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Assessment of rice yield and economic losses caused by ground-level O_3 exposure in the Mekong delta region, Vietnam

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ABSTRACT

The Lower Mekong Delta region (LMD) accounts for 90% of Vietnam's rice exports; however, the air quality in the LMD is remarkably reduced by ground-level ozone (O_3) pollution. This study aimed to quantify the relative yield and economic value losses in rice-growing crop seasons affected by ground-level O_3 concentrations across the LMD. The results of this study can serve as a basis for extensive assessments for the following years and support environmental managers to propose control measures of O_3 precursor emissions (NO_x and VOCs) from man-made sectors, as well as build protective solutions for rice farming in LMD. Two ground-level O_3 exposure metrics of M7 and AOT40 reflecting ground-level O_3 pollution impacts, combined with the model of exposure-relative yield relationship (or surface O_3-crop models), were used to assess losses of crop production (CPL) and economic cost losses (ECL) caused by rice crop yield reductions. For the M7 metric of ground-level O_3 exposure, the average value was 14.746 ppbV, with levels ranging from 13.959 ppbV to 15.502 ppbV, and the affected area was spread across 1309.39 thousand hectares. The AOT40 exposure metric reached an average value of 11.490 ppbV, with a range of 0.000–31.665 ppbV. The highest exposure level was 17.503–31.653 ppbV, covering an area of 747.01 thousand hectares. The total CPL of the three rice crops over the LMD was 9593.52 tonnes (accounting for 0.039% of the total value of rice production in the region), with a total corresponding EPL of 62.405 billion VND (equivalent to 2761.01 thousand USD). The results are considered a baseline study to serve as a basis for extensive assessments for the following years and support for the environmental managers to propose control measures of O_3 precursor emissions (NO_x and VOCs) from man-made sectors as well as build protective solutions in rice farming in LMD shortly.

1. Introduction

Ground-level ozone (O_3), also known as surface-level O_3 or tropospheric O_3, is a greenhouse gas and a significant air pollutant which plays a significant role in tropospheric atmospheric chemistry [1]. Ground-level O_3 pollution is a critical issue in Asia, particularly in Southeast Asia [2]. The levels of O_3 pollution are increasing due to the increase in the anthropogenic emissions of surface-level O_3 precursors, which are mainly nitrogen dioxide (NO_x) and volatile organic compounds (VOCs) [3,4]. Tropospheric O_3 is

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formed through an oxidation process of the chain of catalyst HO_x (hydrogen oxide radicals) of CO and hydrocarbons in the presence of NO_x [3], beginning with the formation of HO_x. Chemical reactions also occur between NO_x and VOCs [5] when pollutants are released from cars, power plants, industrial steam boilers, refineries, chemical plants, and other chemical sources in the presence of sunlight [5]. Ground-level O_3 is the most difficult air pollutant to control worldwide [6]. Pollution from surface-level O_3 has negative effects on human health [4] and impacts the production of different crops [7]. Moreover, surface-level O_3 is harmful to ecosystem operations and

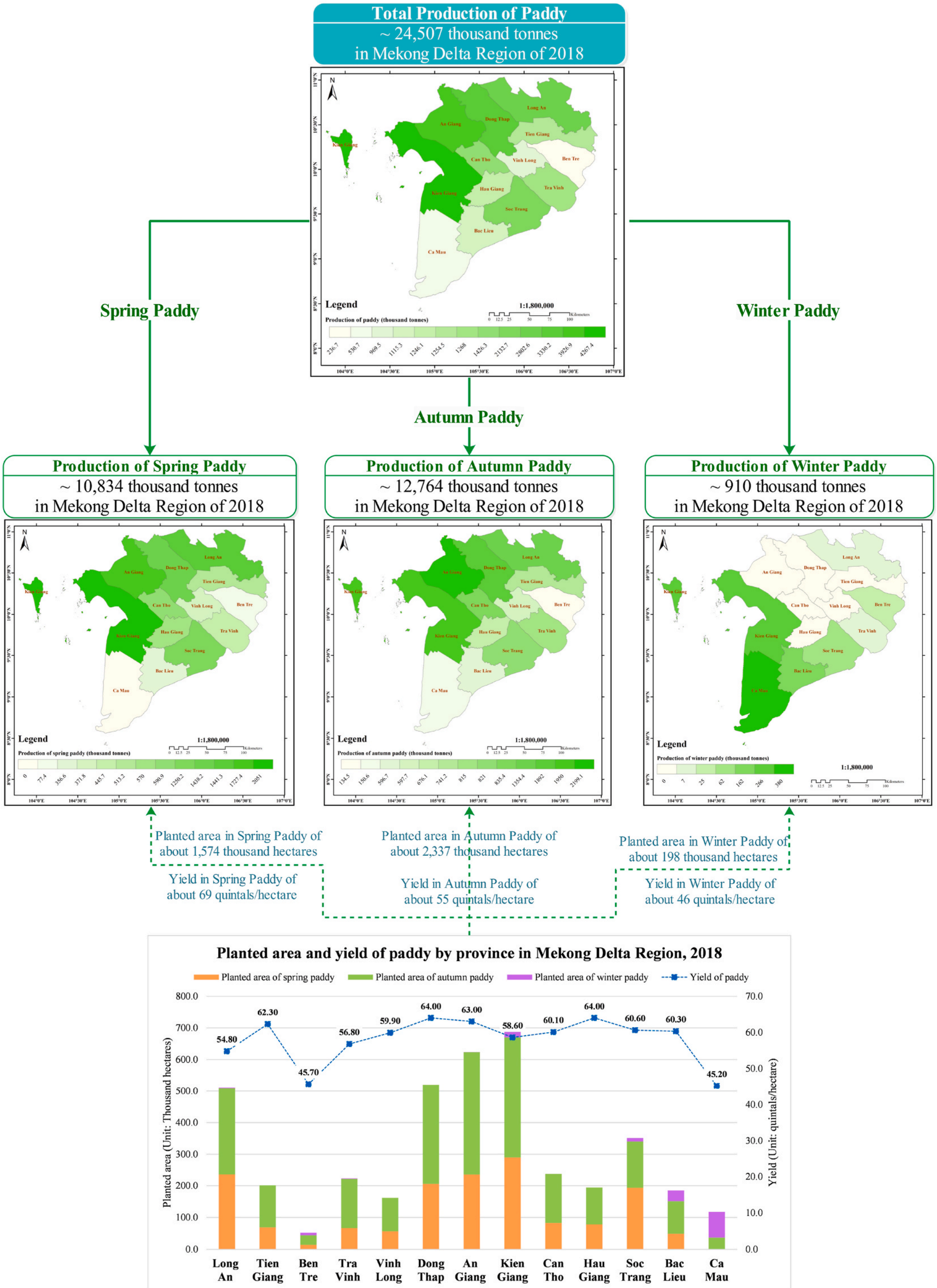

Fig. 1. LMD – the selected study area along with the total cultivated area, yield, and production of Spring, Autumn, and Winter rice crop seasons.

biodiversity [8,9].

Because of the direct ground-level effects on crop growth and yield, surface-level O_3 pollution has also become an economic and social issue of concern, particularly in economically active and densely populated areas [10,11]. Typical O_3 exposure effects on crops include reduced seed/fruit filling, ovules, and seed destruction in subsequent developmental stages [7]. Regarding field crops, such as wheat, rice, maize, beans, soybeans, rapeseed, and sorghum, ground-level O_3 can reduce seed size, seed weight, grain nutritional quality, and grain yield [12,13]. With seed crops, such as beans, the fruit is usually smaller or reduced in number [7]. Tuber size is markedly reduced in tuberous crops such as potatoes [7], and the protein or oil content of nuts or grains may also be affected [14]. Surface-level O_3 pollution has a significant impact on rice yield. Studies in China reported that the total relative yield losses (RYLs) of wheat and rice were 18.4–49.3% and 6.2–52.9% between 2014 and 2018, respectively [15–18]. Ground-level O_3 pollution can reduce individual grain weight and the number of rice grains by up to 5% and 20%, respectively [19–21] and of wheat by up to 18% and 11%, respectively [22,23].

Although surface-level O_3 is attributed to crop yield decline effects, it has remained challenging to quantify the RYLs caused by O_3 properly [7,11,24]. Recommended ground-level O_3 thresholds that affect crop growth, photosynthesis, and yield have been proven in many previous studies [22,25–27]. Over the past few decades, several experiments based on technically sound environmental conditions have been carried out to assess ground-level O_3 concentration increase effects on different crops. Specifically, free atmospheric concentration enrichment (FACE) and open-top field chamber (OTC) systems have been used [11]. These studies aimed to establish relationships between relative yield (RY) and different surface-level O_3 exposure metrics to predict the global, regional, and national impacts of ground-level O_3 pollution on agricultural production [24,26].

Various O_3-exposure metrics were considered as specific impact thresholds of ground-level O_3, including the accumulated hourly ground-level O_3 concentration over a threshold of 40 ppbV (AOT40), the mean 7-h/12-h daytime O_3 concentration (M7/M12), the accumulation of hourly O_3 concentrations above 60 ppbV (SUM06), and the accumulated hourly O_3 concentration with a weighting factor (W126) [28,29]. The AOT40 metric is defined as the accumulated ground-level O_3 critical above 40 ppb under effective light conditions (from 8:00 a.m. to 7:59 p.m.) during the crop growing season [30,31]. The SUM06 metric is the sum of the hourly surface-level O_3 concentrations above a threshold of 60 ppb per year [32]. Both the AOT40 and SUM06 metrics have been primarily applied to estimate accumulated O_3-induced crop failure in Europe and the United States [33–36]. In contrast, both the M7 and W126 metrics are defined as the average hourly O_3 concentration values from 9:00 a.m. to 3:59 p.m. and from 8:00 a.m. to 8:00 p.m. (only between May and September for W126) [37,38].

The studies of [24,39,40] used these surface-level O_3 exposure metrics to assess losses due to crop yield reduction. Moreover, the study results of [24] reported that ground-level O_3-induced yield losses of wheat, soybean, and maize ranging from 4.0% to 26.0%, 9.5%–19.0%, and 2.5%–8.7%, respectively, based on the AOT40 and M12 metrics during the growing seasons, which is defined as three months before the harvest period starts [41], along with economic damage varying between 12 and 35 billion USD per year [42]. Furthermore, the results of [42] also showed that wheat yield losses due to surface-level O_3 exposure in 2000 ranged from 6.4% to 14.9% in China and 8.2%–22.3% in India, as derived by applying different surface-level O_3 exposure metrics [43] during the growing season of roughly 90 days, focusing on harvest days.

Vietnam is a major agricultural country in Southeast Asia region [44] and the second largest rice exporter worldwide. China is also the seventh largest rice consumer worldwide [45–48]. The Lowe Mekong Delta region (LDR) in Vietnam is the world's largest rice bowl and has a significant influence on global food security [49]. It provides rice for domestic consumption and contributes 20% of global rice exports, typically to Africa and Asia. Nevertheless, the LMD is currently facing challenges from air pollution due to socioeconomic development and urbanisation. The assessment of surface-level O_3 exposure impacts is of great significance for developing environmental management policies to reduce economic losses by controlling anthropogenic O_3 emissions. This study aims to quantify the effects of different ground-level O_3 concentrations on rice yield and production, as well as the corresponding economic value losses for the LMD. Hourly ground-level O_3 concentration distributions across the LMD, simulated from the coupled models of the Weather Research and Forecasting model (WRF)/Community Multiscale Air Quality Modelling System (CMAQ), were used to analyse the spatial distributions of the M7 and AOT40 exposure metrics for the RYL estimation of the rice-growing seasons in 2018. An uncertainty analysis was performed to objectively assess the study outcomes.

2. Material and methods

2.1. Study area

The study area was limited to Vietnam (Fig. 1). The LMD (8°34′N to 11°02′N and from 103°49′E to 106°48′E) has a form like a peninsula with three sides, East, South, and Southwest, bordering the sea (with a coastline of about 700 km). The west borders Cambodia while the North borders the Southeast economic region, which is the largest economic region in Vietnam. Generally, the LMD has relatively flat terrain, and the network of rivers and canals is densely distributed, which is convenient for navigation in and out of Vietnam. The LMD is the largest food production, tropical fruit tree, and export area in Vietnam, and is an important land for the southern region and whole country in terms of economic development, investment cooperation, and international trade [44]. The LMD provides more than 50% of domestic rice production, 90% of rice production for export, 70% of fruit, 40% of fish, and 74% of aquaculture products [50,51]. The LMD has 13 administrative units, including one city directly under the Central Government (Can Tho City) and 12 provinces (Long An, Dong Thap, An Giang, Tien Giang, Ben Tre, Vinh Long, Tra Vinh, Hau Giang, Kien Giang, Soc Trang, Bac Lieu, and Ca Mau).

In 2018, the total rice production was 24,506.9 thousand tonnes out of the total cultivated area of 4107.5 thousand hectares in LMD (with a total rice yield of 5.97 tonnes/ha) [52]. In particular, Kien Giang province had the highest rice production with 4267.4 thousand tonnes (roughly 17%) of that obtained from the total cultivated area of 728.4 thousand hectares (with a total rice yield of 58.6 quintals/ha), whereas Ben Tre province had the lowest production, with 236.7 thousand tonnes (about 1%) of that obtained from the total cultivated area of 51.8 thousand hectares (corresponding rice yields of 45.7 quintals/ha) [52] (Fig. 1). Spring and autumn rice seasons are the two main rice crops in the study area, with the total rice production reaching 23,597.4 thousand tonnes in 2018, accounting for approximately 96% of the total produce [52]. Specifically, the spring rice crop production was the highest in Kien Giang province, with 2051.0 thousand tonnes of that obtained from the total planted area of 290.0 thousand hectares (with an estimated rice yield of 70.7 quintals/ha), whereas the highest autumn rice crop production was obtained in An Giang province, with 2199.1 thousand tonnes of that obtained from the total cultivated area of 388.0 thousand hectares (with a corresponding yield of 56.7 quintals/ha) [52]. In general, the common provinces of LMD with high rice production (above 10%) were Kien Giang (17.4%), An Giang (16.0%), Dong Thap (13.6%), and Long An (11.4%) (Fig. 1).

In addition, because of the lack of ground-level measurements of O_3 concentrations in the LMD, it was necessary to verify the simulations from the coupled WRF/CMAQ models. Thus, the computational simulation domains were extended to the entire south-eastern region (nearby) to take advantage of the measurement results from ground-level O_3 monitoring stations in Binh Duong Province, Vietnam. The monitoring surface-level O_3 data from 11 measuring sites (NT1, N, GT2, GT3, DT1, DT3, DT4, DT6, CN1, CN2, and CN4) in 2018 in Binh Duong Province (Table S1) were provided by the Center of Natural Resources and Environment Technical – Monitoring of Binh Duong (Figure S1) [53]. The field-measured O_3 concentration data were collected manually and measured four times (09.00, 11.00, 13.00, and 15.00) on monitoring days.

2.2. Characteristics of rice cropping seasons

In 2018, many provinces of the LDR promoted economic restructuring and achieved remarkable achievements, including in agricultural production. Many provinces in the LMD have actively transformed their crop structures to adapt to drought and saltwater intrusion, specifically converting rice to fruit crops and aquaculture. Although the cultivated area has decreased, rice production has increased because farmers have prioritised the use of high-quality short-term rice varieties, fragrant rice varieties that are suitable for the market requirements, and a reduction in the percentage of medium-quality rice varieties and sticky rice. Simultaneously, promoting the use of certified varieties with good yield, quality, hardiness, and resistance to falling (such as ST24 and ST25) has resulted in a high yield and high-quality rice ratio of over 50% [44]. Furthermore, farmers have increased the application of technical advances in production, use of mechanical sowing tools, use of transplanters, and mechanisation in rice harvesting [44]. Most provinces in the LMD (Long An, Ben Tre, Tra Vinh, An Giang, Kien Giang, Soc Trang, and Bac Lieu) produce three rice crops a year, including spring, autumn, and winter paddies (Table S2). The remaining provinces (Tien Giang, Vinh Long, Dong Thap, Can Tho, and Hau Giang), only produce two rice crops, consisting of spring and autumn paddies, while Ca Mau province commonly produces autumn and winter paddies (Table S2) [52].

The arrangement of rice crops in the LMD depends on the selection of suitable rice varieties, in which short-term rice varieties ($\leq$90 days) with high yield and quality are suitable for rice production areas with three rice crops per year. In contrast, for regions producing two rice crops per year, rice varieties with longer duration (100–110 days) are selected, and for areas producing two rice crops combined with rice-shrimp, rice-aquaculture generally uses seasonal rice or high-yield hybrid varieties [54,55]. Overall, the spring paddy is sown from October to January each year, with a total area of more than 1.50 million ha [54,56]. In particular, the sowing of the spring paddy occurs in November and December in most provinces of the LMD, in October in the high hilly area of grey land along the Cambodia-Vietnam border and the coastal area in Kien Giang (in the districts of Vinh Thuan, U Minh Thuong, An Bien), and in January in the low-lying and slow-draining areas of the Dong Thap Muoi and Long Xuyen Quadrangle of the LMD. The autumn paddy in the LMD also has a total area of more than 1.55 million ha [54,56] and the sowing dates also differ between provinces. The autumn paddy is sown early in March in Tien Giang, An Giang, Dong Thap, Vinh Long, Can Tho, and Hau Giang, mainly in April and May in most provinces of LMD, and late in June in areas affected by saltwater intrusion and in areas with less active water resources. Winter paddies commonly have a smaller total sowing area [54,56] and sowing is carried out frequently from July to September, depending on the locality in the LMD (except for the provinces of Ben Tre, Tra Vinh, Bac Lieu, and Ca Mau).

2.3. Spatio-temporal ground-level O_3 concentration distributions

The WRF model ver.3.8 [57,58] combined with the air quality model (CMAQ) ver.5.2.1 [59–61] were applied to simulate the distribution of tropospheric O_3 concentration in LMD. The CMAQ simulation is a modern scientific method widely used in current research and policy-making to analyse and evaluate physical and chemical processes that determine the transport, reaction, and formation of tropospheric O_3 [62–64]. The research framework for assessing O_3-related impacts on rice was based on the spatio-temporal allocation outcomes of ground-level O_3 pollution levels across the LMD, modelled by coupled WRF/CMAQ models. In this study, two nested domains consisting of the first domain (D01) combined with the second domain (D02) were established in the coupled WRF/CMAQ models; details of the domain technical parameters are shown in Table S3. Specific information for the model configuration, emission inventories, chemical transport mechanisms, initial/boundary conditions, and modelling performance verification can be found in detail in previous studies [65–68]. The simulation efficiency of ground-level O_3 concentration by this system was assessed based on a wide range of statistical indicators, including the Nash efficiency index, mean bias (MB), root mean-squared error (RMSE), normalised mean bias (NMB), normalised mean gross errors (NME), and *R* correlation coefficient from our previous studies [67,68].

2.4. Estimating surface-level O_3 exposure metrics for RYL assessment

To determine agricultural production losses attributed to ground-level O_3 exposure to rice crops in LMD, two different exposure indicators including (1) the average metric of M7 and (2) the cumulative metric of AOT40 [41] used. Specifically, the M7 indicator shows an average exposure of 7 h (from 9:00 a.m. to 3:59 p.m.) and the AOT40 index indicates the concentration of O_3 accumulated during daytime hours over a threshold of 40 ppbV [41]. AOT40 is an accumulated O_3-exposure metric currently used as a standard in many regions worldwide to estimate the effects of ground-level O_3 pollution on crops, such as in China [18,69,70], India [15,71], Europe [72,73], and the United States [74,75]. Furthermore, the AOT40 index is strongly correlated with the relative yields of different crops [76–78]. According to research by Ref. [24], concentration-response functions (CRFs) commonly require statistical indicators to assess the trend of surface-level O_3 exposure throughout the rice-growing seasons. In particular, with two types of indicators based on ground-level O_3 exposure, the cumulative metric (AOT40) reflects the greater influence of surface-level O_3 concentration with higher accuracy when estimating crop yield losses than when using the average exposure metric of M7 [79]. The average exposure metric (M7) and cumulative metric (AOT40), as well as the relationship between these metrics in CRFs (Table 1) were estimated according to equations Eq. (1) and Eq. (2) below [24,41,80].

$$M7(ppbV) = \frac{1}{n} \cdot \sum_{i=1}^{n} [C_{O_3}]_i \tag{1}$$

$$AOT40\ (ppbV) = \sum_{i=1}^{n} \left([C_{O_3}]_i - 40 \right), \text{where } C_{O_3} \geq 40 \text{ ppbV} \tag{2}$$

where $[C_{O_3}]_i$ is the hourly average O_3 concentration (in parts per billion) according to daylight hours in LMD with the metric of M7 from 9:00 a.m. to 3:59 p.m. and the metric of AOT40 from 8:00 a.m. to 7:59 p.m.; and n is the total number of hours in the growing seasons of rice crops under observations. Moreover, hourly ground-level O_3 concentration levels used in this study is simulated results by the coupled WRF/CMAQ models in LMD during the dry and wet seasons and according to the local paddy calendar for the year 2018.

2.5. Integrated assessment of rice yield and production losses

Concentration-response functions (CRFs) were used represent the relationship between surface-level O_3 exposure and RY of the rice-growing seasons (Eq [3]. to Eq [10]), based on available empirical studies (OTC and FACE), as presented in Table 1. Based on the estimated results of the O_3-exposure metrics, including M7 (Eq. (1)], and AOT40 [Eq [2]), each equation in Table 1 was applied to determine the RY values for the LMD provinces in 2018. This calculation process supports the determination of the minimum-to-maximum value ranges and the mean value of RY. Based on the RY values for the rice crops, the RYL levels were calculated using Eq. (11) [71,81] and were used to determine the minimum to maximum value ranges and the average value of RYLs for the provinces. Subsequently, according to the methods of [78,82], rice crop yield losses for each province in the LMD based on the simulated ground-level O_3 concentration distributions were estimated by applying Eq. (12). The value of RYL was considered to be the reduction in crop yield when compared to the theoretical yield of the crop without the effects caused by ground-level O_3 pollution [24, 82].

$$RYL_i = 1 - RY_i \tag{11}$$

$$CPL_i = \frac{RYL_i}{1 - RYL_i} \times CP_i \tag{12}$$

where RYL_i is the value of the relative yield losses for the simulation year, RY_i is the relative yield value in the calculation year, CPL_i is the value of CPLs, and CPL is estimated in each province of LMD based on the values of CP_i and RYL_i, where CP_i is the value of annual rice crop production in the simulation year. Data on paddy production and crop production (CP) of provinces with LMD in 2018 were obtained from the General Statistics Office of Vietnam [52]. Thus, the CPL values of the study area are the total values of CPLs for all provinces in the study area (CPL_i) within the range of the coupled WRF/CMAQ computing domain [82] (as shown in Eq [12]).

Table 1
The summary of details for the concentration-response functions to determine rice RY.

Sites	Exposure-relative yield relationships		Facility	Reference
Synthesis	$RY = \exp[-(M7/202)^{2.47}]/\exp[-(25/202)^{2.47}]$	(3)	OTC	(Adams et al., 1989)
Punjab and Haryana, India	$RY = \exp[-(M7/86)^{2.5}]/\exp[-(25/86)^{2.5}]$	(4)	OTC	(Sinha et al., 2015)
Synthesis (Japan, the UK, the USA)	$RY = 0.94–0.0000039 \times AOT40$	(5)	OTC	(G. Mills et al., 2007)
Dingxing, Hebei, China	$RY = 1–0.0053 \times AOT40$	(6)	OTC	(Z.-W. Feng et al., 2003)
Jiangdu, Jiangsu, China	$RY = 1–0.0160 \times AOT40$	(7)	FACE	(Pang et al., 2009)
Dongguan, Guangdong, China	$RY = 1–0.0390 \times AOT40$	(8)	OTC	(Xu et al., 2021)
Jiaxing, Zhejiang, China	$RY = 1–0.0095 \times AOT40$	(9)	OTC	(Xiaoke Wang et al., 2012)
Punjab and Haryana, India	$RY = 0.95–0.00001 \times AOT40$	(10)	OTC	(Sinha et al., 2015)

2.6. Quantification of economic cost losses caused by rice yield reduction

Economic cost losses (ECLs) for rice crops in the calculation year are considered financial damage to agricultural crop seasons (rice-growing crops) caused by ground-level O_3 concentration exposure [71]. The minimum ECL value is estimated based on the minimum support prices (MSPs) for rice-growing crops in the respective simulation year, as determined by equation Eq. (13) [71,78,81,83] as

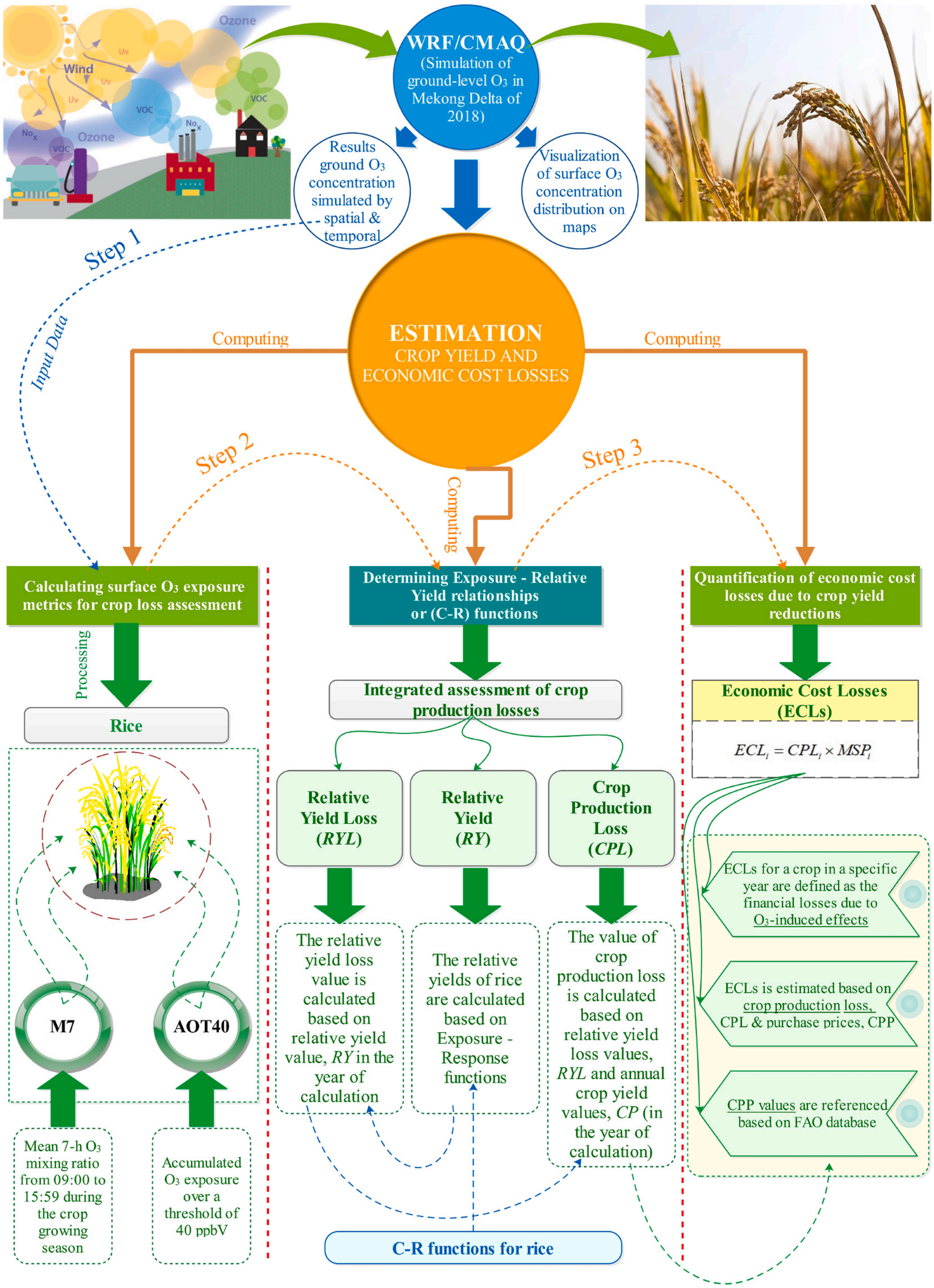

Fig. 2. Study framework and implementation steps.

follows:

$$ECL_i = CPL_i \times MSP_i \tag{13}$$

where ECL_i is the value of the economic cost loss for crop *i* in the simulation year, and MSP_i is the minimum price of crop *i* supported in the simulation year. The MSP is considered as a fixed price at which the government buys products from the farmer [71] also known as the purchase price of crops (CPP) [81,84]. This study used the CPP values in 2018 for rice with approximately 287.8 USD per tonne from the World Food Organization's aggregated statistical database (FAOSTAT) (http://www.fao.org/faostat/).

2.7. Framework and implementation steps

The methodology framework that quantifies yield loss, rice yield loss, and losses due to economic costs is shown in Fig. 2. There are three steps to be taken: (i) estimating ground-level O_3 exposure indices for rice, (ii) the second step is estimating the loss of rice production, and (iii) the third step is quantifying the economic value lost due to the reduction in yield and rice production due to exposure to ground-level O_3 pollution. In the first step, input data source was the hourly average surface O_3 concentration values (in the LMD provinces) during daylight hours (simulation results using the simulation models WRF/CMAQ). For the M7 metric, concentration values between 9:00 a.m. and 3:59 p.m. were used, and for the AOT40 metric, concentrations between 8:00 a.m. and 7:59 p.m. were used. The outputs were two types of surface O_3 exposure metrics: the M7 metric (ppbV) reflecting the average 7-h exposure and the AOT40 metric (ppmh) reflecting the hourly cumulative daytime O_3 levels above the threshold of 40 ppbV (Fig. 2).

In step (ii), CRFs representing the relationship between exposure and RY of rice were selected. These functions were built based on M7 and AOT40 metrics. In this step, the relative yield loss value (RYL, %) was estimated by applying the selected CRFs combined with the output from step (i), including the M7 and AOT40 metrics. These are the input data for the CRFs. Based on these results, relative yield loss (RYL, %) was determined. Next, the total CPLs of rice (tonnes) were estimated; this CPL value is considered as one of the main results of step (ii) and the present study. Finally, for step (iii), the inputs included the value of the total CPLs of rice production (CPL, tonnes) from the second step and the data source on the minimum support for rice in 2018 (MSP). The ECLs caused by the reduction in rice production because of ground-level O_3 pollution was determined.

3. Results

3.1. Results of estimated ground-level O_3 exposure metrics for rice

The estimated outcomes of O_3-exposure metrics (M7 and AOT40) for rice crops in 2018 were presented under the types of graphs by each province of LMD (shown in Figs. 3 and 5) and spatial distributions across LMD (shown in Figs. 4 and 6).

The estimated values of the two metrics, M7 and AOT40 (mean, maximum, and minimum), for the 13 provinces in the LMD are shown in Figs. 3 and 5 respectively. For the M7 exposure metric during the rice-growing period, the average value was 14.746 ppbV,

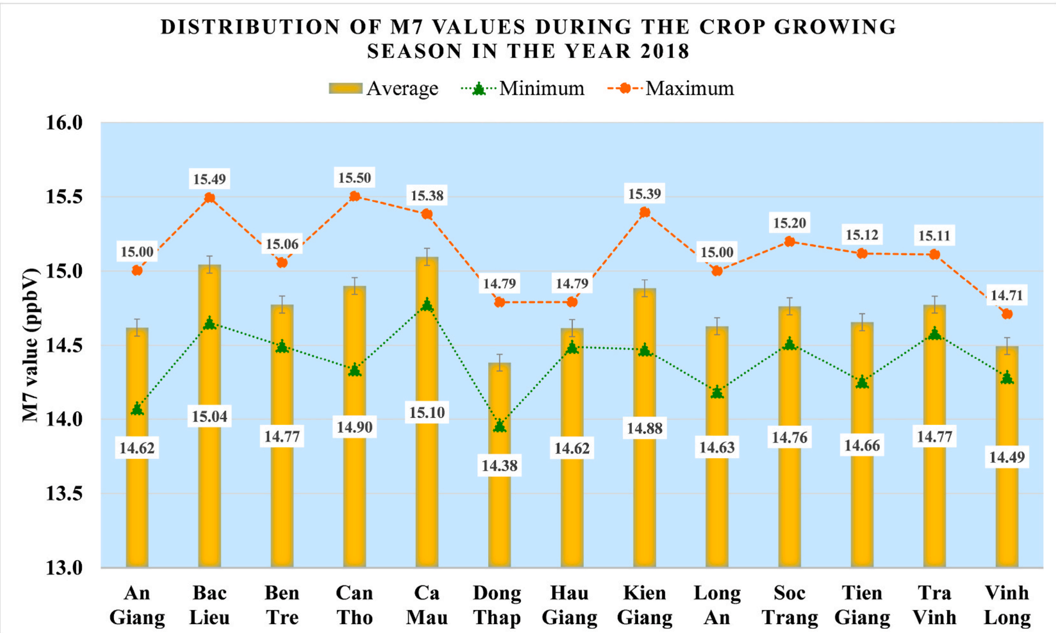

Fig. 3. Estimated results of M7 exposure metric values for crops in the LMD, 2018.

ranging from 13.959 ppbV to 15.502 ppbV. Kien Giang province had the highest M7 values, with an average value of 14.883 ppbV, ranging from 14.472 ppbV to 15.394 ppbV. Vinh Long province had the lowest M7 values in the region, with an average value of 14.495 ppbV, ranging from 14.286 ppbV to 14.710 ppbV. Fig. 4 shows the spatial distribution of the M7 metric values in the study area. It can be seen that the exposure value from 13.96 to 14.607 ppbV covers an area of 1309.39 thousand ha, which is concentrated in the Dong Thap, Vinh Long, and Can Tho provinces and parts of the An Giang, Kien Giang, Hau Giang, Soc Trang, Tra Vinh, Ben Tre, Tien Giang, and Long An provinces. Exposure values ranged from 14.608 to 14.952 ppbV, concentrated in the provinces of Ben Tre, Tra Vinh, Soc Trang, and a part of An Giang, Kien Giang, Hau Giang, Bac Lieu, Ca Mau, Tien Giang, and Long An provinces, with the largest distribution area reaching 1847.63 thousand hectare. Exposure values from 14.953 to 15.502 ppbV were concentrated in the western

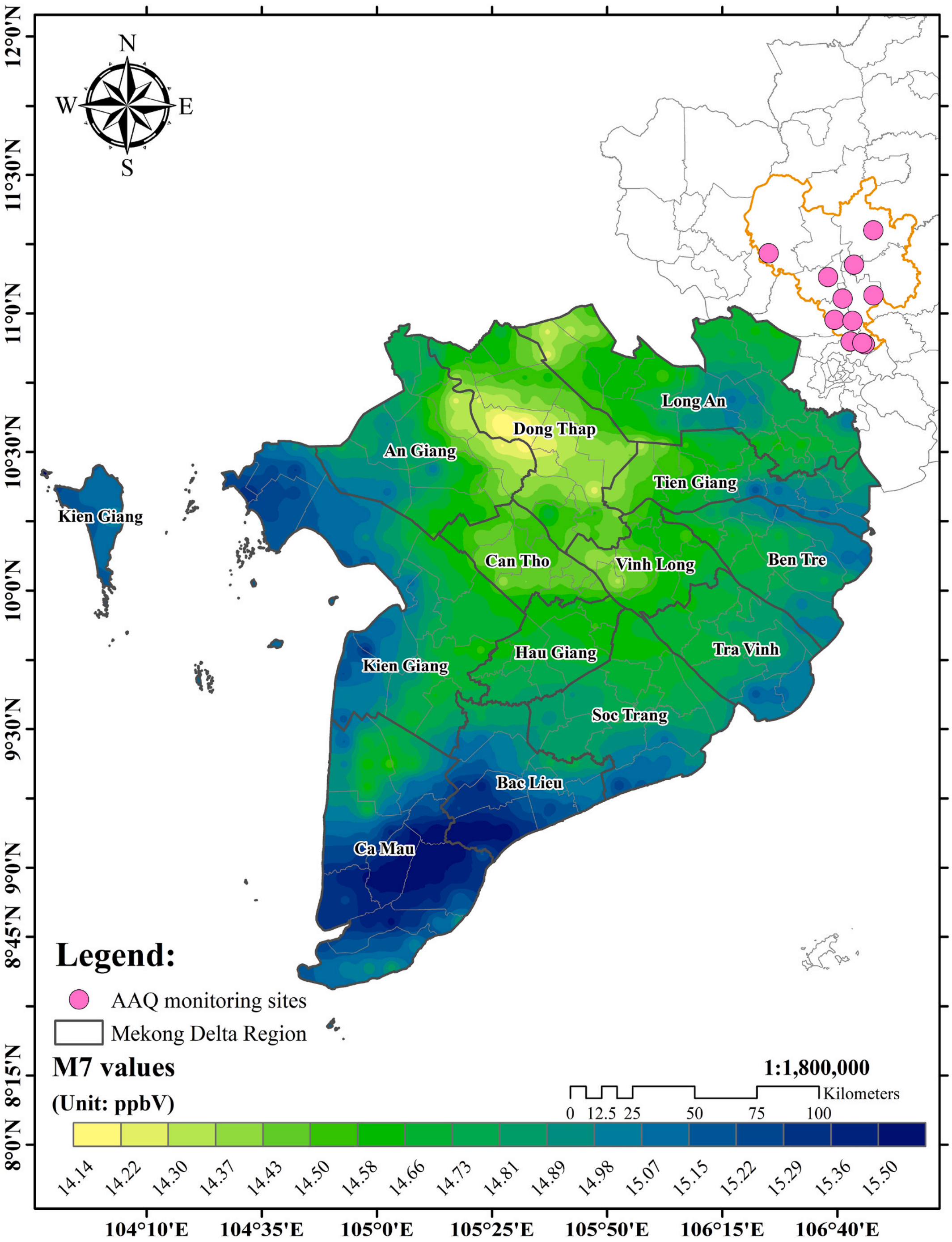

Fig. 4. Spatial distribution of M7 metric of ground-level O_3 exposure metric in LMD, 2018.

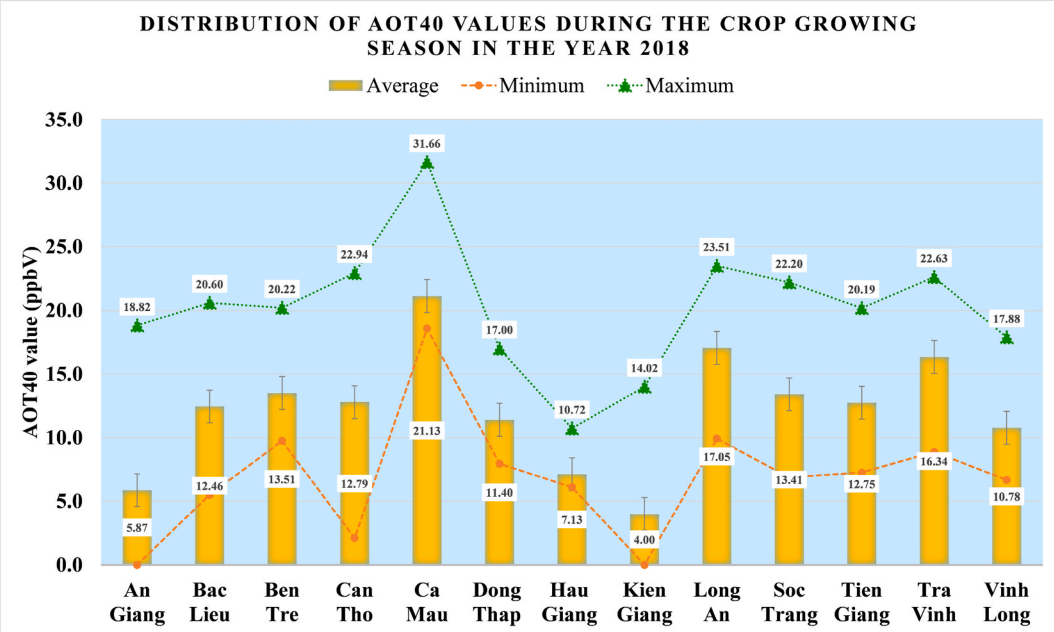

Fig. 5. Estimated results of AOT40 exposure metric values for crops in the LMD, 2018.

coastal districts of Kien Giang province, the southernmost districts of the Ca Mau Peninsula, the districts along the East Sea of Bac Lieu and Soc Trang provinces, and parts of the Tra Vinh and Ben Tre provinces, with the smallest area being 868.12 thousand ha (Fig. 4).

The exposure metric AOT40 reflects the hourly cumulative daytime O_3 concentration above the 40 ppbV concentration threshold (Fig. 5). The estimated results showed that the average AOT40 value was 11,490 ppbV, with a range of 0.000–31.655 ppbV (Fig. 6). Ca Mau province had the highest AOT40 values, ranging from 18.565 to 31.655 ppbV, with a mean value of 21.135 ppbV. Hau Giang province had the lowest AOT40 values, with an average value of 7.134 ppbV, ranging from 6.106 to 10.722 ppbV. Exposure values range from 0.000 to 4.345 ppbV, covering an area of 522.48 thousand ha, concentrated in a part of Kien Giang, An Giang, and Can Tho provinces. Exposure values ranged from 4.346 to 9.062 ppbV, covering an area of 893.66 thousand ha, concentrated in Hau Giang, Can Tho, and some of the provinces of Ca Mau, Bac Lieu, Soc Trang, Tra Vinh, Vinh Long, Dong Thap, An Giang, Kien Giang, and Tien Giang. Exposure values from 9.063 to 13.034 ppbV cover the largest area, 1056.49 thousand ha; these areas are concentrated in the Dong Thap, Ben Tre, Vinh Long provinces and parts of the Long An, Tien Giang, Tra Vinh, Soc Trang, Bac Lieu, Ca Mau, and An Giang provinces. Exposure values ranged from 13.035 to 17.502 ppbV, covering an area of 805.50 thousand hectare, mainly concentrated in Dong Thap, Long An, Tien Giang, Ben Tre, Tra Vinh, Soc Trang, Bac Lieu, and Ca Mau provinces. The highest exposure values ranged from 17.503 to 31.653 ppbV, with an area of 747.01 thousand ha, concentrated in the northern districts of Long An province, the eastern coastal area of the provinces of Ben Tre, Tra Vinh, Soc Trang, Bac Lieu, and the southern part of the Ca Mau Peninsula (Fig. 6).

3.2. Assessment of CPLs and ECLs

The O_3 exposure metrics of M7 and AOT40 were determined for the corresponding rice seasons (spring, autumn, and winter). These metrics were also used to estimate O_3 exposure-related effects on rice yield. The estimation outcomes of the RYLs and CPLs for each province in the LMD for rice crops due to ground-level O_3 exposure were based on the CRFs shown in Table 1, where CP_i is the annual crop yield value (in 2018) of the provinces located in the study area. Table 2 presents the statistical calculations for average rice production (CP) in 2018 for each province in the study area. From the aggregated results in Tables 2 and it could be seen that Kien Giang, An Giang, Dong Thap, and Long An are the four provinces with the largest rice CP values in 2018 in the entire region; the values for the respective provinces are, 4267.4 thousand tonnes (accounting for 17.41% of the whole region), 3926.8 thousand tonnes (accounting for 16.02% of the whole region), 3330.2 thousand tonnes (accounting for 13.59% of the whole region), and 2802.7 thousand tonnes (accounting for 11.43% of the whole region) respectively.

The total CPL of rice yield in three rice crops was 9593.52 tons (accounting for 0.039% of the total value of rice production in the entire region) (Table 3 and Fig. 7). The largest loss of rice yield occurred in the provinces of Long An, Dong Thap, and Soc Trang at 1865.29 tons, respectively; 1481.78 tons; 1116.32 tons; meanwhile, the lowest loss of rice yield was in Ben Tre province with about 124.81 tons. Damaged rice yields for the An Giang, Bac Lieu, Can Tho, Ca Mau, Hau Giang, Kien Giang, Tien Giang, Tra Vinh, and Vinh Long provinces ranged from 346.78 to 899.20 tons. Thus, the total CPL of the rice yield was determined. Specifically, the economic loss, ECL_i, for rice in the year calculated due to ground-level O_3 in the LMD totalled 62,405 billion VND (equivalent to 2761.01 thousand USD). The largest economic loss occurred in the provinces of Long An, Dong Thap, and Soc Trang, at 12.133 billion VND (equivalent to 536.83 thousand USD), 9.639 billion VND (equivalent to 426.46 thousand USD), and 7.262 billion VND (equivalent to

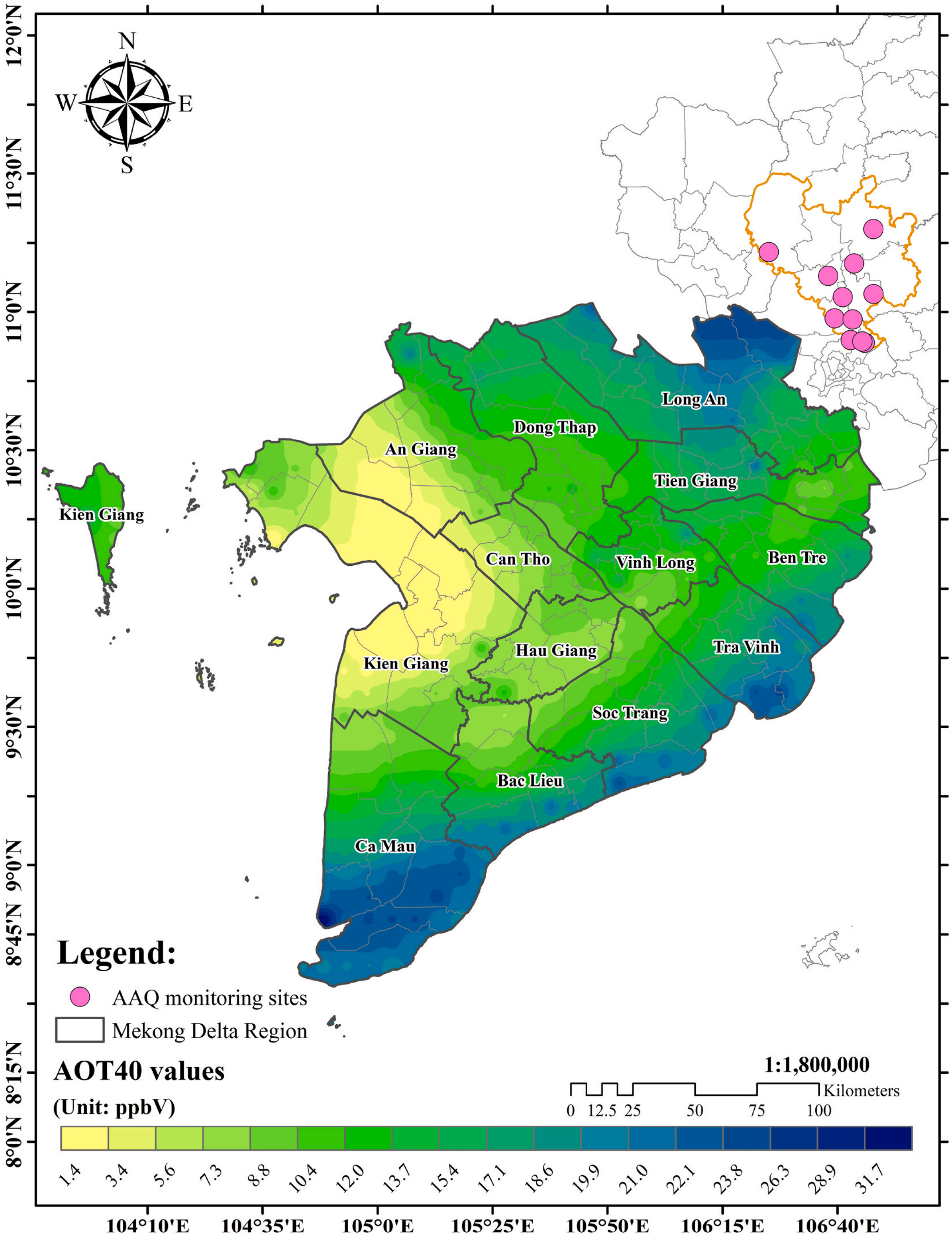

Fig. 6. Spatial distribution of AOT40 metric of ground-level O_3 exposure metric in LMD, 2018.

321.28 thousand USD), respectively, while the lowest economic loss is in Ben Tre province with about 0.812 billion VND (equivalent to 35.92 thousand USD), and the economic loss in the remaining provinces ranges from 2.256 to 5.849 billion VND (equivalent to 99.80–258.79 thousand USD).

3.3. Uncertainty analysis

The uncertainty in the calculation results is a composite assessment of the uncertainties accumulated during each simulation calculation process. The limitations and uncertainties were analyzed.

Table 2
Summary of statistical paddy production during three rice crops of 2018 in LMD (Unit: Thousand tonnes).

Rice crop production (CP)	Provinces in LMD						
	An Giang	Bac Lieu	Ben Tre	Can Tho	Ca Mau	Dong Thap	Vinh Long
Spring Paddy	1727.4	356.6	77.4	590.9	3.9	1438.2	371.8
Autumn Paddy	2199.1	596.7	134.5	835.4	150.6	1892.0	597.7
Winter Paddy	0.3	162.0	24.8	–	380.1	–	–
Total	**3926.8**	**1115.3**	**236.7**	**1426.3**	**534.6**	**3330.2**	**969.5**
Rice crop production (CP)	**Provinces in LMD**						
	Hau Giang	**Kien Giang**	**Long An**	**Soc Trang**	**Tien Giang**	**Tra Vinh**	**Total**
Spring Paddy	570.0	2051.0	1441.3	1250.2	513.2	445.7	10,837.6
Autumn Paddy	676.1	1950.0	1354.4	821.0	741.2	815.0	12,763.7
Winter Paddy	–	266.4	7.0	61.6	–	7.4	909.6
Total	**1246.1**	**4267.4**	**2802.7**	**2132.8**	**1254.4**	**1268.1**	**24,510.9**

Table 3
Summary of estimated impacts on paddy production and related economic costs in LMD by the province during three rice crops of 2018.

Provinces in LMD	Losses of crop production and economic cost valuation			
	CPL_{Min} (Rice, Tonnes)	CPL_{Max} (Rice, Tonnes)	ECL (Rice, Thousand USD)	ECL (Rice, Billion VND)
An Giang	122.162	899.204	258.7909	5.8492
Bac Lieu	182.667	542.132	156.0255	3.5265
Ben Tre	191.755	124.806	35.9190	0.8118
Ca Mau	54.602	356.827	102.6947	2.3211
Can Tho	506.654	354.714	102.0866	2.3074
Dong Thap	226.562	1481.777	426.4555	9.6388
Hau Giang	67.488	346.782	99.8040	2.2558
Kien Giang	137.959	665.128	191.4238	4.3266
Long An	451.747	1865.291	536.8308	12.1335
Soc Trang	247.448	1116.324	321.2782	7.2615
Tien Giang	162.847	624.101	179.6163	4.0597
Tra Vinh	208.709	808.699	232.7436	5.2605
Vinh Long	91.776	407.731	117.3451	2.6522
Total	**2652.376**	**9593.517**	**2761.0141**	**62.4046**

First, to assess the yield and rice yield losses for the LMD, this study used two metrics for estimation: M7 for the average exposure over 7 h (from 9:00 a.m. to 3:59 p.m.) and AOT40 for hourly daytime cumulative concentrations above 40 ppbV (from 8:00 a.m. to 7:59 p.m.). Applying the cumulative index AOT40 to the exposure-relative yield functions to determine the RYL, the resulting damage was higher than if the M7 metric was used. Since AOT40 focuses on weighting the accumulated hourly daytime O_3 concentrations over a threshold of 40 ppb [85], the instantaneous dynamics of daily peak O_3 concentrations have not yet been evaluated [82,86]. Thus, this is an uncertain factor when performing simulations.

Second, the exposure-related yield relationships for the paddy fields and coefficients of CRFs in this study were based on large-scale experiments developed for the rice varieties grown in North America, China, Japan, and India. Currently, the problem is the lack of actual data and fundamental studies (CRF) for rice varieties in Vietnam, particularly for LMD. This is one of the causes of errors in the calculation of rice yield loss and the associated economic cost loss. Some results have demonstrated that differences between geographical areas, regional climatic conditions, and different plant varieties lead to completely different levels of ground-level O_3 impacts [70,86,87]. Typically, the results of [80] demonstrated that the sensitivity to ground-level O_3 was more pronounced among rice varieties grown in China compared with rice varieties grown in China or United States. The study of [78] described the difference in impact levels between rice varieties in South Asia and China. Their results showed that the level of interaction between ground-level O_3 and two different cultivars (wheat) is significantly different in China [88]. Therefore, it is necessary to use field-experimental models to study the given CRFs in LMD and develop additional types of relationships, such as pollutant flux–response relationships, cotton formation, and rice grain yield loss [26,89]. These results also support an improvement in the estimation accuracy of ground-level O_3-related impacts on crops.

Third, the estimation of total rice yield loss and associated economic losses may be lower than actual losses in the region, because not only ground-level O_3 but also other pollutants, such as SO_2, NO_x, particulate matter (PM), and aerosols of $PM_{2.5}$, have different levels of direct and indirect effects on plants. The results of this study only partially reflect the actual situation as well because the causes of losses due to the relationship between air pollution and agricultural production is not considered. CRFs for the relative yield-exposure relationship based on the cumulative index AOT40 were developed based on experiments using open-top field chambers (OTC). The AOT40 accumulation index used in this study was estimated from the ground-level O_3 concentration in the ambient air of

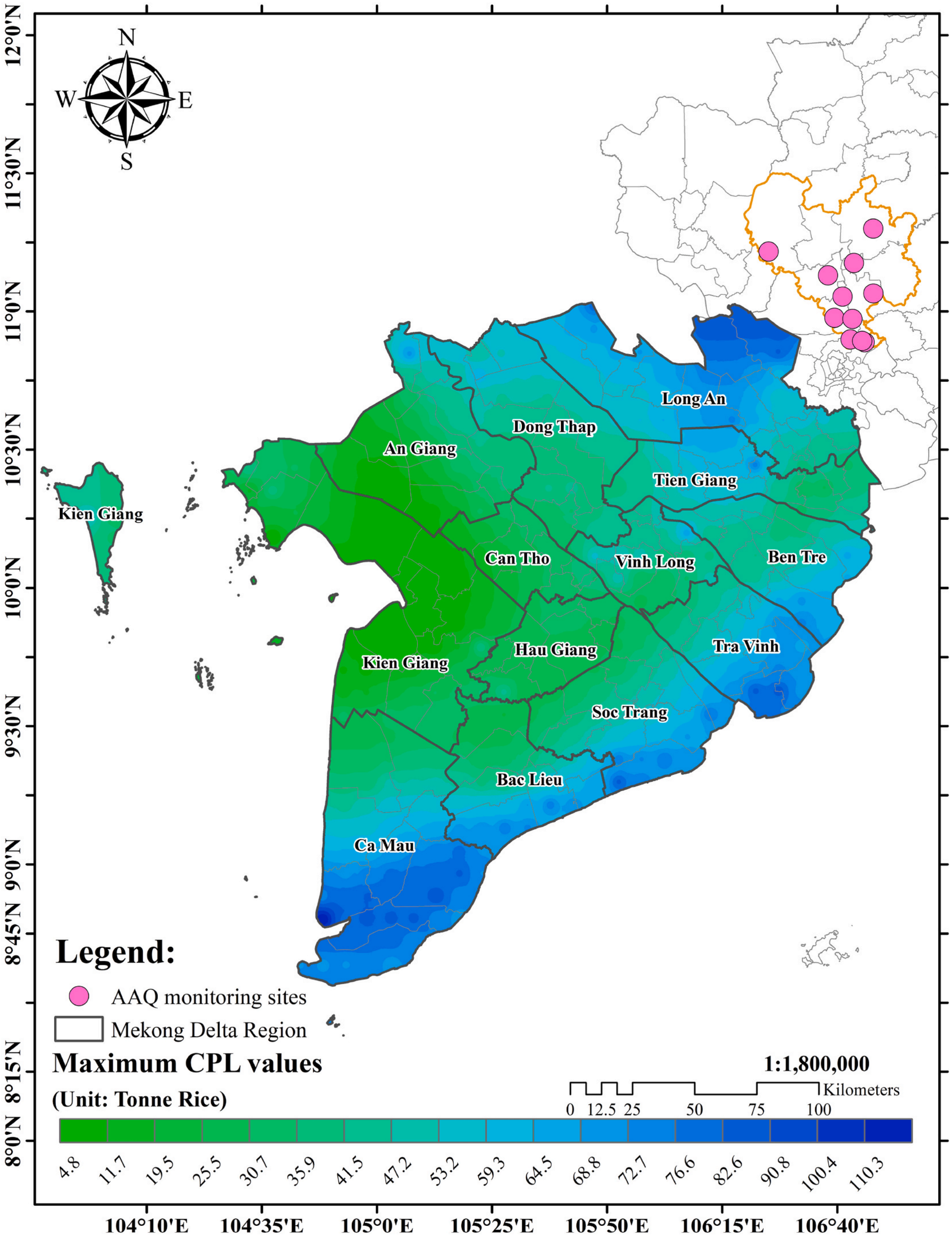

Fig. 7. Spatial distribution of rice yield loss due to ground-level O_3 exposure in LMD, 2018 (based on ground-level O_3 concentration and the M7 and AOT40 metrics).

the area. Significant differences between the actual natural environmental conditions and those in the OTC chamber where the experiments were conducted have not been comprehensively noted [88,90]. Therefore, the impact of ground-level O_3 on rice plants may be larger than estimated because the AOT40-based CRFs used in this study were derived from OTC experiments [91].

Fourth, the definition and determination of the rice-growing season are a matter of uncertainty, which has implications for simulation results. The variation in the length of time the plants were exposed to ground-level O_3 suggests that changing the growing season normally alters the results by less than 5% [70,86]. The rice season and growing period of rice are not uniformly similar among the provinces in the LMD. In the study area, up to 7/13 provinces have 3-crop rice production, and the remaining 6 out of 13 provinces have 2-crop rice production. The difference in the planting season schedule comes from the local level between wards/communes, and districts within the same province are an uncertain factor. In the LMD, there are many seed groups: the 115-day seed group (CR-203 variety group) and the 125-day seed group (C-70 variety group) [55] showed that during the growth process, the different stages of plant development, rice goes through 3 different growth – development stages. The vegetative growth period, which takes up 50–60 days, is evaluated as the main different stage. The period of actual growth was approximately 35 days, and the period of seed formation and maturation was approximately 30 days. In practical terms, it is difficult to assess productivity and economic loss. CRFs based on AOT40 or M7 of different rice varieties in LMD need to be studied and evaluated experimentally, and this needs to be taken into account in future studies. An investigation of the practice of rice production and cultivation at the local level in each province should be carried out to accurately determine the growing season to ensure the simulation is accurate.

Fifth, limitations may come from the results of local and regional emission inventories. The simulated ground-level O_3 concentration value used in this study, obtained from the WRF/CMAQ model system, was also an uncertain factor, causing errors in the damage quantification model. Differences in ground-level O_3 concentrations between urban and rural areas, differences in ground-level O_3 precursor emissions, and different meteorological factors, in which VOC/NO_x ratios influence the formation of ground-level O_3 [84]. Ground-level O_3 concentrations generally increased with increasing VOCs concentrations but decreased with increasing NO_x concentrations.

4. Discussion

Based on the hourly average ground-level O_3 concentrations, the average exposure metric of M7 and the cumulative exposure metric of AOT40 were calculated and used for quantifying the CPL in total rice production in three rice crops and the total ECL in LMD. They were found to be 9594 tonnes and 62.405 billion VND (equivalent to 2761.01 thousand USD), respectively, accounting for 0.0076% of the gross domestic product (GRDP) of LMD (823,170 billion VND) [52]. The heaviest damage occurred in five provinces, including Long An province with a loss of 12.134 billion VND (equivalent to 536.83 thousand USD), Dong Thap province with a loss of 9.639 billion VND (equivalent to 426.456 thousand USD), Soc Trang province with a loss of 7.262 billion VND (equivalent to 321.278 thousand USD), An Giang province with a loss of 5.849 billion VND (equivalent to 258.791 thousand USD), and Tra Vinh province with a loss of 5.261 billion VND (equivalent to 232.744 thousand USD).

Comparing with [92], that evaluated the effects of surface-level O_3 on both rice and maize in Tay Ninh Province (in the southeast region of Vietnam) in 2018, the damage level in the LMD was significantly higher in this study. Specifically, the highest total loss of rice production (CPL) in Tay Ninh Province was 417 tons, which was approximately 23 times lower than the total CPL of the LMD. Similar studies conducted in several regions, including in China and India, have been shown similarities to our results for the LMD. However, the estimated damage to rice production and farming activities due to ground-level O_3 in these studies was significantly higher than that in the present study. The study of [93] showed that the maximum RYL in 2018 was 14.2% in Xiaochang in Hubei County for the double-early rice period, whereas for the double-late rice period, the average RYL value over the crop growth seasons was 8.0% over the nine southern provinces of China. Furthermore, the total ECL was estimated at 8081.03 million USD, compared with an ECL of only approximately 2.76 million USD for the LMD. A case study by Ref. [94] that evaluated the RYLs of rice in China from 2013 to 2020 found that in 2018, the total CPLs for single rice, double-early rice, and double-late rice crops were 796×10^4, 119×10^4, and 148×10^4 t, respectively, outperforming the total CPL of the study area.

The results of this study were also compared with similar studies from other time periods. In specific, a case study by Ref. [83] performed simulations for 31 Chinese provinces and cities (excluding Hong Kong, Macau, and Taiwan); the exposure scenario where rice was subjected to ground-level O_3 showed that the damage levels in the years 2015–2017 were many times higher than those in the LMD. In 2015–2017, for single-crop rice, the lowest CPL occurred in Laizhongliuxue province at 31.6×10^4 tons (32.9 times higher than in the LMD); 120.4×10^4 tons (125.5 times higher than the this study area); 131.5×10^4 tons (137.1 times higher than the this study area); while for double-early rice and double-late rice, the lowest CPL losses occurred in Guangdong province in 2015, with about 17.5×10^4 tons (higher than 18.2 times compared with the study area), and in Jiangxi province in 2015, with about 44.0×104 tons (45.9 times higher than the study area). Similarly, the study results of [83] showed the quantifiable amount of damage to rice caused by ground-level O_3; the lowest ECL value for the whole of China in 2015 for early 2-crop rice was 47.5×10^7 USD, about 172.1 times higher than the loss value in 2018 in the whole LMD. However, a result from another case study in China by Ref. [86] showed that the total rice production (including single-crop rice, paddy rice early crops and late rice) loss caused by the impact of ground-level O_3 in 2006 was 4602.64 thousand tons, with an equivalent economic loss of 1524×10^6 USD, about 2.08 times lower than those estimated for the other crops in the LMD in this study.

The results of a study by Ref. [78] conducted in the two states of Punjab and Haryana in India, during the period 2011–2014 also showed very large economic damage; it was many times higher than that in the LMD. When considering only rice exposure, the total yield loss was approximately 5.4 million tons in the period 2012–2013 (562.9 times higher than in the LMD) and approximately 3.2 million tonnes in the period 2013–2014 (333.5 times higher than that of LMD). Correspondingly, the level of economic loss was quantified as 67 billion INR (roughly 1.1 billion USD) [78]. This loss was approximately 398.4 times higher than that in the this study.

The research of [95] conducted a case study in the Southeast region of Vietnam, including in Ho Chi Minh City and the provinces of Ba Ria Vung Tau, Binh Duong, Binh Phuoc, Dong Nai, and Tay Ninh; they estimated the loss of rice production due to ground-level O_3 exposure in 2010. The lowest loss of rice production was in the second rice crop over the cultivated year, with an estimate of 6800 tons; this loss was 1.41 times lower than that in our study area. The highest loss in rice production occurred in the first rice crop, with total losses of up to 25,800 tons, which are 2.69 times higher than those in our study area.

5. Conclusion

Ground-level ozone O_3 pollution is already a very important issue in LMD. Ground-level O_3 pollution fluctuates seasonally over time, and O_3 concentrations are generally higher in the dry season than in the wet season. The highest concentrations of O_3 ranged from 17.2 to 102.1 μg/m^3. It needs attention because of its important role in global food security and its harmful properties to food plants, which cause reductions in crop yields in the area. The following results were obtained in this study.

Modelled concentrations from WRF/CMAQ were used to obtain hourly ground-level O_3 concentrations, based on which exposure metrics M7 and AOT40 were calculated and used to quantify the impact of ground-level O_3 on rice yield. These metrics were calculated for the one year, paying attention to crop factors such as nutritional growth period and the actual growth period; the periods of seed formation and ripening were also taken into account.

An economic loss assessment model was used to quantify the loss in output and related costs. The calculated results were obtained for each province in the region. Research has shown that the economic cost of losses related to ground-level O_3 pollution is significant. The total CPL in the three rice crops in the region reached 9594 tons, equivalent to a total ECL of approximately 62,405 billion VND lost (equivalent to roughly 2761.01 thousand USD). The study also showed that the five provinces which suffered the most damage were An Giang, Kien Giang, Soc Trang, Dong Thap, and Long An provinces.

This study evaluated the potential risk of ground-level O_3 pollution for 3-crop rice production (Spring, Autumn, and Winter rice crops) and 2-crop rice production (Spring and Autumn rice crops or Spring and Winter rice crops) in the LMD, and the average exposure metric M7 and cumulative exposure metric AOT40 were determined.

The study results support to develop strategies and policies to control ground-level O_3 pollution and minimise potential risks to agricultural production activities. In the future, surface O_3-rice crop models need to be developed in more detail for the regions of Vietnam to improve the efficiency and accuracy of calculating the damage caused by ground-level O_3 pollution. With economic growth, ground-level O_3 concentrations could continue to rise rapidly, leading to a decline in crop yields, not just rice. Therefore, to protect Vietnam's food security, strict measures and sanctions should be introduced to control O_3 precursor emissions.

Author contribution statement

Long Bui Ta: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Phong Hoang Nguyen: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e17883.

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