Agriculture and Natural Resources 50 (2016) 114–119

Contents lists available at ScienceDirect

Agriculture and Natural Resources

journal homepage: http://www.journals.elsevier.com/agriculture-and-natural-resources/

Original article

Effect of gases and particulate matter from electricity generation process on the radial growth of teak plantations surrounding Mae Moh power plant, Lampang province

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ARTICLE INFO

Article history:
Received 9 June 2015
Accepted 11 July 2015
Available online 9 June 2016

Keywords:
Gases
Growth
Mae Moh power plant
Particulate matter
Teak

ABSTRACT

The objectives of this study were to investigate radial growth patterns and influences of polluting gases and particulate matter on the radial growth of teak plantations surrounding the Mae Moh Power Plant. Twenty-four 32-year-old teak trees were selected from Mae Jang and Mae Moh plantations, which were 5 km and 15 km from the Mae Moe power plant, respectively. Forty-eight sample cores were collected from the 24 trees (two cores per tree). The growth patterns of all the cores were analyzed following the standard methods of dendrochronology. The relationships between the growth pattern and the amounts of sulfur dioxide, nitrogen dioxide, carbon monoxide and particulate matter were measured as average daily rates and then analyzed. The study showed that the best-fit model for the relationship between the radial current annual increment at breast height (CAI_{dbh}) and time (Y) was an exponential equation. The fitted equations were: $CAI_{dbh} = 10.657e^{(-0.031Y)}$ for Mae Moh plantation and $CAI_{dbh} = 12.518e^{(-0.032Y)}$ for Mae Jang plantation. The coefficient of determination for the fitted equations was 0.410 and 0.423 for the Mae Moh and Mae Jang plantations, respectively. Moreover, carbon monoxide (CO) and sulfur dioxide (SO_2) had a statistically significant effect on radial teak growth (RT) in the Mae Jang plantation, with a coefficient of determination of 0.69 ($RT_{mj} = 0.571 + 0.429(CO) - 0.023(SO_2)$).
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Introduction

Electrical power is important for human communities and is derived from a variety of manufacturing processes using charcoal fuel, water, wind and solar sources which can have different impacts on the surrounding environment (Breeze, 2014). The combustion of charcoal fuel, which is commonly used in central and northern Thailand, causes pollution from sulfur dioxide (SO_2), carbon monoxide (CO) and nitrogen dioxide (NO_2) (College of Public Health Sciences, 2001). For example, the extreme air pollution that was emitted from the Mae Moh Power Plant in Lampang province, Thailand in 1992 and 1997 (Pollution Control Department, 2000) affected human health and property, animals and plants in the surrounding area. In those cases, the Thai government compensated for losses of over USD 35,000 million (College of Public Health Sciences, 2001). Generally, the study of the effect of air pollution from the combustion process in Thailand has focused only on human health, not on tree health. In the current study, dendrochonological techniques were used due to their high accuracy (Schweingruber, 1996) and appropriateness for studying the correlation between air pollution and growth (Marco et al., 2002). For example, in a study involving a charcoal fuel power plant in Penzberg, Germany, tree rings of silver fir were used to investigate the effect of pollution on plant health and on missing rings during the emission period (Elling, 2001). Another study involved analysis of the growth pattern of *Pinus thunbergii* near a chemical plant in South Korea that reported growth had significantly decreased after the establishment of the plant (Kim and Fukazawa, 1997).

Teak (*Tectona grandis L.f.*) was selected for the current study as is it one of the most important economic timber trees of Thailand that is indigenous in northern Thailand (Paoin, 1993) and it has distinct annual growth rings (Palakit et al., 2012). Both genetic and environmental factors (rainfall, air temperature and air pollution) affect teak growth (Brandan et al., 2007). Thus, it is reasonable to use tree ring analysis to investigate the effect of pollution on annual teak

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http://dx.doi.org/10.1016/j.anres.2016.06.001
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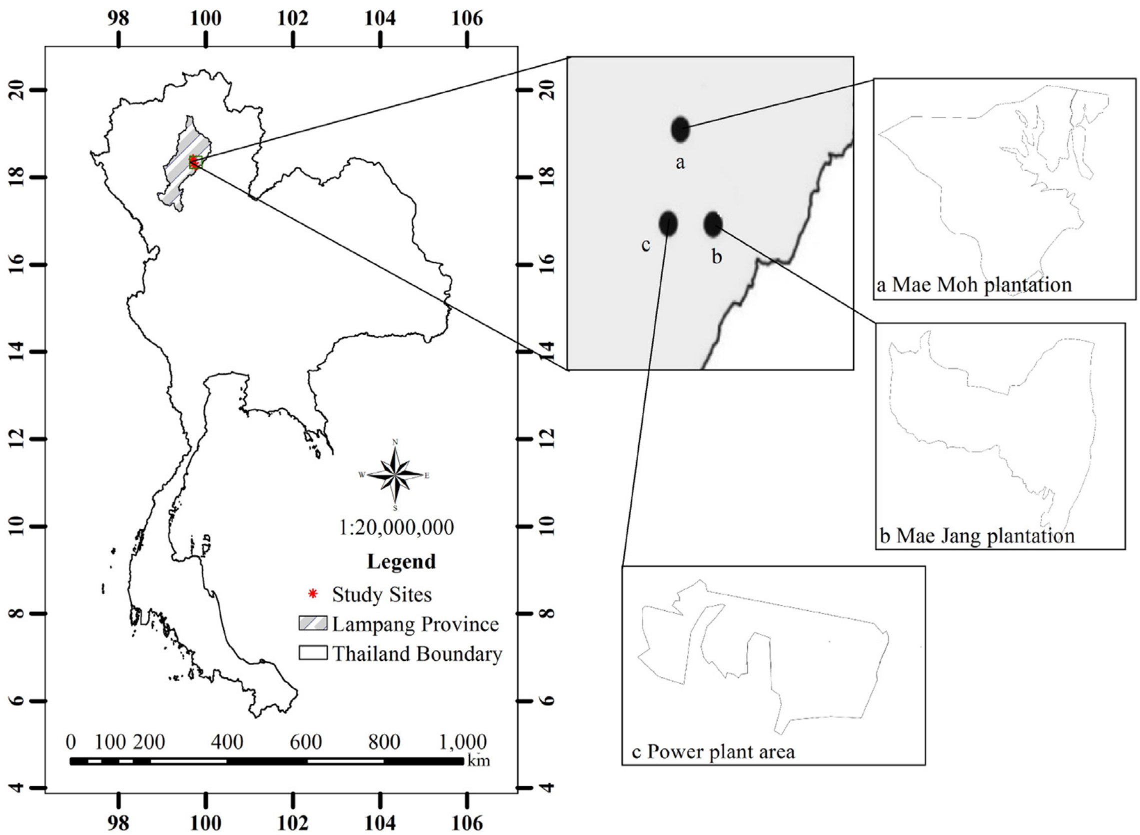

Fig. 1. Study area.

growth. The current study investigated the growth patterns and influence of air pollution gases and particulate matter on teak growth in plantations surrounding the Mae Moh Power Plant, Lampang province, Thailand.

Materials and methods

Study site

Teak trees in the Mae Moh and Mae Jang plantations used in the study were 15 km north and 5 km east of the power plant, respectively. Both plantations belong to the Forest Industry Organization of Thailand and are located in Mae Moh district, Lampang province, northern Thailand, at 2,036,195 N, 576,618 E and 2,019,739 N, 580,309 E, respectively (Fig. 1) The teak trees in this study were planted in 1979 and were aged 32 yr at the time of measurement. The spacing was 4 m × 4 m with similar topography, silvicultural systems and elevations above mean sea level in the two plantations (Tables 1 and 2).

Air pollution concentration data

The air pollution concentration data were obtained from the Soppat air quality monitoring station (5 km south of Mae Jang plantation) and the Tarsee air quality monitoring station (5 km north of Mae Moh plantation) for analysis of the tree growth data from the Mae Jang and Mae Moh plantations, respectively, which are under the control of the Pollution Control Department, Thailand. Data were obtained as a time series of averages of daily air pollution concentration data consisting of sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2) and particulate matter. Data for a 14 yr period from 1998 to 2011 were obtained (Table 3).

Tree core collection

The distribution of diameter at breast height (1.3 m) over bark (DBH) of teak (Table 4) in both plantations was determined from a forest inventory using the systematic random sampling method (Wilks, 2006). In total, 292 and 370 trees were sampled from Mae Moh and Mae Jang plantations, respectively. Sample sizes for both plantations were calculated using Equation (1) (Shiver and Borders, 1996) as 290 and 296 teak trees, respectively. The optimal number of sample trees from the forest inventory should be higher than the calculation.

$$n = \frac{t^2 (\mathrm{cv})^2}{\mathrm{AE}^2} \tag{1}$$

Table 1
Silvicultural practices in Mae Moh and Mae Jang plantation.

Plantation	Silvicultural practice			
	Spacing (m)	Thinning		Final cutting (year)
		First (year)	Second (year)	
Mae Moh	4 × 4	23	24	32
Mae Jang	4 × 4	23	30	32

Table 2
Topography and climate of Mae Moh and Mae Jang plantations.

Plantation	Elevation above mean sea level (m)	Mean annual rainfall (mm)	Mean annual temperature (°C)
Mae Moh	300–500	1212	25.31
Mae Jang	300–450	1200	26.00

Table 3
Average daily air pollution release data at Soppat and Tasee meteorological stations.

Year	Soppat meteorological station				Tasee meteorological station			
	CO[b] (ppm)	NO_2[c] (ppb)	SO_2 (ppb)	PM_{10}[a] (μg/m^3)	CO (ppm)	NO_2 (ppb)	SO_2 (ppb)	PM_{10} (μg/m^3)
1998	10.73	75.93	28.16	1071.26	4.62	43.94	40.92	1242.04
1999	8.15	62.83	22.06	1142.57	6.14	42.08	19.85	2264.52
2000	5.32	48.74	7.11	924.51	9.99	94.82	30.14	1571.50
2001	5.29	58.42	9.99	1178.71	9.85	85.31	24.17	1477.12
2002	4.42	45.60	11.82	1024.14	6.01	89.48	18.69	1090.81
2003	4.46	72.73	11.76	1180.35	8.87	113.52	21.15	1372.93
2004	5.68	73.42	14.80	1036.74	8.21	94.86	22.59	1202.52
2005	4.45	94.55	11.83	784.44	11.13	111.39	21.41	921.06
2006	5.96	82.16	12.60	794.94	12.49	168.60	24.55	983.82
2007	3.59	63.23	4.28	780.02	13.86	149.81	42.45	725.30
2008	8.57	68.02	90.53	851.15	8.57	68.02	90.53	851.15
2009	5.46	88.25	12.78	892.81	10.06	97.91	29.45	1065.27
2010	10.64	34.95	15.93	728.73	5.37	33.85	30.72	684.46
2011	16.90	75.89	31.56	1018.66	7.27	43.51	32.37	1110.90

[a] Particulate matter.
[b] Parts per million.
[c] Parts per billion.

where n is the target number of sample trees, t is the confidence value at the 95% probability level, cv is the coefficient of variation for DBH and AE is the allowable standard error in DBH.

The DBH distribution was classified into three classes (Table 5). Four trees in each class were selected to represent the whole plantation area (12 trees in each plantation yielding a total of 24 trees for both locations). Selected trees with a straight trunk and low scar occurrence were drilled using an increment borer until the pith was reached at 1.3 m height from the ground. Two cores perpendicular to each other were collected from each sample tree (48 cores in total). Tree core samples were stored in plastic tubes and transported to the laboratory.

Tree core sample preparation and measurement

The tree core samples were prepared in the Laboratory of Tropical Dendrochronology, Faculty of Forestry, Kasetsart University, Bangkok, Thailand following the standard methods of dendrochronology (Stokes and Smiley, 1996). Each tree core sample was removed from the plastic tube and mounted using glue on a slate and left at room temperature until the glue has completely dried. Then, the samples were scrubbed with sandpaper of several grades until the boundaries of annual rings were clear enough for microscopic investigation. Cross-dating and cross-matching techniques were used to define the growth ring in each year. The accuracy of growth ring identification was verified using the program COFECHA (Holmes, 1983) after each ring had been measured to a resolution of 0.001 mm.

Data analysis

Tree ring data series were analyzed using the mean sensitivity (MS) to investigate the external factors affecting the tree ring width. MS is a statistic measuring the mean relative change between adjacent ring widths, that is, the average relative difference from one ring width to the next. MS was classified into three levels: 1) low sensitivity, 0.10–0.19; 2) intermediate sensitivity, 0.20–0.29; and 3) high sensitivity value greater than 0.30, where the higher the value, the better the correlation between growth and external factors (Mayer, 2001). MS was calculated using Equation (2) (Bunn et al., 2013):

$$MS_x = \frac{1}{n-1}\sum_{t=1}^{t=n-1}\left|\frac{2(x_{t-1}-x_t)}{x_{t-1}+x_t}\right| \qquad (2)$$

where x_t is a measure of growth, n is the number of ring widths in each tree sample core and $t = 1, 2, 3, \ldots, n$.

The expressed population signal (EPS) quantifies how well the chronology based on a finite number of trees represents the hypothetical perfect or true chronology and was calculated using Equation (3) (Cook and Kairiukstis, 1990):

$$EPS = \frac{t \times \bar{r}}{((t \times \bar{r}) + (1-\bar{r}))} \qquad (3)$$

where t is the number of tree series averaged-one core per tree and "$\bar{r}$" is the mean between-tree correlation.

The EPS was analyzed to check the reliability of tree ring data based on the number of samples and the correlation of all tree ring samples for values of the EPS of more than 0.85 (Wigley et al., 1984).

The teak growth patterns in the Mae Moh and Mae Jang plantations were analyzed using simple regression to obtain the best fit growth model. Time and teak growth were defined as the independent variable and dependent variable, respectively. The best-fit model was selected based on three criteria: 1) coefficient of

Table 4
Diameter at breast height and basal area of sample trees.

Plantation	Diameter breast height (cm)				Basal area per tree (cm^2)			
	Max[a]	Min[b]	Mean	SD	Max	Min	Mean	SD
Mae Moh	38.80	15	22.80	4.78	1181.77	176.63	426.55	185.84
Mae Jang	41.50	15	24.11	5.16	1351.97	176.63	477.03	209.88

[a] Maximum.
[b] Minimum.

Table 5
Diameter classes and numbers of tree samples and tree core samples.

Plantation	Diameter class	DBH[a] (cm)	Number of sample trees	Number of sample cores
Mae Moh	1	15.00–23.00	4	8
	2	23.00–31.00	4	8
	3	31.00–39.00	4	8
Mae Jang	1	15.00–24.00	4	8
	2	24.00–33.00	4	8
	3	33.00–42.00	4	8

[a] Diameter at breast height over bark.

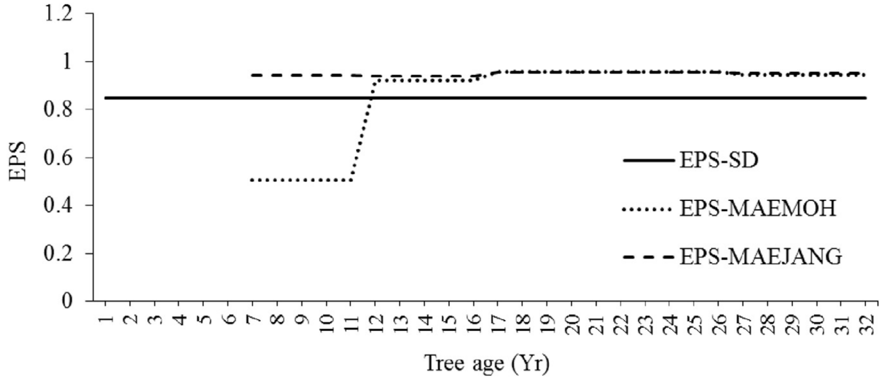

Fig. 2. Expressed population signal (EPS) of teak in Mae Moh (MAEMOH) and Mae Jang (MAEJANG) plantations (EPS-SD is standard EPS line = 0.85).

determination (R^2) close to 1; 2) lowest standard error of estimate (SE); and 3) statistical significance (p value).

The relationships between teak growth and the influences of gases and particulate matter from the electricity generation process were determined using simple correlation and multiple regression analysis. Teak growth was considered as the dependent variable and the air pollution factors were classified as independent variables.

Results

Mean sensitivity of tree ring data series

Tree cores of Mae Moh and Mae Jang plantations had 32 years of ring width data averaging 3.491 mm and 3.883 mm, respectively. Data analysis of the EPS in Mae Moh plantation in the initial phase was less than the standard, but then was greater than the standard EPS (0.85) as shown in Fig. 2. Thus, only years 12–32 data of the Mae Moh plantation were used which were already covered by the air pollution release data (from 1997 to 2012). The MS analysis values for Mae Moh and Mae Jang plantations were 0.451 and 0.403, respectively, which were considered as high sensitivity (above 0.3). Therefore, tree ring data from both plantations in the study were appropriate for establishing a relationship between teak growth and environmental factors.

Teak radial growth pattern and model

Teak radial growth in Mae Moh plantation was in the stationary phase, in which the growth rate was stable especially during terminal growth. The mean annual increment of diameter at breast height over bark at 1.3 m (MAI_{dbh}) ranged from 3.552 mm to 9.498 mm, with an average of 8.084 mm. The MAI_{dbh} increased in years 1–9 and then decreased after year 9. The current annual increment of diameter breast height over bark at 1.3 m (CAI_{dbh}) ranged from 2.062 mm to 14.110 mm with an average of 6.982 mm. The trend of the CAI_{dbh} was similar to the MAI_{dbh} with the highest value in year 10 (Fig. 3). However, the CAI_{dbh} slightly increased after the first silvicultural thinning in year 22 but in the next year (year 23), the CAI_{dbh} decreased.

Teak growth in Mae Jang plantation was in the stationary phase, as in the Mae Moh plantation. The MAI_{dbh} ranged from 5.747 mm to 11.666 mm with an average of 9.337 mm. The MAI_{dbh} successively increased from year 1 until year 10, then growth decreased until year 18 and stabilized from year 19 until year 31. The CAI_{dbh} ranged from 3.111 mm to 15.061 mm with an average of 8.017 mm. Growth in the first two years was slow but rapidly increased after year 2 until year 11, and then the CAI_{dbh} gradually decreased until year 32 (Fig. 4). The trend in the CAI_{dbh} after silvicultural thinning was similar to that in the Mae Moh plantation.

The growth pattern model for prediction was determined using regression analysis, where equations of the forms linear, exponential, logarithmic and S-curve were fitted. In both plantations, the exponential equation was found to best fit the relationship between the radial growth (CAI_{dbh}) and time (Y, the number of year). The fitted equations were: $CAI_{dbh} = 10.657e^{(-0.031Y)}$ for Mae Moh plantation and $CAI_{dbh} = 12.518e^{(-0.032Y)}$ for Mae Jang plantation. The R^2 values for the fitted equations were 0.410 and 0.423 for Mae Moh and Mae Jang plantations, respectively, which were highly significant ($p < 0.01$) as shown in Table 6. The negative exponential equation provided in this model was the optimum equation based on the regression analysis. Note that this simple

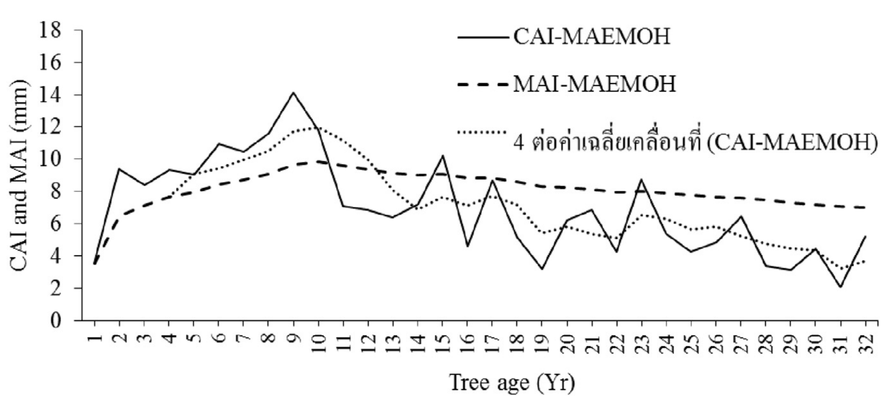

Fig. 3. Current annual increment (CAI) and mean annual increment (MAI) of teak in Mae Moh plantation (4 per. Mov. Avg is moving average of CAI at age 4 yr).

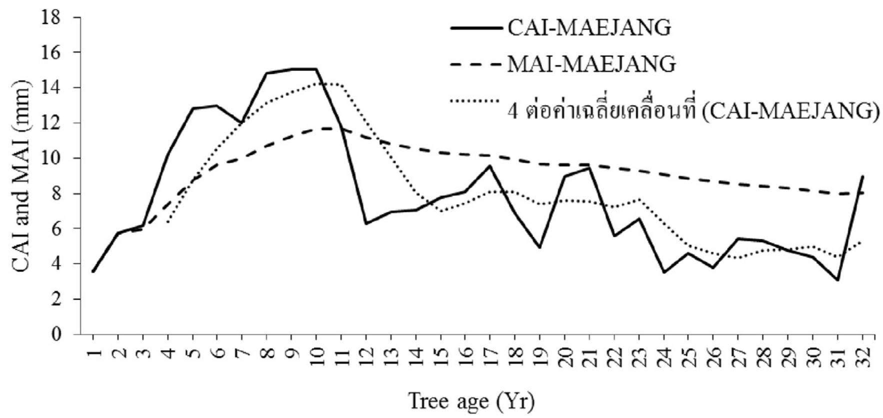

Fig. 4. Current annual increment (CAI) and mean annual increment (MAI) of teak in Mae Jang plantation (4 per. Mov. Avg is moving average of CAI at age 4 yr).

model is unsuitable (biased) for expressing the initial phase of increasing CAI (age less than 10 years) because of the nature of the model and the EPS in this phase was under the standard. However, this period of increasing CAI was less critical in the current study, which focused mainly on the effects of pollution on teak growth from the time the Mae Moh Power Plant was expanded and the pollution was noticeable (when the plantation was over 10 years old).

Effect of gases and particulate matter on teak growth

Mae Moh plantation

The relationship between the teak growth data series and air pollution release data in the current year of Mae Moh plantation was not statistically significant ($p > 0.05$), based on correlation analysis. Furthermore, when using the air pollution release data for a year before a growth year, the relationship was not statistically significant ($p > 0.05$).

Mae Jang plantation

The relationship between the teak growth data series and air pollution release data in Mae Jang plantation, based on correlation analysis, showed that only carbon monoxide was statistically significant ($p < 0.01$), with a correlation value of 0.726 (Table 7). Stepwise regression analysis to determine the effect of gases and particulate matter on teak growth in Mae Jang plantation showed that carbon monoxide and sulfur dioxide had the highest R^2 value (0.69) and met all the criteria of the best-fit curve. Therefore, the relationship between radial growth of teak (RT_{mj}) and the concentration of CO and SO_2 in the same year was determined and is shown in Equation (4):

$$RT_{mj} = 0.571 + 0.429(CO) - 0.023(SO_2), \quad R^2 = 0.690 \tag{4}$$

where RT_{mj} is the radial growth of teak in Mae Jang plantation (in millimeters), CO is the carbon monoxide released in each year (in parts per million; ppm) and SO_2 is the sulfur dioxide released in each year (in parts per billion; ppb).

From Equation (4), the concentration of CO and SO_2 could explain 69% of the growth of teak. The higher the CO concentration, the better the growth (positive correlation), while the lower the SO_2 concentration, the better the growth (negative correlation). However, when each gas was considered separately, CO had a higher impact on growth than SO_2 and was statistically significant but still the correlation value was lower than for both CO and SO_2 together. In addition, when using the air pollution release data in a year before a growth year, the relationship was not statistically significant ($p > 0.05$).

Table 6
Teak growth model from 32-year data of teak.

Plantation	Equation form	Growth model	R^{2b}	SE (mm)	*p*-Values
Mae Moh	Exponential	$CAI^{c} = 10.657e^{(-0.031Y)}$	0.41	0.36	0.00[a]
Mae Jang	Exponential	$CAI = 12.518e^{(-0.032Y)}$	0.42	0.34	0.00[a]

[a] Highly significant ($p < 0.01$).
[b] Correlation coefficient.
[c] Current annual increment (cm/yr).

Discussion

The effects of gases and particulate matter on each plantation were not similar due to many factors. First, the distance from the power plant to each plantation was different with Mae Jang plantation (5 km) being three times closer to the power plant than Mae Moh plantation (15 km). Long and Davis (1999) reported that the distance affected the distribution of air pollution, with the shorter distance resulting in more impact from pollution. Another important factor is the concentration of pollution. For example, the research of Costonis (1971) showed that a concentration of SO_2 of more than 0.04 ppm did not have an effect on plants and an SO_2 level of 0.5 ppm had to be released for 4 h for plants to show any effect of toxicity (Thomas, 1961). Other factors causing different effects of gases and particulate matter between the plantations include those that normally affect teak growth, especially rainfall and temperature, which can be more important than the effect of pollution (Suwannapinant, 2001). For example, a study of the climatic effect on growth of *Pinus merkusii* in Suphanburi province, Thailand showed that the growth of the pine was related to rainfall (Lamyai, 2009). Moreover, plants have a tolerance to some degree to environmental factors in the growth stage (Fritts, 1976); therefore, teak may have tolerance to the air pollution from the power plant to some level, whereby the pollution did not affect teak growth in the Mae Moh plantation.

Conclusion

Teak growth pattern

The teak trees sampled in Mae Moh plantation were aged 32 yr and their CAI ranged from 2.062 mm to 14.110 mm with an average of 6.982 mm. It increased in years 1–9 and then decreased after

Table 7
Correlation value between growth of teak in Mae Moh, Mae Jang plantations and air pollution release data.

Air pollutant	Statistic	Mae Moh plantation	Mae Jang plantation
SO_2	Correlation value	−0.209	−0.007
	Significance (2-tailed)	0.494	0.983
	Degrees of freedom	13	13
NO_2	Correlation value (r)	−0.491	−0.308
	Significance (2-tailed)	0.088	0.306
	Degrees of freedom	13	13
CO	Correlation value (r)	−0.408	0.726[a]
	Significance (2-tailed)	0.166	0.005
	Degrees of freedom	13	13
PM_{10}	Correlation value (r)	0.442	0.134
	Significance (2-tailed)	0.130	0.662
	Degrees of freedom	13	13

[a] Highly significant ($p < 0.01$).

year 9 with the highest value being in year 10; after that, the CAI gradually decreased until year 32. An exponential equation was found to best describe the relationship between growth and time for Mae Moh plantation.

The teak trees sampled in Mae Jang plantation were aged 32 yr. The CAI ranged from 3.111 mm to 15.061 mm with an average of 8.017 mm. The growth in the first two years was slow but rapidly increased after year 2 until year 11, and then the CAI gradually decreased until year 31. An exponential equation was found to best describe the relationship between growth and time for Mae Jang plantation.

Effect of gases and particulate matter from electricity generation process on teak growth

The correlation between the teak growth data series and air pollution concentration data in the same year at Mae Moh plantation was not statistically significant. The correlation between the teak growth data series and air pollution released data in Mae Jang plantation showed that only carbon monoxide was statistically significant. A regression analysis to determine the effect of gases and particulate matter on teak growth in Mae Jang plantation indicated that both carbon monoxide and sulfur dioxide had a significant impact on teak growth.

Hopefully, this study provides information which can be used by anyone to assist in making decisions and undertaking research on the effect of pollution on tree growth in plantations or natural forest.

Conflict of interest statement

The authors declare that there are no conflicts of interest.

Acknowledgments

The authors wish to thank Dr A.Y. Omule, International Consultant and Adjunct Professor, Kasetsart University, Dr Krittadapan Palakit and Dr Nisa Leksungnoen for their tireless help, valuable comments and suggestions for research and improvement of this manuscript. This study was supported by The Graduate School of Kasetsart University and the Laboratory of Tropical Dendrochronology, Department of Forest Management, Faculty of Forestry, Kasetsart University, Bangkok, Thailand.

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