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Ozone phytotoxicity evaluation and prediction of crops production in tropical regions

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HIGHLIGHTS

► Predicted crop reduction in Malaysia by adopting the AOT40 index method.
► Nine AOTX indexes were analyzed, crop responses tested and its reduction predicted.
► The AOT50 index gave the highest R^2 value between the AOT50 and the crops reduction.
► The critical level for AOT50 index if the crop reduction is 5% was 1336 ppb h.
► The AOT40 index in Malaysia gave a minimum percentage of 6% crop reduction.

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ABSTRACT

Increasing ozone concentration in the atmosphere can threaten food security due to its effects on crop production. Since the 1980s, ozone has been believed to be the most damaging air pollutant to crops. In Malaysia, there is no index to indicate the reduction of crops due to the exposure of ozone. Therefore, this study aimed to identify the accumulated exposure over a threshold of X ppb (AOTX) indexes in assessing crop reduction in Malaysia. In European countries, crop response to ozone exposure is mostly expressed as AOT40. This study was designed to evaluate and predict crop reduction in tropical regions and in particular, the Malaysian climate, by adopting the AOT40 index method and modifying it based on Malaysian air quality and crop data. Nine AOTX indexes (AOT0, AOT5, AOT10, AOT15, AOT20, AOT25, AOT30, AOT40, and AOT50) were analyzed, crop responses tested and reduction in crops predicted. The results showed that the AOT50 resulted in the highest reduction in crops and the highest R^2 value between the AOT50 and the crops reduction from the linear regression analysis. Hence, this study suggests that the AOT50 index is the most suitable index to estimate the potential ozone impact on crops in tropical regions. The result showed that the critical level for AOT50 index if the estimated crop reduction is 5% was 1336 ppb h. Additionally, the results indicated that the AOT40 index in Malaysia gave a minimum percentage of 6% crop reduction; as contrasted with the European guideline of 5% (due to differences in the climate e.g., average amount of sunshine).

1. Introduction

Malaysia relies heavily on agriculture with agricultural output of critical importance due to increasing population (Department of Statistic, 2010). In Malaysia, ozone is an important issue due to increasing sources of ozone precursors. Ozone is a secondary pollutant formed by chemical reactions that occur in the air (WHO, 1976). Ozone arises from natural sources (e.g., vegetation), mobile sources (e.g., motor vehicles), and stationary sources (power plants, industrial facilities, residential and commercial establishments) (Placet et al., 2000). Ozone from these sources has increased due to rapid development in Malaysia.

The Malaysian Environmental Quality Act 1974 (EQA) sets out ozone level guidelines. The ozone acceptance level can be up to 100 ppb on average in 1 h or 60 ppb in 8 h (Malaysia Environmental Quality Report, 2008). The guideline focuses only on the impact on human health, and not on plants. Ishii et al. (2004) reported that there could be a significant impact on the growth and yield of rice (paddy) even though the crop ozone exposure is lower than the level of the Malaysia air quality guidelines. Therefore, as the Malaysian economy is dependent on agriculture the effect of ozone on plants is an important research objective.

Numerous studies have reported that ozone contributes to many adverse effects on plants. Ranieri et al. (2001) claimed that ozone

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exposure could cause a reduction in plant photosynthesis and an imbalance in cell redox status, which lead to premature senescence. Therefore, any basis that might increase the concentration of plant metabolites' interaction with antioxidant capacity will also increase the negative impact of ozone (Fagnano et al., 2009). The value of the potential global agricultural losses due to the increase of surface ozone was estimated to be up to 35 billion USD in 2030 (Avnery et al., 2011).

In European countries, Accumulated Exposure over a Threshold of 40 ppb (AOT40) is used as a guideline for ozone in minimizing its effects on crops. The AOT40 is a cumulative exposure index, which is calculated as the sum of the differences between the hourly concentration (in ppb) and 40 ppb for every hour when the concentration exceeds 40 ppb. This index is based on the ozone concentration level (UNECE, 1999). AOT40 is supposed to provide a good linear relationship between the exposure to ozone concentration and reduction in crops. It is an expression of the critical levels of ozone to protect the plant, which depends on critical loads of ozone, and to exhibit the ozone impacts on vegetation (Fuhrer et al., 1997).

This study was carried out to identify potential reduction in crops due to different ozone concentrations. The focus of the study was how crop reduction might vary, which could occur by varying the level of ozone expressed by AOTX indexes. Each of the indexes demonstrated different accumulated value of ozone concentrations. Therefore, variation in crop reduction can be determined by the different level of ozone concentration. Other parameters that might affect the yield such as temperature, sun, humidity, soil, and water were held constant in the analysis, which was based on the available crops records. Due to the lack of studies concerning the effects of ozone on crops in Malaysia, this study aimed to evaluate and predict the reduction in yield considering the Malaysian climate. The AOT40 index method was adopted and improvised based on Malaysian climatology as well as Malaysian air quality records.

2. Accumulated exposure over a threshold of X ppb (AOTX) on evaluating crop response in other regions

Accumulated exposure over a threshold of 40 ppb (AOT40) is the key indicator in evaluating ozone impacts on vegetation in Europe. The European benchmark assumes a 5% reduction in agricultural yield if the accumulated ozone concentration within a three-month period is above 3000 ppb h (Ishii et al., 2007). Many researchers have reported findings regarding the relationship between AOTX and crop response, especially AO40 in order to correlate the risk of ozone-damage to vegetation.

In Europe, 23% of the land areas which support crops (12 agricultural and seven horticultural) are sensitive to ozone (Mills et al., 2007). This result was obtained from the derivation of AOT40-based critical levels, where the ecological risk was assessed by the measured ozone concentration data, using linear regression. In France, Italy, Spain and Switzerland, Gerosa et al. (2007) estimated the AOT40 index using passive sampling at 81 forest monitoring stations from 2000 to 2002. The estimation was based on the ozone daily profile as a function of the relative altitude. The results showed that 77–100% of the monitored sites had exceeded the critical level of 5000 ppb h Piikki et al. (2009) estimated the AOT ozone indexes from the time-integrated ozone data and hourly air temperature in southwest Sweden from 2005 to 2007. From the study, they suggested that the AOT index estimation should be based on the ozone data combined with hourly temperature measurements in order to improve the spatial resolution in AOT evaluations. This suggestion was adopted and details are given in the following section.

3. Materials and methods

3.1. Study area and local meteorology

The analyses were based on the seven monitoring stations located in Kedah, Perak, Negeri Sembilan, Pulau Pinang, Selangor, and Pahang as shown in Fig. 1.

Malaysia has notoriously high humidity. The mean relative humidity varies from as low as 72% to as high as 87%. The minimum relative humidity is normally found in January and February. The maximum, however, is generally found in the month of November. The temperature in the study area was usually between 27 and 30 °C during the daytime and 22–24 °C at night (Malaysian Meteorological Department, 2008).

According to the Malaysia Meteorological Services (MMS), the Malaysian climate is divided by the two monsoon seasons, the south-west monsoon and the north-east monsoon. The South-west monsoon occurs from the latter half of May or early June until the end of September, while the north-east monsoon occurs from early November until March. During the south-west monsoon, this area is drier with higher temperature and less rainfall, as compared to the other months, which receives heavy rainfall.

The monthly rainfall pattern shows that the two periods of maximum rainfall are separated by the two periods of minimum rainfall. The primary maximum commonly occurs from October to November while the secondary maximum normally occurs from April to May. The primary minimum takes place from January to February and the secondary minimum is from June to July (Jamaludin et al., 2010).

3.2. Ozone and crops data

The quality-assured data of ozone was collected at the continuous monitoring stations located in Bakar Arang (Kedah) (05°37.886 N 100°28.189 E), Seberang Jaya (Pulau Pinang) (05°23.890 N 100°24.194 E), Shah Alam and Kajang (Selangor) (03°04.636 N 101°30.673 E and 02°59.645 N 101°44.417 E), Ipoh (Perak) (04°37.781 N 101°06.964 E), Nilai (Negeri Sembilan) (02°49.246 N 101°48.877 E), and Jerantut (Pahang) (03°58.238 N 102°20.863 E) as shown in Fig. 1. Data was provided by the Department of Environment (DoE) Malaysia. The data is regularly subjected to standard quality control processes and quality assurance procedures by the DoE. Data was collected continuously from January 2004 to December 2009 and recorded on an hourly basis from 7 am to 7 pm every day.

Samples of the ozone concentrations were collected using a UV Absorption Ozone Analyzer Model 400A (EPA Approved EQOA 0992–087). The model 400A UV Absorption Ozone Analyzer, is a microprocessor-controlled analyzer that uses a system based on the Beer–Lambert law for measuring the low ranges of ozone in the ambient air.

The agricultural crop used in this study was paddy (*Oryza sativa*), recorded from 2004 to 2009 for every selected site (Fig. 1). Paddy was used to estimate the reduction of agricultural crop production due to the effects of ozone concentration levels. Crop data was obtained from the Department of Agricultural (DoA) Malaysia. There are two seasons for paddy planting in Malaysia; the main season and the off season (DoA, 2010a,b). In the main season (July–September) paddy is grown without depending on irrigation systems while the in the off season (March–May) irrigation is used (DoA, 2010a,b).

3.3. Mathematical models

AOTX index is calculated as the sum of differences between X ppb and the hourly ozone concentration which is more than X

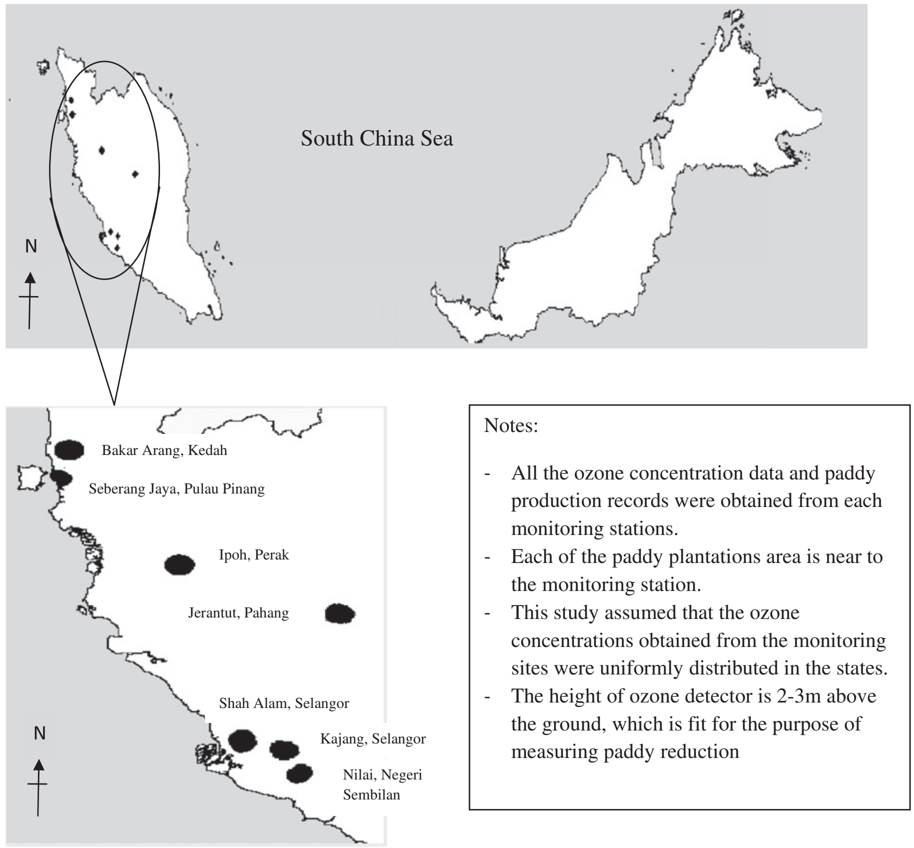

Fig. 1. Location of monitoring stations in Malaysia.

ppb, for each daylight hour with the global radiation more than 50 W m^{-2} for a period of 3 months. AOTX is calculated as shown in Equation (1).

$$\mathrm{AOTX} = \sum_{i=1}^{n} [C_{O_3} - X]_i \text{for } C_{O_3} > X \text{ ppb[unit : ppb h]} \quad (1)$$

Where, C_{O_3} is the hourly ozone concentration in ppb, i is the running index, and n is the number of hours with C_{O_3} more than X ppb, during the time evaluation (Grunhage et al., 1999).

In order to find the suitable AOTX index in Malaysia, we must first find the possible value of ozone concentration, which may have a detrimental impact on the crops. Due to a lack of studies on the effects of ozone on crop production in Malaysia, there are no available statistics that can be used in this study. Therefore, one of the methods used was to divide the threshold value for each AOTX index with the total of ozone concentration. This value was assumed to be the preliminary crop reduction likely to occur due to ozone exposure. The percentage of crop reduction for each AOTX index for both seasons was then calculated using the formula shown in Equation (2).

$$\text{Possible occurence of paddy reduction(\%)} = \frac{\text{AOTX value}}{\sum \text{Ozone Concentration}} \times 100\% \quad (2)$$

Where, X is the index of AOT.

We assumed that the paddy production data obtained from the Malaysian DoE, was post damage production. Therefore, to estimate paddy reduction, the percentage value, which was obtained from Equation (3), was multiplied with the post-damage paddy production.

$$\begin{aligned}&\text{Esimated paddy reduction(metric tonne)}\\ &= \text{Possible occurence of paddy reduction}\\ &\quad \times \text{Paddy production after damage(metric tonne)} \quad (3)\end{aligned}$$

The calculation was conducted using the Microsoft Office Excel 2007.

Most studies done on response relationships are usually indicated by fitting linear, quadratic, or Weibull functions. Studies by Fuhrer et al. (1997) showed that the AOTX indexes were close to the linear relationship. Therefore, the relationship between the crops reduction and the AOTX indexes were tested using linear regression analysis. The coefficient of determination, R^2, between the parameters were calculated and compared. This analysis was done using SPSS Version 11.5.

As Malaysia does not have indicators for the reduction of crops from ozone exposure, an analysis of the estimation of crop reduction using the AOTX indexes needs to be carried out. As European guidelines state that 5% reduction in yield for agricultural crops will be expected to occur if the accumulation of ozone concentration within that duration is above 3000 ppb h (Ishii et al., 2007; LRTAP Convention, 2004), we used the same critical limit as the European benchmark in order to differentiate the dissimilarity of responses between the European and Malaysian regions. Therefore, the analysis using Equation (4) was carried out to identify the possible crop reduction likely to occur for each AOTX index in Malaysia. In this analysis, 3000 ppb h was used as the critical level, similar to the European concentration-based critical level (LRTAP Convention, 2004).

$$\text{Estimated crops reduction}(\%) = \frac{\text{Calculated crops reduction(calculation)}(\%)}{\text{Total AOTX(ppb h)}} \times 3000\ \text{ppb h} \tag{4}$$

Where 3000 ppb h is the European concentration-based critical level for the AOT40 index (UNECE, 1996). To investigate crop reduction for all AOTX indexes, 3000 ppb h is employed as the guideline consistent with the European critical level. The estimated crop reduction was calculated based on the total ozone exposure for both seasons and the crop production records obtained from the DoA, Malaysia (2004–2009).

4. Results and discussions

The accumulated ozone concentration over a threshold of 0 ppb, 5 ppb, 10 ppb, 15 ppb, 20 ppb, 25 ppb, 30 ppb, 40 ppb, and 50 ppb (AOT0, AOT5, AOT10, AOT15, AOT20, AOT25, AOT30, AOT40, and AOT50) from 2004 to 2009 in Malaysia are summarized in Table 1.

The threshold values obtained in Table 1 were important to understand the range of threshold values in Malaysia, which will then be used to determine the critical level of the AOTX index. As each AOTX index has its own range of threshold values and the critical limit, they have to be determined separately.

From Table 1, the AOT40 index threshold value range varied between 2000 ppb and 9000 ppb. According to the European benchmark, a threshold value which is above 3000 ppb within a 3 months period is highly probable to result in a minimum of 5% crop reduction. According to the range of ozone threshold of 40 ppb (AOT40) in Malaysia, we can approximately verify that the crop reduction in Malaysia is immensely affected by the ozone concentration of 5–15% due to the high concentration of accumulated ozone exposure (up to 9000 ppb).

Analysis on the effect of AOTX indexes and paddy reduction was carried out for both the main and the off seasons. Fig. 2 illustrates the relationship between AOTX indexes and paddy reduction under the Malaysian climate for two seasons, from 2004 to 2009.

In Fig. 2, there are two synchronized patterns between the AOTX indexes and paddy reduction in the Malaysian climate. During both seasons, AOT0 gave the lowest paddy reduction while AOT50 showed the highest reduction in paddy compared to the other indexes. The highest percentage for paddy reduction for both seasons was 12.11%, depicted by the AOT50 during the off season. In Malaysia, paddy production was highly affected by ozone exposure during the off season (Fig. 2).

The off season of paddy yield is usually during the South-west monsoon. During this season, the area is drier with higher temperature and less rainfall, as compared to other months. This phenomenon will result in increased ozone formation in the atmosphere. According to Ghazali et al. (2010), the formation of ozone is heavily influenced by sunlight and temperature. The main season of paddy plantation is during the north-east monsoon. This season provides heavy rainfall with high humidity. Rainfall cleans the atmosphere, thus, removes pollutants such as nitrogen dioxide, the main precursor of ozone. During the rainy season, the presence of UVB will lessen, the temperature will fall, and humidity will increase (Lal et al., 2000).

Although this phenomenon will reduce the rate of the ozone transformation, higher humidity and mild temperatures can increase stomatal conductance and thus the ozone uptake by the leaves of plants, which results in yield loss (Wang et al., 2005). This scenario can be clearly observed from the results illustrated in the Fig. 2, where the paddy reduction had occurred during the main season although the percentage reduction was less than in the off season.

This analysis was then repeated using the ‘control’ ozone concentration where the value was obtained from a very low ozone site. In Malaysia, the monitoring station in Jerantut, Pahang is a background station established by the Malaysian Department of

Table 1
Summary of ozone concentration's threshold for AOTX indexes in Malaysia from 2004 to 2009.

Year	Month	AOT0	AOT5	AOT10	AOT15	AOT20	AOT25	AOT30	AOT40	AOT50
2004	January–March	33,962	29,006	24,644	20,629	17,065	13,991	11,377	7369	4680
	April–June	35,789	30,727	26,388	22,441	18,844	15,618	12,759	8169	4961
	July–September	30,370	25,472	21,273	17,517	14,099	11,129	8580	4730	2389
	October–December	27,917	23,039	18,830	15,086	11,865	9203	7098	4183	2431
2005	January–March	38,081	32,993	28,378	24,121	20,235	16,772	13,735	8819	5352
	April–June	34,369	29,369	24,990	20,981	17,296	13,902	10,969	6284	3213
	July–September	31,143	26,148	21,855	17,973	14,456	11,371	8712	4680	2280
	October–December	25,439	20,505	16,400	12,857	9839	7332	5332	2709	1318
2006	January–March	20,731	17,264	14,243	11,545	9203	7245	5637	3266	1727
	April–June	33,063	28,178	23,998	20,190	16,729	13,641	10,954	6771	3999
	July–September	31,097	26,187	21,975	18,164	14,738	11,695	9033	4939	2412
	October–December	33,025	28,012	23,692	19,766	16,213	13,056	10,327	6155	3501
2007	January–March	31,863	26,913	22,568	18,576	14,976	11,851	9220	5350	2915
	April–June	30,812	25,923	21,706	17,859	14,382	11,297	8670	4725	2387
	July–September	22,118	18,289	15,145	12,286	9760	7562	5704	2983	1406
	October–December	26,382	21,462	17,379	13,836	10,798	8239	6138	3138	1495
2008	January–March	31,046	25,913	21,517	17,619	14,230	11,360	8939	5307	3035
	April–June	30,617	25,573	21,260	17,383	13,878	10,764	8113	4203	1933
	July–September	28,473	23,428	19,136	15,363	12,078	9266	6905	3531	1566
	October–December	27,614	22,535	18,134	14,233	10,895	8111	5865	2859	1417
2009	January–March	30,656	25,670	21,322	17,409	13,978	11,020	8509	4764	2486
	April–June	31,432	26,403	21,984	17,980	14,437	11,305	8612	4668	2408
	July–September	27,438	22,357	18,083	14,383	11,217	8511	6234	3000	1259
	October–December	26,176	21,254	17,077	13,452	10,376	7876	5878	3133	1570

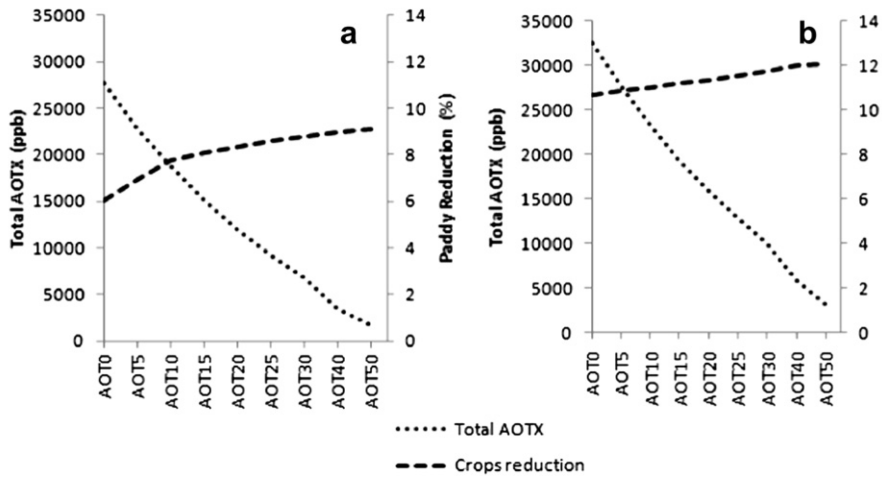

Fig. 2. (a): Main season, (b): Off season: Relationship between AOTX and paddy reduction in Malaysia.

Environment. In this monitoring station, the natural forest, soil dust and a low number of motor vehicles are expected to contribute to air quality status (Azmi et al., 2010). Therefore, this station was selected as the 'control' station in order to identify the possible paddy reduction in a very low ozone site. Fig. 3 demonstrates the relationship between AOTX indexes and paddy reduction in Jerantut, Malaysia.

Fig. 3 illustrates the paddy reduction at the control station against AOTX indexes. This analysis was carried out to identify possible paddy reduction under a low ozone concentration. The result showed that reductions in Jerantut were much lower than other sites in Malaysia although the paddy reduction pattern was analogous with Fig. 2. The highest paddy reduction in Jerantut recorded by AOT50 during the off season was 3.5% (Fig. 3b). This percentage was smaller than the reduction of paddy during the off season in the study areas (12.11%).

The result demonstrated that paddy reduction was highly related to ozone concentration in Malaysia. According to Musselmn et al. (1994), plant response is closely related to ozone exposure, where higher concentrations of ozone cause more injury and loss of productivity in vegetation. In a low ozone site (Fig. 3), the percentage of paddy reduction was lower compared to the area with higher ozone concentration (Fig. 2). Therefore, both of these figures verified that the paddy reduction was likely to occur in the area with higher ozone exposure.

The relationship between the nine AOTX indexes and paddy reduction was tested using linear regression analysis. Table 2 illustrates the R^2 value for the relationship between these two parameters from 2004 to 2009.

Table 2 depicts the R^2 values for the best correlation for the study areas between paddy reduction and the different AOTX indexes from 2004 to 2009. Almost all areas illustrated that the AOT50 index gave the highest R^2 values compared to other indexes, except for Perak and Negeri Sembilan.

Fuhrer et al. (1997) had compared several AOTX indexes such as AOT30, AOT40, and AOT60 in assessing the effect of different AOTX indexes on crops in European countries. He found that the AOT40 index provided a good fit relationship between the index and the crop response. However, as response of crops to ozone are highly related to climate, the different indexes make an important contribution to the observed change in yield and should not be ignored (Fuhrer, 2009; Legge et al., 1996).

The AOTX index was based on the exposure of ozone concentration on crops. Therefore, different ozone exposures between regions of the world can lead to different crop responses. As AOT40 was developed according to European data and scenarios, a similar

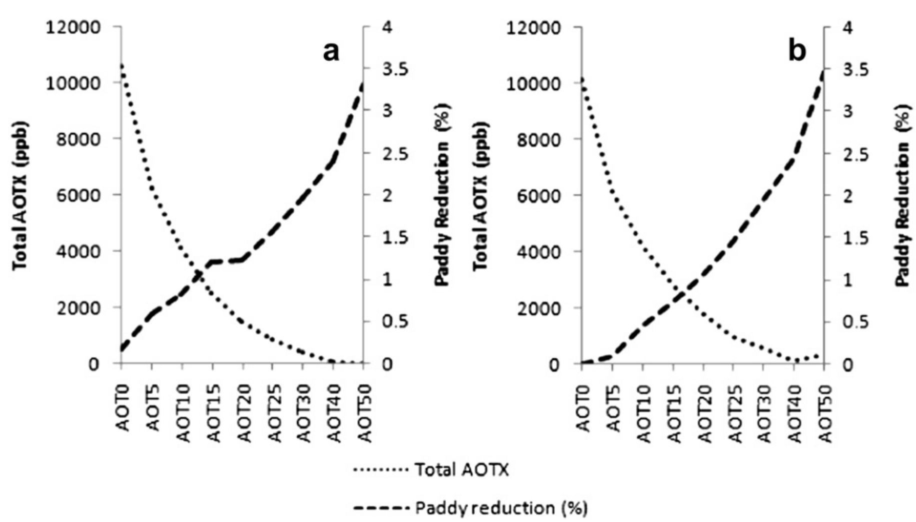

Fig. 3. (a): Main season, (b): Off season: Relationship between AOTX and paddy reduction in Jerantut, Malaysia.

Table 2
(a): Bakar Arang, Kedah, (b): Ipoh, Perak, (c): Kajang, Selangor (d): Nilai, Negeri Sembilan, (e): Seberang Jaya, Pulau Pinang, (f): Shah Alam, Selangor: R^2 value for the relationship between paddy reduction and AOTX indexes in Malaysia from 2004 to 2009.

Sites	AOTX indexes (x)	Coefficient of determination (R^2)	Equation (y = paddy reduction)
a) Bakar Arang, Kedah	AOT0	0.7695	$y = 13{,}080 + 0.7866x$
	AOT5	0.7302	$y = 11{,}816 + 1.0313x$
	AOT10	0.8596	$y = 11{,}148 + 1.1993x$
	AOT15	0.8933	$y = 10{,}049 + 1.5258x$
	AOT20	0.9200	$y = 8816.7 + 2.0056x$
	AOT25	0.9313	$y = 8302.8 + 2.6285x$
	AOT30	0.9284	$y = 8349.5 + 3.4511x$
	AOT40	0.9062	$y = 10{,}131 + 5.9638x$
	AOT50	0.9426[a]	$y = 11{,}827 + 11.561x$
b) Ipoh, Perak	AOT0	0.6905	$y = -42.962 + 0.4907x$
	AOT5	0.6948	$y = 230.44 + 0.5855x$
	AOT10	0.7012	$y = 371.9 + 0.7097x$
	AOT15	0.7078	$y = 544.64 + 0.8712x$
	AOT20	0.7126	$y = 712.88 + 1.0905x$
	AOT25	0.7147	$y = 869.34 + 1.3992x$
	AOT30	0.7148[a]	$y = 988 + 1.8477x$
	AOT40	0.7109	$y = 1133.5 + 3.5694x$
	AOT50	0.7036	$y = 1270.5 + 7.9314x$
c) Kajang, Selangor	AOT0	0.2963	$y = 5657.1 + 0.104x$
	AOT5	0.3344	$y = 5808.1 + 0.1138x$
	AOT10	0.3721	$y = 5943.5 + 0.1246x$
	AOT15	0.415	$y = 6015.1 + 0.1398x$
	AOT20	0.4729	$y = 6014.7 + 0.1617x$
	AOT25	0.5453	$y = 5920.4 + 0.1942x$
	AOT30	0.6261	$y = 5687.3 + 0.2446x$
	AOT40	0.7761	$y = 4782.5 + 0.4497x$
	AOT50	0.8494[a]	$y = 3465.4 + 0.9551x$
d) Nilai, Negeri Sembilan	AOT0	0.4434	$y = 25.508 + 0.012x$
	AOT5	0.454	$y = 44.711 + 0.0137x$
	AOT10	0.4532	$y = 72.479 + 0.0152x$
	AOT15	0.4462	$y = 103.52 + 0.0168x$
	AOT20	0.4443	$y = 130.61 + 0.0189x$
	AOT25	0.4514	$y = 150.57 + 0.0219x$
	AOT30	0.4822	$y = 156.69 + 0.0271x$
	AOT40	0.5333[a]	$y = 145.06 + 0.0469x$
	AOT50	0.5228	$y = 109.98 + 0.1051x$
e) Seberang Jaya, Pulau Pinang	AOT0	0.0139	$y = 893.92 + 0.0079x$
	AOT5	0.0497	$y = 779.93 + 0.0159x$
	AOT10	0.0917	$y = 732.4 + 0.0232x$
	AOT15	0.1418	$y = 707.28 + 0.0319x$
	AOT20	0.1895	$y = 695.13 + 0.0432x$
	AOT25	0.2316	$y = 685.94 + 0.0594x$
	AOT30	0.2869	$y = 657.94 + 0.0871x$
	AOT40	0.3996	$y = 564.33 + 0.221x$
	AOT50	0.4555[a]	$y = 429.5 + 0.6713x$
f) Shah Alam, Selangor	AOT0	0.1349	$y = 5591.6 + 0.1009x$
	AOT5	0.1317	$y = 6014.7 + 0.1057x$
	AOT10	0.128	$y = 6409 + 0.1107x$
	AOT15	0.1308	$y = 6728.3 + 0.1192x$
	AOT20	0.1383	$y = 6994.3 + 0.132x$
	AOT25	0.1493	$y = 7233 + 0.1503x$
	AOT30	0.1574	$y = 7521.1 + 0.1715x$
	AOT40	0.1882	$y = 7955.3 + 0.2464x$
	AOT50	0.2295[a]	$y = 8211.4 + 0.4043x$

[a] The highest R^2 value for each site.

response between crops and the AOT40 in Europe can be robustly assumed to be different in other regions if different variables are presented; it might be a higher or lower AOTX index. Thus, the result in the Table 2 clearly proves that the response of crops to the AOTX index in tropical regions was different from the European regions.

Therefore, this study strongly suggested that AOT50 index demonstrated a better correlation between reduction of crops due to ozone exposure and crop production, as compared to AOT40 in Malaysia.

An additional analysis to compare the percentage reduction in crops was carried out to further validate that the AOTX indexes can

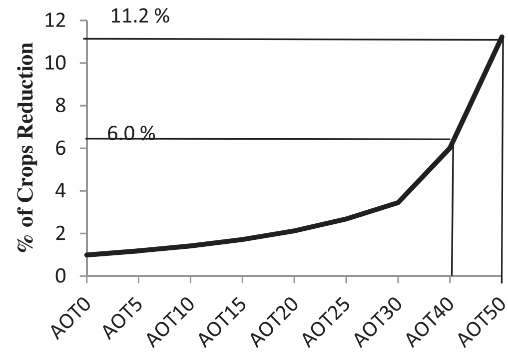

Fig. 4. Estimated crop (Paddy) reduction for each AOTX index under Malaysian climatic conditions for 3000 ppb h ozone exposure over three months.

respond differently in Europe and in Malaysia, with significant findings if the accumulated ozone concentration was above 3000 ppb h in a 3-month period. Fig. 4 illustrates the estimated percentage of crop (paddy) reduction for each AOTX index in the Malaysian climate.

Fig. 4 showed that the AOT40 index gave the minimum percentage in crops reduction of 6%, when accumulated ozone concentration was above 3000 ppb h in three months of the growing season. These results however were different from the European benchmark, which predicts a 5% crop reduction if the accumulated ozone concentration over three months is above 3000 ppb h (Ishii et al., 2007; LRTAP Convention, 2004).

Based on Table 2, the AOT50 index fits best with the Malaysian climate compared to the other indexes (based on R^2 value). However, with the critical level of 3000 ppb h in three months of the growing season, crop reduction seems to be overestimated (11.2%). The result (Fig. 4) implied that the new critical level for the AOT50 index needs to be identified.

Therefore, an analysis was carried out to find the best critical level for AOT50 index for Malaysia by estimating the possible crop reduction for the 5% index. Fig. 5 presents the critical level for the AOT50 index if the estimated crop reduction is 5%.

Fig. 5 demonstrates that the critical level of ozone exposure for AOT50 was 1336 ppb h over a three-month period, if the estimated crop reduction is 5%. The critical level based on the AOTX indexes play an important role in evaluating the ozone impact on crops (Fuhrer et al., 1997). Thus, the new critical level for AOT50 in Malaysia (1336 ppb h) was more reasonable to use in estimating reduction of crops compared to the European critical level (3000 ppb h).

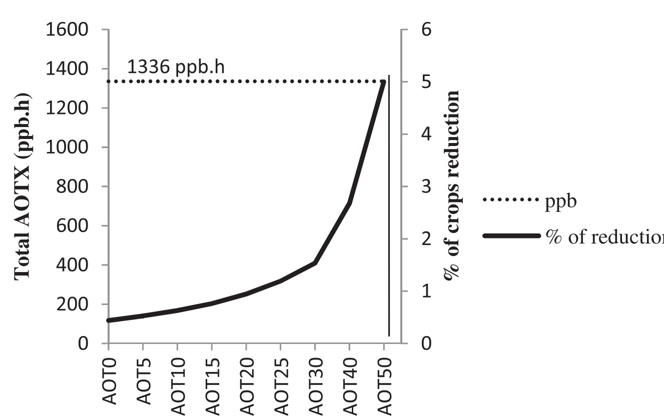

Fig. 5. Estimated critical level of ozone exposure over three months for 5% of crop (Paddy) reduction for AOT50 in Malaysia.

The dissimilarity of percentage crop reduction between the tropical and the European region was due to the different climatic conditions, which can influence the response of crops to ozone concentration (Racherla and Adams, 2007). In Malaysia, the daylight hours are on average 12 h (7 am–7 pm) throughout the year, which increases crops' exposure to ozone. Ozone can encourage the crop's stoma to close and cause a lower rate of photosynthesis (Fagnano et al., 2009). This scenario can leads to increased crop damage and reduced yields (Pleijel, 2000). Thus, crop reduction in tropical regions will be much greater than in Europe due to the longer ozone exposure.

5. Conclusion

The results demonstrated that paddy reduction was higher during the off-season. During this season, the area is drier with higher temperature and less rainfall, which results in increased ozone formation in the atmosphere. This study also showed that AOT50 caused the greatest reduction in crops, compared to all AOTX indexes in both seasons. The result from the linear regression analysis illustrated that AOT50 showed the best fit with the Malaysia climate in estimating the paddy reduction, expressed by the R^2 value. Thus, this study suggests that the AOT50 index is the most suitable index to estimate potential ozone impacts on crops in tropical regions. The difference in the AOTX indexes in Europe and Malaysia is due to the different climatic conditions and due to the longer daylight hours in Malaysia (12 h on average throughout the year).

Additionally, the result illustrated that the AOT40 index gave the minimum percentage in crop reduction of 6%, when the accumulated ozone concentration was above 3000 ppb h over three months of the growing season. This finding was different from the European benchmark, which indicates that a 5% crop reduction would be anticipated. As AOT50 demonstrated the best-fit relationship among all AOTX indexes in Malaysia, a new critical level for AOT50 index was identified. The new critical level for AOT50 index if the estimated crop reduction is 5% was 1336 ppb h.

In assessing crop reduction due to ozone exposure in Malaysia, some decisions must be made in adopting the AOTX index. If AOT40 is used as the index, this study suggests that the estimated crop reduction must be changed from 5% to 6%. The increment of 1% crops reduction will create a large difference. As paddy is a staple crop in this country, decreasing paddy production may threaten food security. However, as the result showed that AOT50 was the best index for the Malaysian climate, this study strongly suggests the AOT50 index with the critical level of 1336 ppb h should be used in estimating the 5% crops reduction anticipated to occur over a three-month period.

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