have to apply for the permission from their local administration before burning crop residues. In a part of burning methods, it includes burning in day time, using dry residue, small size of burning areas or stacks, reducing danger to road users, not causing a nuisance to nearby populated areas such as school and private or government offices, preparing equipment for fire-spread prevention, wearing self-protection equipment during open burning and building fire buffer line before burning. These regulatory measures were applied in some areas in Thailand. However, the number of burning quota areas for each year and province is still not set and legislated by the central government. It should be processed and set for all communities in the north of Thailand to solve the air pollution problem as the long-term policy.

### 5.1.3 Quota burning for the area outside the north of Thailand in the fires season

From the air quality model part, the pollutants in the north of Thailand also were generated from the central part of Thailand. Moreover, fires in the central part of Thailand have occurred through fire season during February to April in year 2012 as shown in Figure 5.2. The fire controlled area should be included the central part of Thailand. However, the air quality model was not run for the central part in this study. Then the number of area controlled should be calculated by the government for the future policy.




(a) Hotspots locations during 26 February to 1 March 2012

(b) Hotspots locations during 1-29 February 2012

(c) Hotspots locations during 1-31 March 2012

(d) Hotspots locations during 1-30 April 2012

**Figure 5.2** Hotspots location during 26 February to 1 March 2012 **(a)** and through fire season in February **(b)**, March **(c)** and April **(d)** year 2012

## 5.2 Building fire resilience landscapes

Vegetation fires are the natural process for some fire dependent ecosystems. Then living with fire occurrences is needed for fire management in the fire risk area. To decrease the severity of damages and impacts on people from fire events, building fire resilience to vegetation area is the method that can process by prescribed burning, and building fire breaks.

### 5.2.1 Fuel reduction by prescribed burning in forest areas

Fuel reductions widely used to manage forests include prescribed fire and mechanical treatment. The mechanical ways use machinery to thin or remove vegetation in the forest. Mechanical fuel treatments may need many labourers, and hence not be economically attractive (Cook and O'Laughlin, 2014). Prescribed burning is one of the techniques used for forest management. The type of forests for prescribed burning are fire-dependent forests such as dipterocarp forests (Ministry of Nataural Resources and Environment, 2015). Generally, forest fires can severely damage forests, whereas for prescribed fires, there are neutral or positive effects on soils and biodiversity (Fernandes et al., 2013, Dale, 2006). In addition, emissions from prescribed burning are generated from herbaceous, fine, and coarse fuels burning which are less than the general forest fires that also consume small trees and some standing trees (Wiedinmyer and Hurteau, 2010, Fernandes et al., 2013). Wiedinmyer and Hurteau (2010) have compared $CO_2$ emissions from prescribe burning with normal fires in Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington and Wyoming from year 2001 to 2008. They found that the percent reduction of $CO_2$ from prescribed burning is around 1 to 26 depending on forest types compared to normal fires.

The management of prescribed burning includes the burning frequency and method. Less frequent fire such as 5-years fire return interval (FRI) emit more pollutants than 2 years FRI per each fire but total emission will be less than for the long term period calculation (Tian et al., 2008). In terms of the reduction of severe fires, the study of the suitable fire-return interval for prescribed burning is rarely found for the forests in Thailand. For the size of prescribed burning to reduce wildfire severity, it is less clear about the size of the landscape to be treated. The United States' policies suggest that the large size is better than the small area (Cook and O'Laughlin, 2014). For the plant structure, too frequent fires in dry dipterocarp forests in Thailand reduce the sprouting capacity of seedlings and saplings and inhibited regeneration (Wanthongchai, 2014). This study suggested that the suitable FRI is 6-7 years for the regeneration of young trees in dry dipterocarp forests. State of Queensland (2007) suggested the suitable FRI as following: every 3–7 years for timber production areas, two years to create fires buffers and two years for prescribed burning for forests with fuel quickly accumulating. However, where annual burning can cause soil erosion, then it is not recommended. The United States Department of Agriculture (2009) suggested FRI at around 3 to >7 years for the prescribed burning.

There are 136,600 ha of dipterocarp forest areas that the Thai government plans to burn every year in the study area (see Table 4.34). Annual budget for prescribed fires is 3,464,560 US$ for every year. The budget will decrease to 1,732,280 or 577,426 US$ per year if the FRI are 2 or 6 years. Beside the budget, total pollutant emissions from 2 and 6 years FRI also are lower than the annual burning in the same forest area.

Generally, prescribed burning method is processed by using low intensity fires, in moderate to high relative humidity weather (30% - 60%), low wind Speed 5–15 mph (= 1.206.7 m/s) and cooler temperatures (1.4 - 21°C) (United States Department of Agriculture, 2009, State of Queensland, 2007). Various techniques of burning (e.g. backing fire, head fire ignition etc.) depend on weather and fuel factors such as wind direction and speed, temperature, fuel moisture, fuel load and vegetation size. Other preparations also are needed such as firebreaks, sensitive areas, (i.e. avoid sending smoke into residential areas, neighbours, airports, hospitals, etc.), safety equipment for controlling fire, and personal protection equipment (United States Department of Agriculture, 2009). Firebreaks are important to control a fire spread. It must be at least 15 feet in width or 4 times the fuel height. Firebreaks include streams, bare soils, roads, burned areas, and mow0wet lined vegetation. Moreover, burning should be conducted in the daytime because temperature inversions frequently hold in the night time that traps the smoke near the ground level.

### 5.2.2 Fires belts and fire breaks

Forests in the north of Thailand are the mosaic forests with 2 main types of plants, evergreen (dry and hill evergreen) and seasonal forests (deciduous and dipterocarp). With the forest mosaic of continental South-east Asia, fires may not be particularly disastrous for tree species and biodiversity effects (Baker et al., 2008). The maintenance of the mosaic plant in Thailand tends to be the fire belt method. The fire belt is a line of vegetation with fire0resistant types and keeping the forest floor clean (Department of Agriculture and Rural Development, 2014). It prevents or decreases the spread of fires. However, evergreen is difficult to ignite but is sensitive to fires. Fires may lead to the transform of evergreen forest to deciduous forest and savanna and consequence to a significant loss of biodiversity for the long-term effects from high frequent fires (Cochrane, 2009).

Due to the limitation of prescribed fire implementation by air quality policy in Thailand, the fuel treatment may not be accessed for all planned areas. In addition, prescribed burning is suitable for dipterocarp and deciduous forests. Mechanical fuel treatments and firebreaks are needed for other forest types for forest resilience and are needed in dipterocarp and deciduous forests for forest resilience to break the fire spread. The evergreen forest is another main type of the forest in the study area that needs management for forest resilience. Generally, the evergreen forest is difficult to ignite but fires can destroy forest ecosystem because of being sensitive to fires. Firebreaks are necessary for this forest type particularly in the drought year in which dry and hot weather is a suitable condition to fire occurrences and spread. The El Niño–Southern Oscillation (ENSO) forecasting can be used as a tool for the preparation. Cochrane (2009) showed that ENSO caused the drought and increased fires in Southeast Asia.

The building of firebreaks may also divide into wet and dry firebreaks. The dry firebreaks include bare soils, roads, and burned areas while the wet firebreak is the various types of streams. Wet fire breaks are the options of Royal Development Project for forest fires management without the fire use for Thailand (Royal Forest Department, 2016b). Check dams are sustainability options for the fire break type and water supply for fire management in Thailand. Building check dams and canals in forests are the wet fire breaks in some forest areas (Royal Forest Department, 2016b). Firebreaks are built between forests and villages in the current plan. The increase of firebreaks inside the forest area should be more focussed for the future plan.

### 5.2.3 Fireguard officers

Australian strategies to respond to wildfires include the policy of 'stay and defend or leave early' when fires come and education programs like 'Community Fireguard'. The Country Fire Authority (CFA) is one of the biggest volunteer-based disaster response organizations in the world with almost 60,000 volunteer fire fighters. In an average year, CFA volunteers attend around 5,000 fires (Cook and O'Laughlin, 2014).

In Thailand, the volunteer system also appears in the action plan every year (Ministry of Nataural Resources and Environment, 2015) but did not cover all target of forest ranging 1 km. To enforce the zero-burning policy, the government has to hire the fireguards. There are 28,500 persons covering the target area 570,000 ha for national parks. For 670,000 ha in forest parks, the fireguards are around 26,800 persons for fire control in forest areas ranging 1 km from agricultural areas who will be the volunteers from the community forest project in the future plan.

## 5.3 The priority of area burned

The management of vegetation fires in the north of Thailand needs a large amount of budget and human resources. The prone fire areas with the most fire frequencies are areas as the first priority to be employed in the plan. All hotspots for years 2009 to 2012 acquired from NASA have been analysed for fire frequencies by using GIS. There are 569 sub-districts in the north of

Thailand but only 465 sub-districts appeared the hotspots. The ranking of top 30 fire frequencies from 465 sub-districts were shown in Table 5.1 and the map of averaged annual fire frequencies during 2009 to 2012 were shown in Figure 5.3.

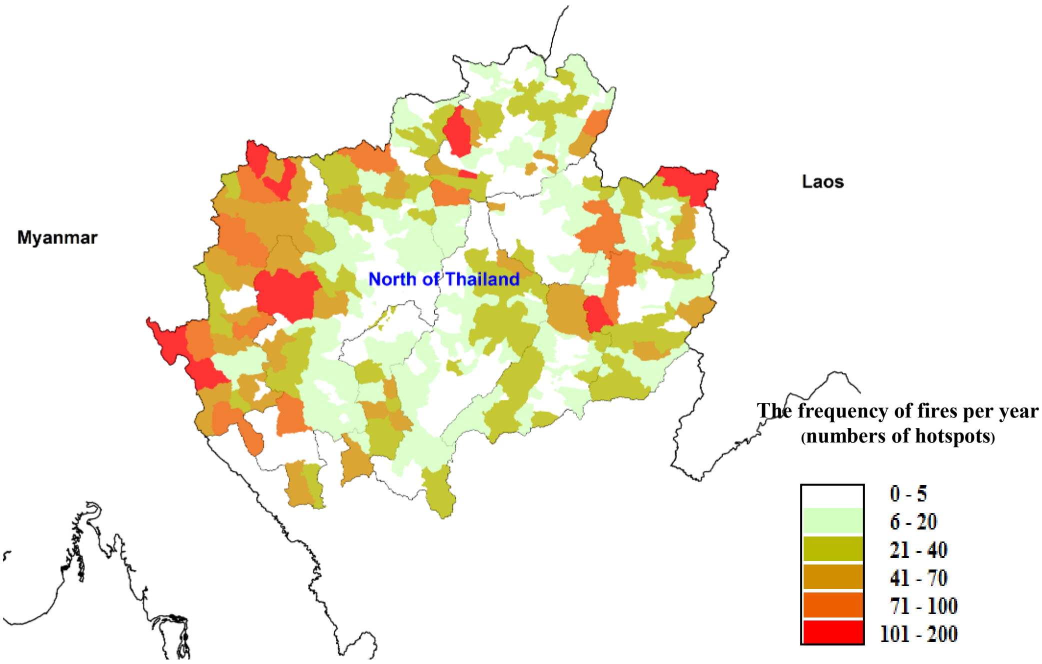



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**Figure 5.3** The map showed averaged annual fire frequencies during 2009 to 2012 in 465 sub-district areas in the north of Thailand**.**

**Table 5.1** The ranking of top 30 fire frequencies in the districts in the north of Thailand during year 2009 to 2012

| | | | | | Averaged Fire Frequency per year | | | |
|---|---|---|---|---|---|---|---|---|
| Rank | Province | District | Sub district | Total Fire Frequency from 2009 to 2012 | Fire Frequency per year | Fire events in agricultural area and forest nearby 1km | Fire events in forest far from agricultural ranging 1 to 4 km | Fire events in forest far from agricultural ranging 4 km |
| 1 | Nan | Chalermphrakiet | Pon | 784 | 196 | 144 | 47 | 5 |
| 2 | Mae Hong Son | Mae Sariang | Mae Khong | 768 | 192 | 39 | 65 | 89 |
| 3 | Chiang Mai | Mae Chaem | Mae Suek | 547 | 137 | 107 | 30 | 0 |
| 4 | Chiang Rai | Mae Suai | Wawi | 511 | 128 | 117 | 11 | 0 |
| 5 | Mae Hong Son | Pang Ma Pha | Soppong | 509 | 127 | 113 | 14 | 0 |
| 6 | Nan | Wiang Sa | Yap Hua Na | 439 | 110 | 49 | 43 | 18 |
| 7 | Chiang Mai | Mae Chaem | Mae Na Chon | 423 | 106 | 80 | 26 | 0 |
| 8 | Phayao | Pong | Pha Chang Noi | 388 | 97 | 62 | 33 | 3 |
| 9 | Mae Hong Son | Mae La Noi | Mae Na Chang | 378 | 95 | 19 | 11 | 0 |
| 10 | Chiang Mai | Chiang Dao | Mueang Na | 359 | 90 | 78 | 12 | 0 |
| 11 | Nan | Muang Nan | Saniang | 345 | 86 | 71 | 15 | 1 |
| 12 | Mae Hong Son | Muang Mae Hong Son | Huai Pong | 333 | 83 | 52 | 25 | 4 |
| 13 | Mae Hong Son | Mae Sariang | Sao Hin | 331 | 83 | 28 | 40 | 15 |
| 14 | Mae Hong Son | Muang Mae Hong Son | Huai Pha | 319 | 80 | 52 | 25 | 4 |
| 15 | Chiang Rai | Wieng Kaen | Po | 317 | 79 | 71 | 9 | 0 |
| 16 | Mae Hong Son | Muang Mae Hong Son | Pha Bong | 309 | 77 | 45 | 27 | 5 |
| 17 | Mae Hong Son | Sop Moei | Mae Suat | 307 | 77 | 45 | 32 | 0 |
| 18 | Phayao | Pong | Khuan | 295 | 74 | 33 | 35 | 6 |
| 19 | Nan | Wiang Sa | Mae Khaning | 293 | 73 | 40 | 33 | 0 |
| 20 | Chiang Rai | Wiang Pa Pao | San Sali | 289 | 72 | 66 | 7 | 0 |
| 21 | Mae Hong Son | Sop Moei | Sop Moei | 287 | 72 | 38 | 29 | 5 |
| 22 | Chiang Mai | Omkoi | Omkoi | 286 | 72 | 56 | 16 | 0 |
| 23 | Lamphun | Li | Ko | 264 | 66 | 10 | 19 | 38 |
| 24 | Chiang Mai | Mae Chaem | Ban Thap | 260 | 65 | 29 | 34 | 2 |
| 25 | Mae Hong Son | Pang Ma Pha | Pang Mapha | 253 | 63 | 57 | 6 | 0 |
| 26 | Chiang Mai | Omkoi | Mae Tuen | 252 | 63 | 46 | 17 | 0 |
| 27 | Nan | Pua | Phu Kha | 244 | 61 | 38 | 22 | 1 |
| 28 | Mae Hong Son | Pai | Mae Na Toeng | 240 | 60 | 28 | 26 | 7 |
| 29 | Chiang Mai | Mae Chaem | Ban Chan | 239 | 60 | 47 | 13 | 0 |
| 30 | Mae Hong Son | Khun Yuam | Khun Yuam | 235 | 59 | 32 | 25 | 2 |

This table shows the importance of tackling the hotspots within 1km of agricultural areas. The areas with high fire frequencies are close to human communities. This information combined with modelling approach in Chapter 3 could form the basis of a strategic management plan.

Tackling areas with highest incidence of fires may be more effective to mitigate air pollutions caused by vegetation fires vigorously in terms of using less times and smaller budgets.

### 5.4 People education, awareness and engagement

The Thai government has focused on public relations via multimedia such as news on television and province announcements for many years. Many people who live close to fire-prone areas built their firebreaks to protect their properties. Generally, indigenous knowledge is considered to be a body of knowledge existing within populations or acquired by local people over a period of time through accumulation of experiences, society- nature relationships, community practices and institutions, and by passing it down through generations (Fernando, 2003). The communities in the Thai forests have also used fire to manage their forests for a long time. Therefore, forest fires often occur behind the firebreak line and rarely spread to villages. Forest fire events caused by people across the fires break line spread to forests and burn the forest areas.

According to theDepartment of National Parks Wildlife and Plant Conservation (2012), for forest fires in the year 2012 problems were caused by local people by gathering forest goods at 66.3%, agricultural activities at 16.6%, other activities 6.2% and unidentified causes at 10.9%. Local people should respond to maintain public forest areas. The right for forest management by local people is the policy option for building people's awareness. This may be operated by extending forest areas for local people managing their forest into the secondary forests and forests near villages.

From the chapter CBA (see Table 4.34), a budget of around $4.73 million per year for all villages near forests to manage their forest areas around the village ranging 1 km is worthwhile for fire management compared with employing government officers (fireguards) by the government, which need the budget of around $24.12 million per year for the fireguard cost. Cook and O'Laughlin (2014) described the collaborative engagement between people and government identified by the National Strategy in Australia "which includes governance, shared information and resources, communications, and monitoring and accountability by the collaboration in fuels management both for public and private lands".

## 5.5 Market-based mechanism

### 5.5.1 Environmental Taxes Measures

The market mechanism for environmental goods and services in Thailand has been applied over the last decade but is not popular. Therefore, the regulation measure as an environmental tax is suitable for enforcing and achieving the environmental management based on market in Thailand (Kokachaporn, 2013). The environmental tax in Thailand is currently in the process of regulations drafting. The higher price of agricultural goods from fire-free production was the farmer's suggestions for pushing on avoiding the fire use in their fields (Pollution Control Department, 2009). The tax rate for the factory may be a tool to support the use of fire-free agricultural materials. However, the tax rate should be effectively reducing the price of fire-free crops compared to the crops.

### 5.5.2 Payments for Ecosystem Services (PES)

Payments for ecosystem services or payments for environmental services (PES) are market-based mechanisms that buyers pay for improving environmental services (e.g. reduced flood risk, clean water etc.) or buy improved services from providers (Department for Environment Food & Rural Affairs (DEFRA), 2013). The buyers include private organisations or individuals, Non-Governmental Organisations (NGOs), and the government and the sellers or providers include farmers, landowner, and environmental organisations. For the vegetation fires management in this study, the main buyer is the government and the sellers are farmers and forest-dwelling communities.

There are vegetation areas in the north of Thailand at 7,764,885 ha including national parks, forest parks and agricultural areas at around 3,392,670 ha, 2,682,170 ha, and 1,690,045 ha, respectively. In February to April 2012, there were 11,007 hotspots (~14,034 ha) in vegetation areas. This affected people's health and ecosystem goods and services in a term of the economic value around $355.21 million (from Table 4.36). Generally, the estimated PES value for the loss of vegetation fires impacts in the north of Thailand should be $355.21 million / 14,034 ha = $25,311per ha per fire season. During the rest period; May to January, fires occurrences rarely appeared in the north of Thailand and had less of an impact on heath. Then impacts value in the fire season may be represented as the annual value.

However, this value is higher than PES values for the forest plantation in many countries such as Costa Rica, Indonesia, Australia, United States, Brazil, and France, which are around 45-230 US$ per ha per year (Smith et al., 2006). This is because the health impact values are more than the ecosystem goods and services values caused by vegetation fires by 45-199 times. From Table 4.34, fire controls ranging 1 km covering area = 172,700 + 1,690,045 + 670,000 + 570,000

= 3,102,745 ha, and fire controls ranging 4 km covering area = 172,700 + 1,690,045 + 2,660,000 + 2,280,000 = 6,802,745 ha are the selected options for fire management in the north of Thailand. The estimated PES value for vegetation fires management in the north of Thailand, the government budget for fire controls1 km will be $48.31 million / 3,102,745 ha = $15.57 per ha per year and for fire controls 4 km will be $216.80 million / 6,802,745 ha = $31.87per ha per year.

Instruments such as taxes and payments for ecosystem services (PES) are options for market-based mechanism for this study. The taxes are methods to encourage environmentally positive behaviour changes by generating the relation of paying more cost for the more polluting practices. However, in countries in which regulatory and taxation systems are not strong enough, payments for ecosystem services (PES) tend to be popular (Fisher et al., 2008).

## 5.6 International cooperation on transboundary haze pollution

The Agreement on Transboundary Haze Pollution of Association of Southeast Asian Nations (ASEAN) came into force in 2013. All member countries including Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam had ratified the Agreement in 2015. The objective of the agreement is to prevent and monitor transboundary haze pollution caused by land and/or forest fires. The development of "Roadmap on ASEAN Cooperation towards Transboundary Haze Pollution Control with Means of Implementation" was started in 2015. This roadmap aims to set measures to improve the situation of regional transboundary haze pollution from vegetation fires through quantitative indicators and targets by 2020. The indicators include increasing numbers of days having good or moderate air quality, reducing hotspot numbers, and decreasing of transboundary haze pollution area (Association of Southeast Asian Nations, 2017).

There are five member-countries in the northern ASEAN; Thailand, Myanmar, Laos, Vietnam and Cambodia. Most countries in this region are classified as the lower middle income economies byWorld Bank (2017).Thailand and Vietnam can be indicated by air quality while other countries need other indicators due to the limitation of air monitoring systems (World Air Quality, 2017). Therefore, the hotspot numbers for each country are set for the northern ASEAN's roadmap target. The cooperation between these member countries to mitigate fire management is carried out via bilateral agreement, which is run by their own money. With limited resources, the transboundary haze pollution needs more efforts, time and resources (e.g. technology and funds or budgets) for achieving the target.

## 5.7 Conclusion and discussion

The severity of fire problems in the north of Thailand affected the people's health and the socio-economic losses. The annual air pollution caused by vegetation fires has trigged the people to become more aware about the haze problem. However, the specific regulations for the vegetation burning in Thailand are not currently sufficiently legislated for. The air quality models are effective tools to investigate the causes and the solutions for controlling fire to meet the air quality standard. Results from the air quality models indicated that a few hotspots in each province can cause the $PM_{10}$to exceed the daily Thai air quality standard because of the weather condition. This can lead to the regulations of the zero burning in the fire season and the quota burning outside the fire season for Thailand.

The costs-benefits analysis is the tool to evaluate the worthwhileness of the selected solutions in terms of a monetary value. This study has integrated these tools for generating optimal policies. The north of Thailand covered with the forest areas is around 6,074,840 ha and agricultural area of about 1,690,045 ha. The government has to spend the budget $216.80 million (see Table 4.36) per year to control fires efficiently. Results from air quality model and CBA showed that fire controlled in agricultural area and forest ranging1 km (cover area 3,102,745 ha) is more worthwhile solution for the budget and the mitigation of the air pollution problem with the budget $48.31million per year. Beside the smaller area for fire controls, the significant decrease of the budgets is the replacement budget of government officers by the budget for people engagement in forest park. However, the net value of the 1 and 4 km fire controls are the positive value. Then, the focus of the fire controlled in agricultural area and forest around agricultural area ranging both 1 km and 4 km are worthwhile for the short-term plan.

The problem of fire management in Thailand is the lack of action within the territorial jurisdictions of each organization. In the last decade, all forest areas are the government's responsibility, but it lacks the budget and human resources for forest management. Then over recent years, the decentralization to the local government responsibilities is considered to be the major plan for Thai policy. The provinces directly respond to the policy from the Prime Minister and are set as the main centre for action plans (Ministry of Nataural Resources and Environment, 2015). The plans include before, during and after fire seasons. Before fire season from November to January, firebreaks creating, fuel reducing, and prescribed burning were included in the plans. Plans during fire seasons are the law enforcement and fire fighting, and after fire season are forest restorations and public awareness building. The next step of the fires policy is that the local community can legislate their own fire control and manage fires problem by themselves.

Most vegetation fires in Thailand are caused by humans. The most important factor for fire management is people's awareness. The regulatory measures such as zero burning in the fire season, prescribed burning in the rest period and quota burning for the area outside the north of Thailand are tools to enforce people avoiding the use of fires and decrease vegetation fire occurrences. The technology measures such as supporting guidelines and machines to managing agricultural residues are tools to build people's abilities to mitigate fire problems. However, it is difficult to control every person. Therefore, building fire resilience landscapes is need for the government policy. This can limit fires to spread in the small size area and less damage to forest and people's health and community. The fire fighters from volunteers and government officers will be the last step to control fires. Not only vegetation fires in Thailand need to mitigate for national air quality but transboundary haze between countries also need to be emphasised for the both of national and international air qualities. With transboundary haze pollutions from neighbouring countries, the achievement of meeting Thai air-quality standards for all districts in the north of Thailand may be not accomplished.

This study was successful in terms of producing a framework to enhance policy development that is based on i) air quality meeting standards and ii) the budget of the government intervention being appropriate for the north of Thailand. There are many studies of forest fire emissions but there is no study for the north of Thailand. This study has applied air quality models investigated forest fires emissions in eight provinces in the north region of Thailand and neighbouring countries. The integrated framework between the use of air quality models to reduce emissions to meet the air quality standard and the cost-benefit of the government intervention has created the framework of policies. This study results will be a practical case study of effective integrated air quality management in a rapidly developing country.

However, with the limitation of time and resources, the air quality simulation was taken only 5 days during 26 February to 1 March 2012 and simulating for the whole year are not processed. In addition, the central part of Thailand was not simulated in this study and neighbouring countries were not evaluated throughout the fire season. Therefore, the exactly time periods and area sizes for prescribed and quota burning in the north and other parts of Thailand throughout the year could not be set in the policy. Moreover, the north of Thailand may be more affected by $PM_{10}$ from neighbouring countries and other parts of Thailand during other periods. Focusing more on other area sources for the air pollution policy in the north may be considered for the future research.

# Chapter 6

## Conclusion and Recommendations for Future Work

### 6.1 Conclusion

The aim of this study was to investigate an air pollution problem caused by forest fires in the northern region of Thailand and develop an integrated framework to enhance policy development for this problem. The development will be based on the both the air quality standards that are to be met and the budget of the government intervention that is appropriate. This will be a practical case study of effective integrated air quality management in a rapidly developing country. The objectives of this study were achieved as follows:

#### 6.1.1 The causes of forest fires, their emissions, and their impacts including health, environmental, social and ecological impacts, from a global view

Vegetation fires tend to be more frequent in hot and dry weather conditions, and human activities are the major cause of fires. Their impacts are from trace gases and aerosols that are released from fires and adversely affect the environment and human health. Air pollution was estimated to cause 7 million global premature deaths in 2012. However, fires also were used to manage fuel loads that may improve watershed conditions, enhanced wildlife habitat, and more resilient forested ecosystems, Fires also reduce fire suppression and fuel treatment costs for forest fire management over the long-term.

#### 6.1.2 The amount of emissions from each source and the processes that influence fires emissions affecting the ambient air quality of the north of Thailand to exceed the Thai air quality standards

The major source of emissions for air pollution caused by vegetation fires in the north of Thailand was from mixed deciduous forests (61.55% of all area), followed by agricultural areas (18.16% of all area). The processes that influence fires emissions affecting the ambient air quality of the north of Thailand to exceed the Thai air quality standards are hotspot numbers and weather conditions. The number of hotspots was the most important factor in the north of Thailand. Hotspots had occurred from December 2011 until 4 May 2012. In January and April, averaged daily of hotspot numbers were 12 and 16 and averaged daily of $PM_{10}$ concentration were 53 and 65 $\mu g/m^3$ in the urban area. The high frequency fires (average > 150 hotspots per day) occurred from 9 February to 31 March 2012 with an average daily of $PM_{10}$ concentration of around 135 $\mu g/m^3$ in the urban areas. Moreover, the wind direction is an important factor that influences the $PM_{10}$ transporting from the sources to other areas. Pollutants were transported by wind from the lower part of Thailand and some parts of Myanmar and Laos to the north of Thailand. Beside these, mixing height is a factor of the air pollution in the study area. The mixing height, which may lead to smoke problem near the ground level, is less than 1,700 feet or 500 metres. Most of the study area had averaged values of mixing height during 26 February to 1 March 2012 of less than 1,700 feet.

### 6.1.3 Scenarios for potential fire controls to find the optimal pollution reduction targets from selected areas

Scenarios to find the optimal pollution reductions from forest fires by reducing biomass-burning emissions from each type of land use were simulated for finding $PM_{10}$ concentrations after controlling fires in neighbouring countries, the agricultural area and forest area in the range 1 and 4 km. Before fires were controlled, the high level of $PM_{10}$ in some district areas of more than 200 $\mu g/m^3$ occurred in every province. Moreover, the averaged $PM_{10}$ throughout the province exceeded the Thai daily standard at 120 $\mu g/m^3$ occurred in six provinces.

### 6.1.4 The main pollutant sources and the numbers of areas needed to control atmospheric emissions from fires in order to meet the air quality standards

After fires controlled in both agricultural areas and forests around agricultural areas within 1 km, $PM_{10}$ in most district areas have decreased below 200 $\mu g/m^3$ and $PM_{10}$ throughout the province averaged met the Thai daily standard at 120 $\mu g/m^3$ in every province with values of 33 to 79 $\mu g/m^3$. After fire controls in agricultural areas and forest areas within a range of 1 km of agricultural areas in the north of Thailand and hotspots taken off in the neighbouring areas, $PM_{10}$ concentrations were greater than120 $\mu g/m^3$ in many areas. $PM_{10}$ concentrations of inner districts the north of Thailand were the same as the previous scenario but this scenarios could mitigate $PM_{10}$ concentrations of districts closed to neighbouring countries. Lastly, fires controlled in both agricultural and forest around agricultural areas up to 4 km, $PM_{10}$ has decreased below 120 $\mu g/m^3$ in every district area, except three districts that are close to nearby provinces or neighbouring countries. $PM_{10}$ throughout the province met the Thai daily standard at 120 $\mu g/m^3$ in every province with values of 28 to 63 $\mu g/m^3$.

### 6.1.5 The effects of forest fires and the value losses of each party affected

The parties affected from fires include the Thai government, people’s health and people's livelihoods affected by impacts on ecosystem goods and services in the north of Thailand area. The economic losses from health impacts through the fire season from 1 February to 30 April

2012 were \$224.16 million by the baseline value at 50 $\mu g/m^3$ and \$974.77 million by the baseline value 20 $\mu g/m^3$. The estimated total value of ecosystem goods and services losses were around \$4.86 million. The government budget for short-term fire management in year 2012 was about \$12.66 million.

### 6.1.6 Costs and benefits to the main parties affected from government interventions after controlling the different main causes of fires

The fire controlled in agricultural area and forest around agricultural area ranging both 1 km and 4 km are the suggested options for the short-term plan. The evaluation of the government interventions includes before and after fire controls in eight provinces in the north of Thailand during 1 February to 30 April 2012. The impacts value from actual vegetation fires were estimated as being between \$229 million to \$980 million based on the baseline value at 50 $\mu g/m^3$ and 20 $\mu g/m^3$, respectively. The economic losses decreased by \$178 million or 77.5% from \$229million to 51million by the baseline value at 50 $\mu g/m^3$, and by \$223 million or 22.8% from \$980 million to \$757 million by the baseline value at 20 $\mu g/m^3$ from fire controlled ranged 1 km. After fires were controlled in the 4-km range, economic losses decreased by \$227 million or 98.9 % from \$229million to \$2.5 million by the baseline value at 50 $\mu g/m^3$, and by \$328 million or 33.5 % from \$980 million to \$652 million by the baseline value at 20 $\mu g/m^3$.

### 6.1.7 Comparison between costs and benefits of the government interventions before and after controlling the different main causes of fire emissions, and select the interventions that are the worthwhile for the government, society and ecosystems

The government budget for fire management suggested by this studywas shown to be a potential worthwhile investment by cost-benefit analysis. The cost of 1-km fire controls is \$48.31 million and \$216.8 million for 4-km fire controls. The net value result of the fires controls in the 1 km range at the midpoint is \$164.33 million and \$72.74 million for the fires controls in the 4-km range. The net value of the 1-km fire controls is more than the 4-km fire controls. The 1-km fire controls should be considered more worthwhile by \$91.59 million compared with 4-km fire controls (at the midpoint value, net value of 1-km fire controls =\$164.33 million, 4-km fire control =\$72.74 million). However, the net value of the 4-km fire controls is also a positive value. Then, the focus of the fire controlled in agricultural area and forest around agricultural area in the range of both 1 km and 4 km are the suggested options for the short-term plan. The fire controlled in agricultural areas and forests ranging1 km cover an area of 3,102,745 ha and fire controls ranging 4 km cover an area of 6,802,745 ha. For fire control in the 1 km range, the budget cost is \$15.57 per ha (=\$48.31 million/ 3,102,745 ha), and for fire control in the 4 km range is \$31.87 per ha (=\$216.8 million/6,802,745 ha). The net value for fire control in the 1 km range is \$52.96 per ha

(=\$164.33 million/ 3,102,745 ha), and \$10.69 per ha (\$72.74 million/ 6,802,745) for fire control in the 4-km range.

### 6.1.8 The government interventions

The integration between zero and quota burning is the suitable policy pattern for the north of Thailand. The policy is divided into two plans; during and outside the fire season. If the zero-burning policy can mitigate the air pollution problem, then it is set to the main policy. Other measures for fire management also include building fire resilience to vegetation areas, supporting the fireguards volunteer system, and market-based mechanism such as environmental taxes and payments for ecosystem services or payments for environmental services (PES).

For theinternational cooperation on transboundary haze pollution, this cooperation needs more effort to mitigate the problem because the most countries in this region are classified as the lower middle-income economies. The resources (e.g. technology and funds or budgets) from the international sources are needed for achieving the target.

## 6.2 Recommendations for Future Work

Due to the limitation of studies of health and ecosystem goods and services impacts values in the north of Thailand, the monetary valuation process may not determine the 'true' values because of the use of the benefit transfer approach from various studies the values of which may be completely different in northern Thailand. Moreover, the values of ecosystem impacts were estimated using the ecosystem goods and services values which were based on the productions from the whole-tree mass or the whole forest area whereas forest fires destroy only some parts of trees or forests. The actual damage values caused by fires being the natural process of forests rarely appeared in the previous studies. Moreover, fires also have some benefits for the ecology. The benefit values of the fire use are needed for a future study.

Results from the air quality model indicate that $PM_{10}$ could be transported more than 1,000 km from source areas. The impact from vegetation fires affects people's health in terms of large amount of deaths and illnesses and economic losses in the north of Thailand. The large amount of the health impact value will increase by calculating all the areas affected. Further study might estimate the transboundary pollutant effects and their value in terms of health impacts.

In recent years, vegetation fire management has been more focussed on the use of fires. This may be an effective method for the forest fire management and some ecosystems, but it heavily affects atmospheric conditions and people's health. The future study may focus on effective methods for forest fire management without the use of fire and weighting costs and benefits between use and non-use fire management.

# Glossary of Terms

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| Aerosols | Small particles or liquid droplets in the atmosphere that can absorb or reflect sunlight depending on their composition |
| Benefit transfer | The process of taking information about economic values from studies already completed and applying it to the target study. |
| Biomass | Organic material both aboveground and belowground, and both living and dead, e.g., trees, crops, grasses, tree litter, roots etc. Biomass includes the pool definition for above and below ground biomass |
| Black carbon (BC) | The most strongly light0absorbing component of particulate matter (PM), and is formed by the incomplete combustion of fossil fuels, biofuels, and biomass. It is emitted directly into the atmosphere in the form of fine particles ($PM_{2.5}$) |
| Broadleaf forests | The general description of forests composed principally of trees and shrubs of the botanical group of flowering species which is in contrast to conifers or pines. |
| CALPUFF | A non-steady-state Lagrangian Gaussian puff model with chemical removal, wet and dry deposition, building downwash, and complex terrain effects. Lagrangian models are based on the concept that pollutant particles in the atmosphere move along trajectories determined by the wind field, the buoyancy and the turbulence effects. |
| Carbon sequestration | The removal and storage of carbon from the atmosphere into natural or man-made reservoirs, including forests and wood products. |
| Combustion efficiency | The fraction of the combusted carbon that is released in the form of $CO_2$. |
| Deciduous | Trees with broad, flat leaves which are shed annually |
| Deforestation | Clearing of forested areas |
| Dipterocarp forest | Deciduous dipterocarp or dry deciduous forests are also called for this type of forest in the north of Thailand. Their characteristics are open canopy and abundant grassland, supporting high mammalian biomass, including important herbivores and grazers such as rhinos, elephants, gaur, banteng and deer. |
| Dry matter (DM) | Dry matter refers to biomass that has been dried to an oven-dry state, often at 70ºC. |
| Ecosystem goods and services | The benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, |

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| | recreational, and cultural benefits; and supporting services such as nutrient cycling that maintain the conditions for life on Earth |
| El Niño-Southern Oscillation (ENSO) | A warm water current that periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. This oceanic event is associated with a fluctuation of the intertropical surface pressure pattern and circulation in the Indian and Pacific Oceans, called the Southern Oscillation. This coupled atmosphere0ocean phenomenon is collectively known as El Niño-Southern Oscillation. During an El Niño-event, the prevailing trade winds weaken, and the equatorial counter current strengthens, causing warm surface waters in the Indonesian area to flow eastward to overlie the cold waters of the Peru current. This event has great impact on the wind, sea surface temperature, and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world. |
| Emission factor | Inventory definition: A coefficient that relates the activity data to the amount of chemical compound, which is the source of later emissions. Emission factors are often based on a sample of measurement data, averaged to develop a representative rate of emission for a given activity level under a given set of operating conditions. |
| Evergreen | A group of trees that do not lose all of their leaves every year but go through a gradual replacement by dropping only their oldest leaves each year. Instead of being bare in winter, these trees have leaves all year |
| Fire controls in agricultural and forest area ranging 1 km, or fires controls in the 1 km range | A fire control in agricultural areas and forest areas within a range of 1 km of agricultural areas is a scenario with the condition that there is no fire in agricultural areas and forest areas (within a range of 1 km of agricultural areas). Results of $PM_{10}$ concentrations in these areas were $PM_{10}$ of fires generating from other areas |
| Fire controls in agricultural and forest area ranging 4 km, or fires controls in the 4 km range | A fire control in agricultural areas and forest areas within a range of 4 km of agricultural areas is a scenario with the condition that there is no fire in agricultural areas and forest areas (within a range of 4 km of agricultural areas). Results of $PM_{10}$ concentrations in these areas were $PM_{10}$ of fires generating from other areas |
| Fire intensity | A measure of the rate of energy release from the organic matter combustion process as kilowatts per metre (kW/m) or kilojoules per meter per second (kJ/m/s) |
| Fire regime | The pattern of fire occurrence, fire frequency, fire seasons, fire size, fire intensity, and fire type that is characteristic of a particular geographical area and/or vegetation type. |
| Fire resistant species | Species which has morphological or seasonal growth characteristics that give it a high probability of surviving a wildfire. |

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| Fire return interval | (or "fire free interval"," fire interval") The number of years between two successive fires documented in a designated area (i.e., the length of time between two successive fire occurrences) (units = years). |
| Fire sensitive species | Species with a relatively high probability of being killed or scarred if a wildfire occurs. Specific examples include trees with thin bark or highly flammable foliage, or animal species that are unable to evade the heat of a wildfire |
| Fire severity | A measure of the loss of aboveground organic matter (i.e. canopy tree, surface litter) and belowground (i.e. soil organic layer) |
| Firebreak | An area on the landscape where there is a discontinuity in fuel which will reduce the fire spread. |
| Forest fires/ Wildfires | An unplanned, unwanted wildland fire including unauthorized human-caused fires, escaped wildland fire use events, escaped prescribed fire projects, and all other wildland fires where the objective is to put the fire out |
| Fuel load | The mass of combustible materials available for a fire by combustion |
| Grassland | An area predominantly covered in one or more species of grass. |
| Hazard reduction burning | Burning of accumulated fuels to reduce fire fuel & thereby reduce the risk and impact of wildfire |
| Haze | Fine dry or wet particles of dust, salt, or other impurities that can concentrate in a layer next to the Earth when air is stable |
| Micrograms per cubic meter ($\mu g/m^3$) | A unit that expresses the concentration of a substance in air. A microgram per cubic meter is one one-millionth of a gram of substance per cubic meter of air |
| Mixing height | The height to which a parcel of air, or a column of smoke, will rise, mix or disperse. A column of smoke will remain trapped below this height. |
| National parks | Public forests under management of the federal government where harvesting is excluded. Recreation and biodiversity conservation are the primary goals |
| Net Present value | The current value of net benefits (benefits minus costs) that occur over time. A discount rate is used to reduce future benefits and costs to their present time equivalent |
| Particulate matter (PM) | Very small pieces of solid or liquid matter such as particles of soot, dust, fumes, mists or aerosols. The physical characteristics of particles, and how they combine with other particles, are part of the feedback mechanisms of the atmosphere |

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| Parts per billion (ppb) | Number of parts of a chemical found in one billion parts of a particular gas, liquid, or solid mixture. |
| Premature death | Deaths that occur before a person reaches an expected |
| Prescribed burn | A planned and supervised burn carried out under specified environmental conditions to remove fuel from a predetermined area of land and at the time, intensity and rate of spread required to meet land management objectives. |
| Primary forest | Naturally regenerated forest of native species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed |
| Purchasing power parities (PPP) | The rates of currency conversion that equalize the purchasing power of different currencies by eliminating the differences in price levels between countries. In their simplest form, PPPs are simply price relatives that show the ratio of the prices in national currencies of the same good or service in different countries. PPPs are also calculated for product groups and for each of the various levels of aggregation up to and including GDP |
| Puff | The puffs in a model are assumed to have Gaussian or bell0shaped concentration profiles in their vertical and horizontal planes |
| Reforestation | Replanting of a forest on cleared, degraded or destroyed forest areas |
| Resilience | A capability to anticipate, prepare for, respond to, and recover from significant multi0hazard threats with minimum damage to social well0being, the economy, and the environment |
| Savanna | A grassland with scattered individual trees |
| Secondary Forest | Regenerate on native forests, which have been cleared by natural or man0made causes, such as agriculture or ranching. They display a major difference in forest structure and/or species composition with respect to primary forests. Secondary vegetation is generally unstable, and represents successional stages |
| Smoke | The atmospheric suspension of small particles of solids and liquids produced by the combustion process |
| Stakeholder | An individual that has a specific stake in a given set of resources, and can be affected by decisions of others |
| Suppression | All work involved in controlling and extinguishing a wildfire. |
| Surface fire | A fire that burns within the surface fuel layer |
| Threshold | The lowest dose of a substance at which a specified measurable effect is observed and below which it is not observed. |

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| Total economic value | The sum of all types of use and non-use values for a good or service. Use value - value derived from actual use of a good or service. Non0use values, also referred to as “passive use” values - values that are not associated with actual use, or even the option to use a good or service |
| Trace gases | Gases such as carbon dioxide, water vapour, methane, oxides of nitrogen, ozone, and ammonia. |
| Tropical Forest | A type of forest found in areas with high regular rainfall and no more than two months of low rainfall, and consisting of a completely closed canopy of trees that prevents penetration of sunlight to the ground and discourages ground-cover growth |
| Vegetation fires | All plant type fires, in this study means agricultural and forest fires |

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