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Ecological risk assessment attributed to rice and maize yield reduction due to long-term ground-level O_3 impacts: A case study in Tay Ninh, Vietnam

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Abstract: The agricultural sector of Tay Ninh province accounts for about 28% of the province's economic structure with agricultural land areas of 269,250 ha, contributing to 66.7%; particularly, cultivation accounts for 80% of the agricultural economic structure value. Sustainable agricultural development is an urgent mission as the local agricultural sector plays a quite important role in the local economy. Currently, tropospheric O_3 has been evaluated as an air pollutant, causing crop yield reduction and significant economic damage. This study had built a methodological framework based on the application of the coupled Weather Research and Forecasting (WRF)/ Community Multiscale Air Quality Modeling System (CMAQ) model to assess the status of ground-level O_3 concentration allocation in Tay Ninh province, Vietnam with typical cases of crop seasons (spring paddy and maize) in 2018, combined with existing exposure-response functions to quantify agro-economic losses. With the simulated 8-hour mean surface O_3 concentration (daytime) ranging from 10.9 to 113.5 $\mu g/m^3$, the economic impacts on rice (the spring season) and maize production were determined to reach more than 184 billion VND, contributing to roughly 0.18% in the total Gross Regional Domestic Product (GRDP) of Tay Ninh province in 2018. Moreover, this is also considered a baseline study to serve as a basis for extensive assessments and propose O_3 precursor emissions control measures shortly.

Keywords: Ground-level O_3; Spatio-temporal distributions; Exposure; Crop production losses; Economic impacts.

1. Introduction

Tropospheric ozone or ground-level ozone (O_3) is one of the major global pollutants, proven to have harmful effects on natural vegetation and harvest in previously available studies [1–3]. High concentrations of O_3 disrupt plant metabolism, promote leaf senescence, and reduce chlorophyll content and photosynthesis rate, leading to reduced crop yields, especially for O_3 sensitive crops such as rice from Asia [4]. Ground-level O_3 is a secondary air pollutant formed from the oxidation of the hydroxyl radical of CO or hydrocarbons in the presence of nitrogen oxides (NO_x) and sunlight [5]. Ozone is not only one of the greenhouse gases that directly contributes to global warming, but also indirectly reduces the carbon sink of the terrestrial ecosystems [6]. Notably, O_3 concentration in Asia is still trending up as rapid industrialization and urbanization continue in these areas, but emissions of precursors of O_3 such as NO_x and VOCs have increased significantly [7]. Particularly in China, O_3 concentration levels have increased at a much higher rate than in other countries in the region, whose quite high O_3 concentration is threatening security of national food staples and could be exacerbated in the future if this trend continues [8]. Several study results reported that China and India might experience heavier crop yield losses (CYLs) soon due to the expected increase in O_3 concentrations [9]. These outcomes presented that the high O_3 concentration predicted in 2020 had resulted in a China-wide corn loss of 7.2%. The study of [10] estimated that O_3 pollution caused a relative yield loss (RYL) for winter wheat in China of 6.4% in 2000 and by 2020 it was about 4.8%. Meanwhile, the RYL for rice ranged from 2.5% to 6.6% between 1990 and 1999 and rose to 9.2% in 2020 in the Yangtze River Delta (YRD). Furthermore, estimates have shown that global crop losses caused by surface O_3 could continue to increase towards 2030, from 4.0% to 26.0% for wheat in specific, from 2.5–26.0% for wheat, 8.7% for corn, and from 9.5–19.0% for soybeans [11].

To assess the effects of O_3 pollution on crop yields, several metrics were developed based on results from both field and open-chamber experiments (OTC). One of the first studies in the world to quantitatively evaluate the effects of surface O_3 concentrations on crops was carried out by the National Crop Loss Assessment Network (NCLAN) based on OTC by establishing seasonal average daytime O_3 concentrations under review including M7 and M12 [12]. Meanwhile, researchers in Europe have found similar adverse effects caused mainly by the cumulative effects of O_3 pollution, hence the concept of critical level (CL). The new metric has been proposed and acknowledged as AOT40 to reflect the cumulative threshold of the dose of surface O_3 concentration (40 ppb) for plants and vegetation [13]. Many studies have been developed to construct correlation functions of productivity-interactions in Asian countries such as China and India. Typically, the study of [14] applied OTC to establish AOT40–interaction function for wheat and rice in YRD, China or similar studies by [15] and [16] based on experiments that increase free emissions (FACE-Free atmospheric concentration enrichment). In India, the study of [17] constructed new yield – O_3 interaction functions based on AOT40 and M7 indices for wheat, rice, and maize through a literature review of OTC studies on these cultivars in South Asia.

Nowadays, air quality simulations play an important role as technical tools applied to air quality management [18]. Air quality simulations provide information about the causal relationship between meteorology, emissions, and pollutant concentrations by simulating transport, conversion, and deposition mechanisms. stagnation [19]. In which for O_3, because of lack issues of data to monitor ground-level O_3 concentrations on a regional scale, chemical transport models have been used more commonly to determine the distribution of O_3 concentrations, as well as assess the risk of CYL for the area under consideration [10, 20–21].

This study has built calculations using data sources at the provincial and local administrative levels of Tay Ninh province to better reflect spatial differences in the effects of ground-level O_3 over the entire province. At the same time, the study also carried out an ecological risk assessment of surface O_3 using the long-term cumulative surface O_3 exposure metric (AOT40) through concentration-response functions (C-R) to estimate yield and yield losses of two common crops, including rice and maize based on multiple O_3-crop models and the corresponding general economic losses for Tay Ninh province in 2018.

2. Methods and data

2.1. Study area

Tay Ninh province is located in the Southeast region of Vietnam, having the coordinate system from 10°57’08” to 11°46’36” North and from 105°48’43” to 106°22’48” East [22] shown in Figure 1. Tay Ninh province is known as a spiritual land with potential and advantages for socio-economic development, especially tourism potential with many ideal attractions. The province is one of the crucial international exchange gateways between

Vietnam and neighboring Cambodia and Asian countries. Tay Ninh is also a province with an important position in the exchange of goods between the provinces of the Mekong Delta and the Southern key economic regions. Therefore, in recent years, the province's economy has developed relatively comprehensively and continuously. Industry and handicrafts are developing steadily. Currently, Tay Ninh province has 2 economic zones (Moc Bai and Xa Mat); 6 industrial zones/export processing zones (Trang Bang Industrial Park, Phuoc Dong - Boi Loi Industrial Park, Thanh Thanh Cong Industrial Park, Cha La Industrial Park, TMTC Industrial Park and Linh Trung Industrial Park & Export Processing Zone) and 5 industrial clusters (Tan Hoi 1 Industrial Park, Thanh Xuan Industrial Park) 1, Hoa Hoi Industrial Park, Ninh Dien Industrial Park and Ben Keo Industrial Park) are operating and are implementing infrastructure construction; In addition, the province has over 150 factories processing agricultural products such as processing sugar, processing tapioca, processing rubber latex and cashew nuts [23].

Facing economic development, specifically industrial development, the problem of pollution and environmental degradation tends to go up. The main source of pollution to the environment in Tay Ninh province is industrial waste from industrial production activities. In addition, activities such as transportation, animal husbandry, farming, etc. also affect the quality of the environment. Under the pressure of population growth, the increasing consumer demand has led to the development of many industries such as textiles, paper production, mechanical engineering, machine manufacturing, shoes, sandals, and tires vehicle... which increases a series of air pollutants, precursors of ground-level O_3 such as NO_x, SO_2, CH_4, CO... from fuel burning, open biomass burning and VOCs from activities textile industry, chemical factories.

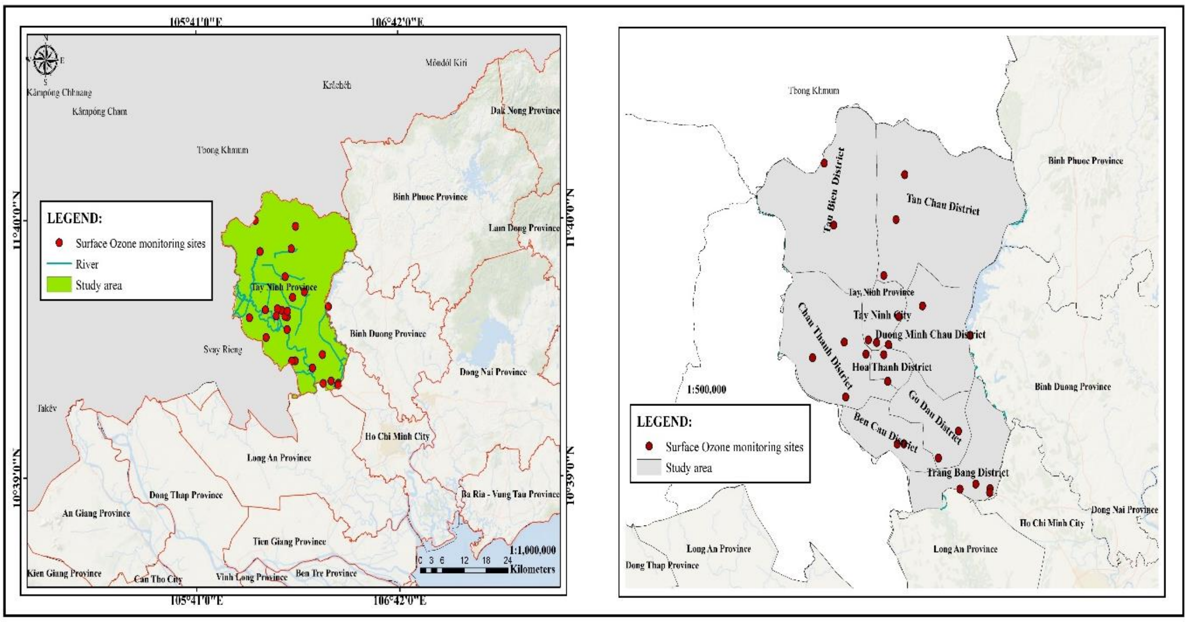

Figure 1. Description of the study area in Tay Ninh province.

2.2. Ground-level O_3 concentration-based exposure metrics

In this study, we considerd a type of long-term cumulative O_3 exposure metrics that have been widely used in quantifying O_3 exposure and its effects on crops. It is the norm in the form of cumulative exposure AOT40. The AOT40 metric for the hourly cumulative daytime O_3 concentration above the 40 ppbV threshold [24]. At the same time, the cumulative index (AOT40) reflects a greater degree of influence from O_3 concentrations with greater accuracy when estimating CYLs than using averages (M7 and M12 metrics) [25]. The cumulative metric AOT40 as well as the relationship between the indexes in the C-R functions (Table 1) estimated according to equation (1) [24, 26] as follows:

$$\text{AOT40 (ppm h)} = \sum_{i=1}^{n}([C_{O_3}]_i - 0.04), \text{ with } C_{O_3} \geq 0.04 \text{ ppm h} \quad (1)$$

where C_{O_3} is the hourly average O_3 concentration according to daylight hours in the study area from 08:00 to 19:59 hours, the ground-level O_3 concentration used in the study is the simulation result by the coupled WRF/CMAQ models for Tay Ninh province from January 2018 to March 2018 and n is the number of hours in the growing seasons of the crop under consideration, including Spring rice (paddy) and maize in 2018.

2.3. Estimation of crop yield and economic cost losses

The relative yield value (RY) calculated for maize and rice was used to further determine the relative yield loss (RYL) and crop-production loss values (CPL) according to below equations [27–28]. RYL is defined as the decline in crop yield, specifically in the study for Spring rice (paddy) and maize, which is based on the basic theoretical yield that is not due to O_3-induced damage [29]. RYL for crops is determined according to equation (2) as follows:

$$RYL = 1.0 - RY \quad (2)$$

The rice and maize production losses (CPLs) are calculated based on the rice production and maize production (CP) respectively combined with RYL according to equation (3) [30–31], where CP of rice and maize can be obtained from a source of national statistical database and annual Statistical Yearbook Reports of Tay Ninh province.

$$CPL = CP \times \frac{RYL}{1 - RYL} \quad (3)$$

As evidenced by the many previous studies available, the total economic loss (TEL) from the levels of economic cost loss (ECL) has been defined as the financial losses caused by the effects of ground-level O_3 exposure on crops and these are determined based on the minimum agricultural purchase price (MPP) for each considered crop. Therefore, the total economic cost damage caused by ground-level O_3 pollution can be determined by the equation (4) as follows:

$$TEL = \sum_{i=1} ECL_i = \sum_{i=1} CPL_i \cdot MPP_i \quad (4)$$

where ECL is the total economic cost loss with ECL_i being the component economic cost loss for each crop; CPL_i is the yield losses for each crop in turn; and MPP_i is the minimum annual Government purchasing price for rice and maize in 2018, respectively.

2.4. Data sources

2.4.1. Simulated surface O_3 concentration allocation over Tay Ninh province

The WRF model with version 3.8 combined with CMAQ air quality model with version 5.2.1 were used to simulate the distribution of ground-level O_3 concentration in tis study area. The CMAQ simulation is a modern scientific method widely used in much current research and policy-making to analyze and evaluate physical and chemical processes that determine the transport, reaction, and formation of tropospheric O_3 [32–33]. The entire research framework applies to the simulation of surface O_3 pollution in Tay Ninh province, specifically the process of setting up computational spatial domains for the combined WRF/CMAQ models, inventory of precursor emissions. The applied chemical mechanisms, initial conditions, boundary conditions, and efficiency verification of WRF models as well as CMAQ models have been detailed in many our previously published studies as a detailed description can be found in studies such as [34–35].

2.4.2. Ground-level O_3-crop models to assess RYL

The C-R function represents the relationship between surface O_3 exposure and RY of crops, including rice (as equations from (5) to (10)) and crops maize (as equation (11)) and based on available empirical studies, presented in Table 1.

Table 1. Overview of the exposure–response functions (ERFs) for evaluating relative yield loss (RYL) of rice and maize in this study.

Crop types	Sign of O_3-crop models	ERFs used for RYL estimation	References
Rice	Model (1)	RY = 1 – 0.0095×AOT40 (5)	[14]
	Model (2)	RY = 1 – 0.0160×AOT40 (6)	[36]
	Model (3)	RY = 1 – 0.0053×AOT40 (7)	[37]
	Model (4)	RY = 1 – 0.0390×AOT40 (8)	[38]
	Model (5)	RY = 1 – 0.0041×AOT40 (9)	[4]
	Model (6)	RY = 0.95 – 0.00001×AOT40 (10)	[17]
Maize	Model	RY = 1 – 0.00577×AOT40 (11)	[39]

2.4.3. Data of purchase prices of crops (MPP)

The MPP value is defined as the fixed price at which farmers sell their crops to the government [28] or purchase prices of crops (CPP) [40]. CPP values are referenced based on the World Food Organization's (FAOSTAT) aggregated statistical database, where the CPP in 2018 for rice was $287.8/ton and for maize was 267.8 USD/ton (http://www.fao.org/faostat/). In addition, the currency value conversion rate between USD and VND of Vietnam for 2018 is 1 USD = 22,602.05 VND according to the data of the World Bank (https://data.worldbank.org/indicator/PA.NUS.ATLS?locations=VN).

2.4.4. Crop area, yield, and production statistics

Statistical data related to the area of crop production (rice and maize production) in the study area in 2018 are collected from the website of the General Statistics Office of the Government and Detailed Statistical Yearbook Reports of Tay Ninh Province in 2018, 2019 and 2020 [22, 41], including area, yield, and yield of Dong Xuan rice and maize by each administrative unit in Tay Ninh province were used in this study. The related information collected from the Department of Agriculture and Rural Development of the province showed that the winter-spring rice production of the province is usually sown concentratedly and simultaneously in 3 batches depending on each locality as follows: (1) the first phase of early winter-spring from November 6 to November 14, 2017, (2) Phase 2 of the main winter-spring season from December 5 to December 13, 2017, and (3) Phase of the late Winter-Spring season from January 3 to January 11, 2018 (up to January 20, 2018) [23]. In the research area, rice variety OM 5451 is grown mainly by many advantages, especially good pest resistance, high yield; along with other key rice varieties from the Mekong Delta such as OM 6976, OM 4900, OM 576, IR 50404,... and production models of new rice varieties such as ST20, ST21, ST24, Hong Ngoc (red rice),…[23].

Rice, along with maize, is one of the traditional crops of Tay Ninh province, occupying a significantly larger area than other local crops (Figure 2) [42–43]. Specifically, in the period from 2010–2018, the province's rice and maize area, respectively, ranged from 142,224 to 155,909 hectares (up to 96.8% of the total cultivated area) and 4,359 to 5,865 hectares (up to 3.7% of the total area), respectively. cultivated area). In which, from 2010 to 2018 the area of winter-spring rice crops was from 42,568 to 47,603 hectares (accounting for 29.9 to 30.5% of the total cultivated area) with the yield and yield of winter-spring rice reaching 51.07 to 59.11, respectively. quintals/ha and 234,408–273,647 tons. On the other hand, from the statistics in Table 2. It could be seen that Tan Chau district and Hoa Thanh town, respectively, have the lowest planting areas of Dong Xuan rice and maize in the province; The highest yield and yield of winter-spring rice were obtained in Chau Thanh district and Trang Bang town, while maize area, yield and yield of Go Dau district was the highest in the whole of Tay Ninh province [22]. Thus, in this study, the total loss of rice and maize production due to ground-level O_3 pollution in Tay Ninh province was estimated by summing up all rice and maize production losses in each administrative unit of the province.

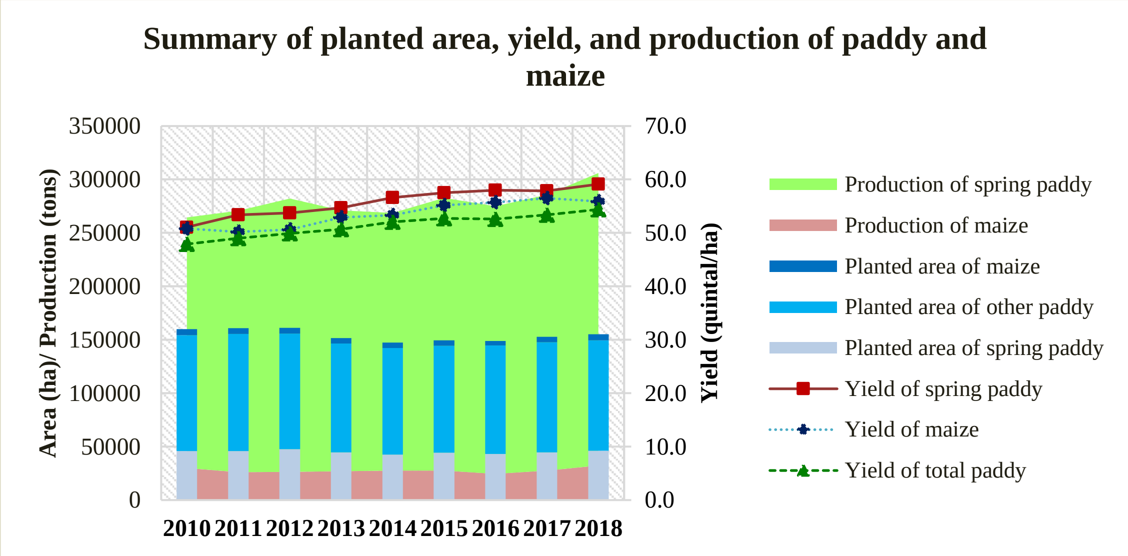

Figure 2. Statistical summary of spring paddy and maize in terms of planted areas, yield, and production in Tay Ninh Province from 2010 to 2018.

Table 2. Statistical planted area (ha), yield (quintal/ha), and production (tons) of spring paddy (rice) and maize by each county in Tay Ninh Province in 2018.

District/ Town/ City	Spring rice (paddy)			Maize		
	Planted area	Yield	Production	Planted area	Yield	Production
Tay Ninh City	463.75	45.10	2,091.66	188.55	44.13	832.06
Tan Bien District	1,531.00	52.01	7,962.90	648.30	46.63	3,022.88
Tan Chau District	144.10	45.63	657.53	200.39	49.02	982.26
Duong Minh Chau District	920.50	50.95	4,690.00	818.60	50.32	4,118.88
Chau Thanh District	14,061.80	57.26	80,516.60	389.00	49.46	1,924.10
Hoa Thanh Town	1,128.20	56.49	6,373.65	104.00	45.05	468.47
Go Dau District	7,311.69	59.94	43,826.27	1,261.30	68.21	8,603.56
Ben Cau District	10,027.65	57.96	58,116.21	599.00	64.11	3,840.11
Trang Bang Town	10,703.50	64.85	69,412.20	743.15	51.27	3,810.16
Total	**46,292.19**	**59.11**	**273,647.02**	**4,952.29**	**55.74**	**27,602.48**

The flow chart of the entire structure of this study is shown in Figure 3.

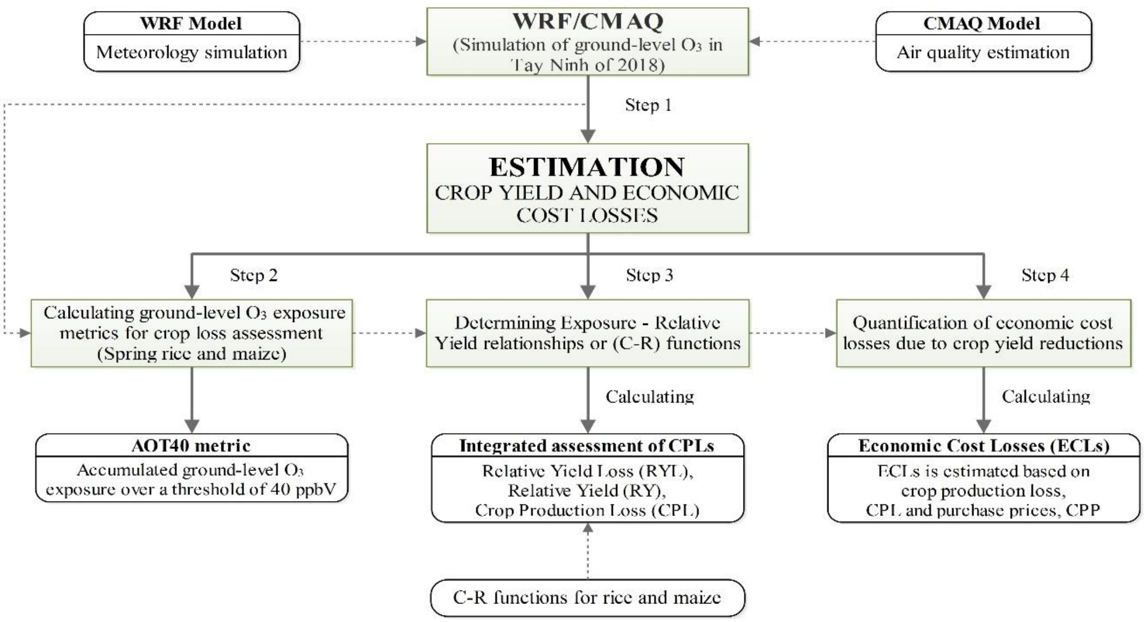

Figure 3. The flow chart of this study structure.

3. Results and discussion

3.1. Assessment of ground-level O_3 concentration levels in Tay Ninh province

In the period from January 2018 to March 2018, the average O_3 concentration level on the ground is the 8-hour day (daytime) from 8:00 a.m. until 7:59 p.m. and tends to fluctuate between 10.987 and 113.496 μg/m^3. Figure 4 represents the spatial-temporal distribution of the 8-hour average ground-level O_3 concentration of the days of the highest concentration in Tay Ninh province in the period January to March 2018. In general, the localities with high average ground-level O_3 concentration in the 8-hour day are mainly concentrated in the northern and eastern districts of Tay Ninh province, including: Tan Chau, Tan Bien, and Duong Minh districts. Chau, Trang Bang, and Go Dau. At the same time, over time, the average ground O_3 concentration level of 8-hour also tends to go up gradually from January 2018 < February 2018 < March 2018 with levels ranging from 10.987 to 75.022 μg/m^3 < from 30.662 to 106.855 μg/m^3 < from 22.831 to 113.496 μg/m^3 as in Figure 5.

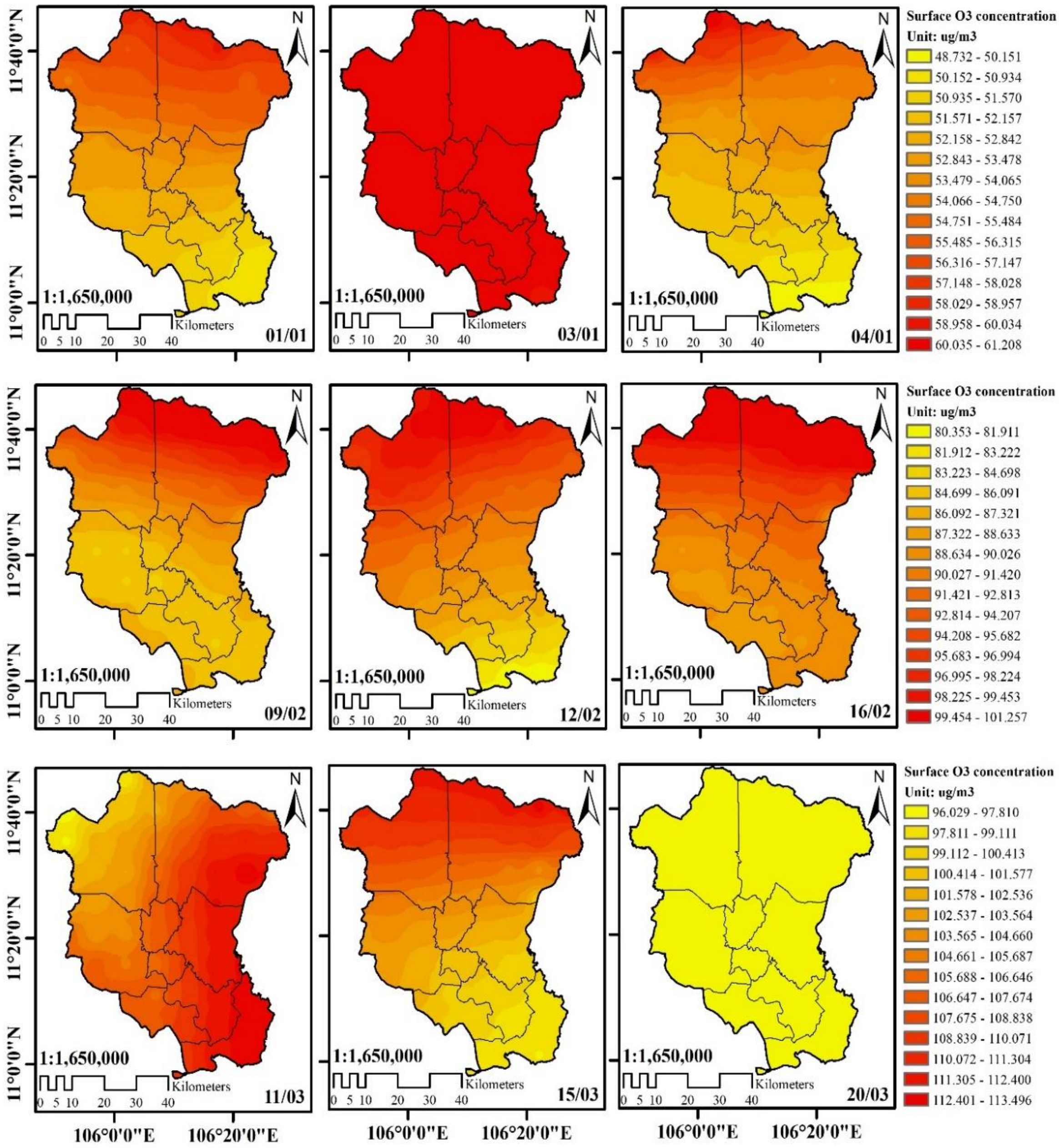

Figure 4. Spatio-temporal ground-level O_3 concentration distributions of the days of the highest concentration in Tay Ninh province between January 2018 and March 2018.

Specifically, in January 2018, ground-level O_3 concentration averaged 8-hour daytime from 8:00 a.m. until 7:59 p.m. average range from 28,236 ± 2,005 µg/m^3 to 33,840 ± 2,573 µg/m^3, still ensuring the allowable limit of NAAQS (particularly QCVN 05:2013/BTNMT, average 8-hour is 120 µg/m^3). The average high 8-hour ground O_3 concentration level usually concentrates on the first days of the month from January 1 to 6, 2018. The ground-level O_3 concentration level tended to decrease from January 1 to 10, 2018 and from January 11 to January 31, 2018, the ground-level O_3 concentration remained relatively stable at 19.955–38.930 µg/m^3. The largest 8-hour average O_3 concentration occurred on January 3, 2018, in the range of 59.724–75.022 µg/m^3. Next in February 2018, the average ground-level O_3 concentration level in 8-hour daytime averaged from 64.406 ± 2.932 µg/m^3 to 75.146 ± 3.499 µg/m^3 and continued to ensure the allowable limit of NAAQS. However, compared to January 2018, the average ground-level O_3 concentration on the 8-hour day was 2.20–2.28 times higher than in January 2018. During the period from February 1, 2018 to February 16, 2018 and peaking on February 16, 2018, the concentration of ground-level O_3 tended to increase sharply from 53.917–63.309 µg/m^3 to 87.966–106.855 µg/ m^3, and from February 17, 2018 to February 28, 2018 the ground-level O_3 concentration level remained stable, with slight fluctuation at a lower level from 60.879 to 87.902 g/m^3. And in March 2018, the average ground-level O_3 concentration in the 8-hour day during day fluctuated from 60.664 ± 4.476 µg/m^3 to 69.739 ± 5.052 µg/m^3 and continued to ensure the allowable limit of NAAQS. Nevertheless, there was a slight decrease compared to February 2018 between 1.06 and 1.08 times. During the period from March 1, 2018 to March 9, 2018 the concentration of O_3 on the ground was relatively low, only from 22.831 to 40.405 µg/m^3; then, from March 10, 2018 to March 20, 2018, the ground-level O_3 concentration tended to go up strongly, ranging from 40.092 to 113.496 µg/m^3 and peaking on March 11, 2018 with concentrations from 96.029 to 113.496 µg/m^3. From March 21, 2018 to the end of March 2018, ground-level O_3 concentration tended to decrease and remained stable at 58.586–92.807 µg/m^3.

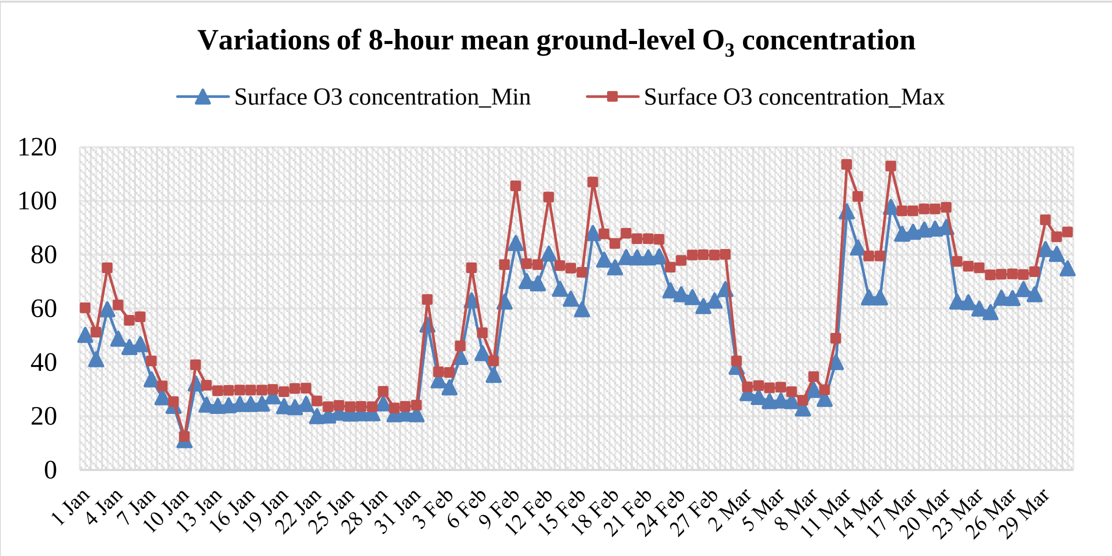

Figure 5. The fluctuation of daytime 8-hour average ground-level O_3 concentration (maximum and minimum) of days in the period January to March 2018 in Tay Ninh province.

3.2. Assessment of AOT40 spatio-temporal distribution

During the period from January 2018 to March 2018, the average AOT40 across the entire Tay Ninh province was 2.561 ppm h, ranging from 2,014 to 3.766 ppm h (Figure 6). The AOT40 level in Tan Chau and Tan Bien districts was higher than in other localities in the study area, ranging from 2.316–3.615 ppm h (average at 3.018 ppm h) and 2.184–3.513 ppm h (average at 2.673 ppm h), respectively. Meanwhile, Chau Thanh, Hoa Thanh, Go Dau, and Ben Cau districts are the localities with the lowest AOT40 levels in the study area during this period. In specific, the AOT40 range occurs from 2.014 to 2.272 ppm h (average at 2.105 ppm h) in Chau Thanh district, 2.027 to 2.236 ppm h (average at 2.119 ppm h) in Hoa Thanh district, respectively. 2.075–2.414 ppm h (average at 2.213 ppm h) in Go Dau district, and 2.038–2.194 ppm h (average at 2.138 ppm h).

Generally, the spatial variation of AOT40 levels tended to increase gradually from localities in the direction from West to East and from Southwest to Northeast during the evaluation period. At the same time, the accumulation of ground-level O_3 exposure according to AOT40 also tended to increase gradually from January 2018 to March 2018 (Figure 6). Specifically, in January 2018 the average AOT40 level across Tay Ninh province was 0.003 ppm h (ranging from 0.0000 to 0.0048 ppm h) mainly on January 3, 2018; for February 2018 the average AOT40 level was 0.9805 ppm h (ranging from 0.6522–1.8167 ppm h) mainly occurred in the period from February 5, 2018 to February 28, 2018; and for March 2018 the average AOT40 level reached 1.5800 ppm h (ranging from 1.3374–2.0492 ppm h) mainly occurred in the period from 11 March 2018 to 31 March 2018. The highest AOT40 levels occurred in Tan Bien district in January 2018 and Tan Chau district in February 2018 and March 2018.

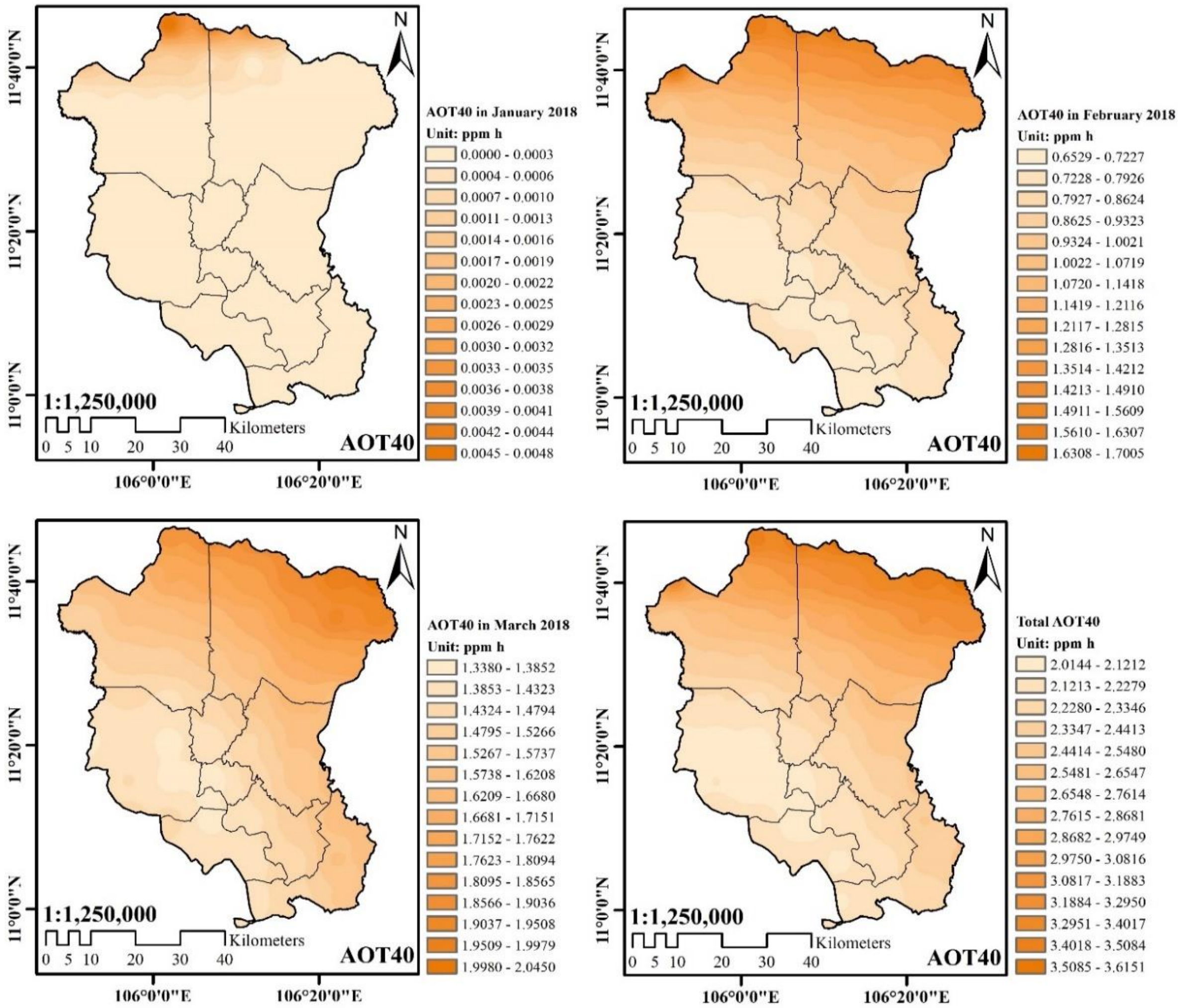

Figure 6. Spatio-temporal AOT40 metric distributions in Tay Ninh province between January 2018 and March 2018 based on ground-level O_3 concentration.

Thus, from the above analysis and evaluation results, the space-time distribution of the cumulative surface O_3 exposure metric (AOT40) in the first 3 months of 2018 shows a consistent trend for surface O_3 concentrations across Tay Ninh province. The surface O_3 concentration and cumulative AOT40 exposure have continuously increased from January 2018 to March 2018 and peaked in March 2018 due to the relatively high temperature increase occurring at the peak period of the dry season in 2018 in the Southeast provinces of Vietnam, of which Tay Ninh is one of the typical areas, with the average temperature of January, February and March 2018 being 27.0°C < 27.4°C < 28.7°C, respectively [22, 41]. It is the difference in ground-level O_3 concentration in different localities and the time-varying changes of AOT40 levels in the growth stages of different crops in the study area that have had a significant impact in terms of yield and yield of crops [38].

3.3. The mean rice and maize RYL estimated using O_3-crop multiple models

In this study, we calculated the RYL for the winter-spring rice and maize crops in different localities of Tay Ninh province from various O_3-crop models (Table 1) and the results have been shown. shown in Table 3 and Figure 7. The mean RYL for Winter-Spring rice in 2018 from the O_3-crop models was 3.988% (ranging from 3.315% to 5.472%) and the average RYL for maize was 1.478% (ranging from 1.162% to 2.173%). On the other hand, for rice, the O_3-crop (4) model had the highest RYL level with an average RYL of 9.987% (ranging from 7.856% to 14.687%) and the O_3-crop (5) model had a low RYL level with an average RYL of 1.050% (ranging from 0.826% to 1.544%).

Table 3. The RYL of Spring rice and maize by each county in Tay Ninh province between January and March 2018 estimated using the corresponding O_3-crop models.

District/ Town/ City	Spring paddy (rice)						Maize
	RYL_1 [(a)] min	**RYL_2 [(b)] min**	**RYL_3 [(c)] min**	**RYL_4 [(d)] min**	**RYL_5 [(e)] min**	**RYL_6 [(f)] min**	**RYL [(g)] min**
Tay Ninh City	2.067	3.481	1.153	8.485	0.892	5.0022	1.255
Tan Bien District	2.042	3.439	1.139	8.382	0.881	5.002	1.240
Tan Chau District	2.198	3.701	1.226	9.021	0.948	5.002	1.335
Duong Minh Chau District	1.926	3.244	1.075	7.907	0.831	5.0020	1.170
Chau Thanh District	1.914	3.223	1.068	7.856	0.826	5.0020	1.162
Hoa Thanh Town	1.926	3.244	1.075	7.907	0.831	5.0020	1.170
Go Dau District	1.936	3.261	1.080	7.948	0.836	5.0020	1.176
Ben Cau District	1.936	3.261	1.080	7.948	0.836	5.0020	1.176
Trang Bang Town	2.007	3.381	1.120	8.241	0.866	5.0021	1.219
District/ Town/ City	**Spring paddy (rice)**						**Maize**
	RYL_1 [(a)] max	**RYL_2 [(b)] max**	**RYL_3 [(c)] max**	**RYL_4 [(d)] max**	**RYL_5 [(e)] max**	**RYL_6 [(f)] max**	**RYL [(g)] max**
Tay Ninh City	2.314	3.897	1.291	9.499	0.999	5.0024	1.405
Tan Bien District	3.382	5.697	1.887	13.885	1.460	5.004	2.054
Tan Chau District	3.578	6.026	1.996	14.687	1.544	5.004	2.173
Duong Minh Chau District	2.542	4.282	1.418	10.437	1.097	5.0027	1.544
Chau Thanh District	2.106	3.546	1.175	8.644	0.909	5.0022	1.279
Hoa Thanh Town	2.100	3.536	1.171	8.619	0.906	5.0022	1.275
Go Dau District	2.326	3.918	1.298	9.550	1.004	5.0024	1.413
Ben Cau District	2.088	3.517	1.165	8.573	0.901	5.0022	1.268
Trang Bang Town	2.397	4.037	1.337	9.840	1.034	5.0025	1.456
District/ Town/ City	**Spring paddy (rice)**						**Maize**
	RYL_1 [(a)] average	**RYL_2 [(b)] average**	**RYL_3 [(c)] average**	**RYL_4 [(d)] average**	**RYL_5 [(e)] average**	**RYL_6 [(f)] average**	**RYL [(g)] average**
Tay Ninh City	2.176	3.664	1.214	8.932	0.939	5.0023	1.321
Tan Bien District	2.540	4.277	1.417	10.426	1.096	5.003	1.543
Tan Chau District	2.867	4.829	1.600	11.772	1.238	5.003	1.742
Duong Minh Chau District	2.256	3.800	1.259	9.262	0.974	5.0024	1.370
Chau Thanh District	2.000	3.369	1.116	8.211	0.863	5.0021	1.215
Hoa Thanh Town	2.013	3.390	1.123	8.263	0.869	5.0021	1.223
Go Dau District	2.103	3.541	1.173	8.632	0.907	5.0022	1.277

Ben Cau District	2.031	3.420	1.133	8.336	0.876	5.0021	1.233
Trang Bang Town	2.210	3.721	1.233	9.071	0.954	5.0023	1.342

Note: (a) Wang et al. 2012; (b) Pang, Kobayashi, and Zhu 2009; (c) Feng et al. 2003; (d) Xu et al. 2021; (e) Mills et al. 2007; (f) Sinha et al. 2015; (g) Peng et al. 2019
Min: Minimum; max: Maximum

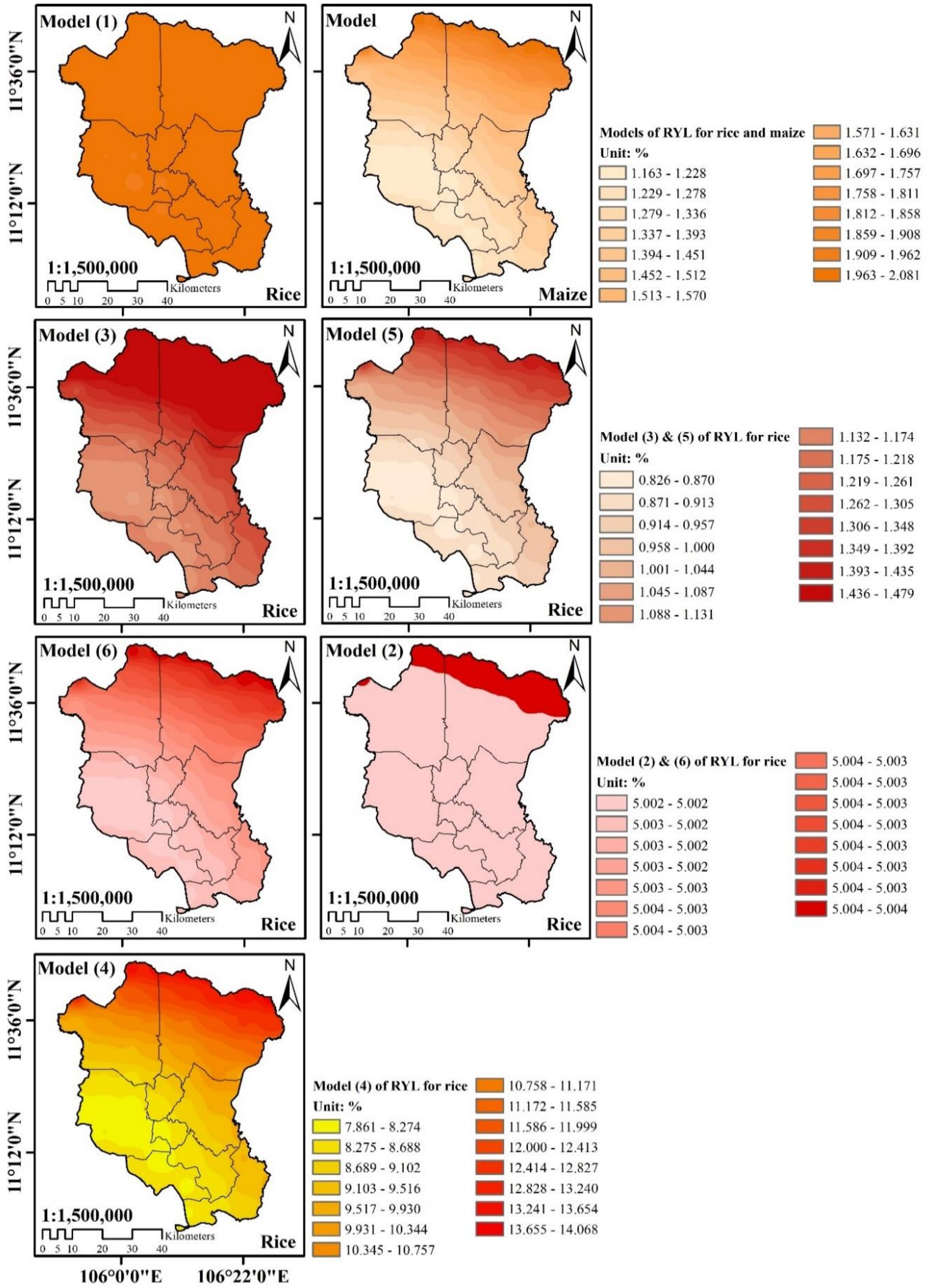

Figure 7. The RYL spatial distributions are estimated according to corresponding O_3-crop models in Tay Ninh province for Spring rice and maize.

Because RYL values are determined based on AOT40 the cumulative level of ground-level O_3 exposure; therefore, they tend to have a similar spatial distribution to the AOT40. Specifically, Tan Chau and Tan Bien districts had the highest RYL of winter-spring rice 2018 in the whole of Tay Ninh province, ranging from 9.047–14.068% and 8.520–13.672% for the the O_3-crop model (4), and in turn from 0.951–1.479% and 0.896–1.437% for the O_3-crop model (5). Chau Thanh, Hoa Thanh, Go Dau, and Ben Cau districts are respectively the localities with the lowest RYL of winter-spring rice in 2018 in the whole of Tay Ninh province, with levels ranging from 7.861–8.841%, 7.911–8.708%, 8.112–9.406% and 7.950–8.554%, respectively for the O_3-crop (4) model, and from 0.826–0.929%, 0.832–0.915%, 0.853–0.989% and 0.836–0.899%, respectively for the O_3-crop model (5). Similarly, Tan Chau and Tan Bien districts have the highest maize RYL levels in the entire study area at 1.338–2.081% and 1.260–2.023%, respectively; meanwhile, the lowest maize RYL levels occurred in Chau Thanh, Hoa Thanh, Go Dau, and Ben Cau districts of Tay Ninh province with values of 1.163–1.308%, 1.170–1.288%, 1.200–1.392%, and 1.176–1.266%, respectively.

3.3. CPL and TEL in Tay Ninh province attributed to surface O_3 pollution

Detailed statistics of CPL (tons) and ECL (thousand USD) results by administrative unit under Tay Ninh province are presented in Table 4. Because of the relatively large difference in crop production (including rice and maize) between localities in Tay Ninh province, the distribution of CPLs is not completely in the same trend as the distribution of RYL and RYL. The localities with large CPLs are mainly concentrated in the central and southern areas of Tay Ninh province. For rice, the total CPL of Spring rice in 2018 in Tay Ninh province ranges from 2.34 to 27.98 thousand tons and the equivalent total economic loss (ECL) can be up to from 15.20 to 181.98 billion VND (about 672.35–8,051.28 thousand USD). It could be found that Chau Thanh and Trang Bang districts have the highest CPL of Spring rice in the province with 670.91–7,808.80 tons and 606.65–7,442.30 tons, respectively with an EPL equivalent of about 4.36–50.80 billion VND (about 193.0–2,247.37 thousand USD) and 3.95–48.41 billion VND (roughly 174.59–2,141.89 thousand USD). The lowest CPL level of Winter-Spring rice occurs in Tan Chau district of Tay Ninh province at merely from 6.31 to 107.64 tons and the total equivalent ECL is estimated about from 41.07 to 700.22 million VND (between 1.82 and 30.98 thousand USD).

Table 4. Summary of CPL (tons) and ECL (thousand USD) outcome details of major crops by each county in this study area.

District/ Town/ City	Spring rice (paddy)				Maize			
	CPL min	**CPL max**	**ECL min**	**ECL max**	**CPL min**	**CPL max**	**ECL min**	**ECL max**
Tay Ninh City	18.2	218.4	5.2	62.9	10.2	11.8	2.7	3.2
Tan Bien District	72.0	1,261.1	20.7	363.0	38.6	62.4	10.3	16.7
Tan Chau District	6.3	107.6	1.8	31.0	13.3	20.9	3.6	5.6
Duong Minh Chau District	41.9	542.4	12.1	156.1	52.0	64.2	13.9	17.2
Chau Thanh District	670.9	7,808.8	193.1	2,247.4	22.6	25.5	6.1	6.8
Hoa Thanh Town	53.5	608.0	15.4	175.0	5.5	6.1	1.5	1.6
Go Dau District	377.0	4,550.1	108.5	1,309.5	104.5	121.4	28.0	32.5
Ben Cau District	489.8	5,436.5	141.0	1,564.6	45.7	49.2	12.2	13.2
Trang Bang Town	606.7	7,442.3	174.6	2,141.9	47.0	55.4	12.6	14.8
Total	**2,336.2**	**27,975.3**	**672.4**	**8,051.3**	**339.6**	**416.9**	**90.9**	**111.6**

Similarly, for maize, the total CPL level of maize in Tay Ninh province ranges from 339.55 to 416.88 tons and the equivalent total economic loss cost can be up to 2.06–2.52 billion VND (about 90.93–111.64 thousand USD). Specifically, Go Dau district has the highest corn CPL level, up to 104.51–121.41 tons with an EPL equivalent of about 632.60–734.89 million VND (roughly 27.99–32.51 thousand USD), followed by Duong Minh Chau and Trang Bang, Ben Cau, and Tan Bien districts; whilst the lowest maize CPL occurs in Hoa Thanh district with a CPL of between 5.55 and 6.11 tons and an equivalent EPL at 33.58–37.01 million VND (about 1.486–1.637 thousand USD). Thus, from the estimated results, the total CPL level for 2 main crops in Tay Ninh province in the period from January 2018 to March 2018 can be up to 2.68–28.39 thousand tons and total economic losses (TEL) are estimated at 17.25–184.50 billion VND (equivalent to roughly 763.28–8,162.92 thousand USD). At the same time, it is also easy to see that the total CPL and TEL levels for Spring rice in 2018 are significantly higher than CPL and TEL for maize in Tay Ninh province, specifically from 6.88 to 67.11 times for CPL and from 7.39 to 72.12 times for TEL.

4. Conclusion

The ground-level O_3 pollution simulation results based on WRF/CMAQ model are used to estimate damage in agricultural production due to ground ozone (O_3) exposure for 2 major crops in the province. Tay Ninh, including rice and maize. The values of the cumulative exposure metric of AOT40 were determined for the crop seasons (Spring rice and maize) to calculate the damage caused by ground-level O_3 to crop yield and yield. Relative yield loss, RYL and crop yield loss, CPL for each administrative unit of Tay Ninh province for each crop due to ground-level O_3 exposure were estimated using multi-model O_3-crop to determine economic losses in the study area during the 2018 crop seasons. Total yield loss, CPL and total economic loss, TEL for Winter-Spring rice, respectively, are possible. up to 28 thousand tons and 182 billion VND (equivalent to about 8 million USD). In the case of maize, the total yield loss, CPL, and total economic loss, ECL could amount to 417 tons and 2.5 billion VND (roughly 112 thousand USD), respectively. The results of estimating damage because of ground-level O_3 exposure in Tay Ninh province in January, February, and March 2018 are the basis for initial judgments in the implementation of evaluation studies for the following stages as well as the implementation of policies to control ground-level O_3 pollution in Tay Ninh province and the whole Southeast region of Vietnam in general.

Nevertheless, the outcomes of this study also have certain limitations, and the research will continue to be developed to comprehensively demonstrate the impact of the ground-level O_3 problem on the activity of agricultural production in Tay Ninh province shortly. Specifically, the study will need to be extended to the remaining months (April to December) in 2018; furthermore, the effects on rice will be further calculated for the summer-autumn and winter rice crops, as well as extending the calculation to other crops such as sweet potatoes, cassava, and legumes.

Author contribution statement: Conceived and designed the experiments; Analyzed and interpreted the data; contributed reagents, materials, analysis tools or data: L.T.T.L.; Performed the experiments; contributed reagents, materials, analyzed and interpreted the data, wrote the draft manuscript: N.H.P.; and Manuscript editing: B.T.L.

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References

1. Betzelberger, A.M.; Yendrek, C.R.; Sun, J.; Leisner, C.P.; Nelson, R.L.; Ort, D.R. Ainsworth, E.A. Ozone exposure response for U.S. soybean cultivars: Linear reductions in photosynthetic potential, biomass, and yield. *Plant Physiol.* **2012**, *160(4)*, 1827–1839.
2. Feng, Z.; Hu, E.; Wang, X.; Jiang, L.; Liu, X. Ground-level O_3 pollution and its impacts on food crops in China: A review. *Environ. Pollut.* **2015**, *199*, 42–48.

3. Mills, G.; Sharps, K.; Simpson, D.; Pleijel, H.; Broberg, M.; Uddling, J.; Jaramillo, F.; Davies, W.J.; Dentener, F.; den Berg, M.V.; Agrawal, M.; Agrawal, S.B.; Ainsworth, E.A.; Büker, P.; Emberson, L.; Feng, Z.; Harmens, H.; Hayes, F.; Kobayashi, K.; Paoletti, E.; Dingenen, R.V. Ozone pollution will compromise efforts to increase global wheat production. *Glob. Chang. Biol.* **2018**, *24(8)*, 3560–3574.
4. Mills, G.; Buse, A.; Gimeno, B.; Bermejo, V.; Holland, M.; Emberson, L.; Pleijel, H. A synthesis of AOT40-based response functions and critical levels of ozone for agricultural and horticultural crops. *Atmos. Environ.* **2007**, *41(12)*, 2630–2643.
5. Monks, P.S.; Archibald, A.T.; Colette, A.; Cooper, O.; Coyle, M.; Derwent, R.; Fowler, D.; Granier, C.; Law, K.S.; Mills, G.E.; Stevenson, D.S.; Tarasova, O.; Thouret, V.; von Schneidemesser, E.; Sommariva, R.; Wild, O.; Williams, M.L. Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer. *Atmos. Chem. Phys.* **2015**, *15(15)*, 8889–8973.
6. Sitch, S.; Cox, P.M.; Collins, W.J.; Huntingford, C. Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. *Nature* **2007**, *448(7155)*, 791–794.
7. Verstraeten, W.W.; Neu, J.L.; Williams, J.E.; Bowman, K.W.; Worden, J.R.; Boersma, K.F. Rapid increases in tropospheric ozone production and export from China. *Nat. Geosci.* **2015**, *8(9)*, 690–695.
8. Lin, Y. et al. Impacts of O_3 on premature mortality and crop yield loss across China. *Atmos. Environ.* **2018**, *194*, 41–47.
9. Amin, N.; Ken, Y.; Toshimasa, O.; Junichi, K.; Kazuyo, Y. Evaluation of the effect of surface ozone on main crops in East Asia: 2000, 2005, and 2020. *Water. Air. Soil Pollut.* **2013**, *224(5)*.
10. Tang, H.; Takigawa, M.; Liu, G.; Zhu, J.; Kobayashi, K. A projection of ozone-induced wheat production loss in China and India for the years 2000 and 2020 with exposure-based and flux-based approaches. *Glob. Chang. Biol.* **2013**, *19(9)*, 2739–2752.
11. Cao, J.; Wang, X.; Zhao, H.; Ma, M.; Chang, M. Evaluating the effects of ground-level O_3 on rice yield and economic losses in Southern China. *Environ. Pollut.* **2020**, *267*, 115694.
12. Lesser, V.M.; Rawlings, J.O.; Spruill, S.E.; Somerville, M.C. Ozone Effects on Agricultural Crops: Statistical Methodologies and Estimated Dose-Response Relationships. *Crop Sci.* **1990**, *30(1)*, 148–155.
13. Fuhrer, J.; Skärby, L.; Ashmore, M.R. Critical levels for ozone effects on vegetation in Europe. *Environ. Pollut.* **1997**, *97(1)*, 91–106.
14. Wang, X.; Zhang, Q.; Zheng, F.; Zhen, Q.; Yao, F.; Chen, Z.; Zhang, W.; Hou, P.; Feng, Z.; Song, W.; Feng, Z.; Lu, F. Effects of elevated O_3 concentration on winter wheat and rice yields in the Yangtze River Delta, China. *Environ. Pollut.* **2012**, *171*, 118–125.
15. Shi, G.; Yang, L.; Wang, Y.; Kobayashi, K.; Zhu, J.; Tang, H.; Pan, S.; Chen, T.; Liu, G.; Wang, Y. Impact of elevated ozone concentration on yield of four Chinese rice cultivars under fully open-air field conditions. *Agric. Ecosyst. Environ.* **2009**, *131(3)*, 178–184.
16. Zhu, X.; Feng, Z.; Sun, T.; Liu, X.; Tang, H.; Zhu, J.; Guo, W.; Kobayashi, K. Effects of elevated ozone concentration on yield of four Chinese cultivars of winter wheat under fully open-air field conditions. *Glob. Chang. Biol.* **2011**, *17(8)*, 2697–2706.
17. Sinha, B.; Singh Sangwan, K.; Maurya, Y.; Kumar, V.; Sarkar, C.; Chandra, B.P.; Sinha, V. Assessment of crop yield losses in Punjab and Haryana using 2 years of continuous in situ ozone measurements. *Atmos. Chem. Phys.* **2015**, *15(16)*, 9555–9576.
18. Nguyen, G.T.H.; Shimadera, H.; Uranishi, K.; Matsuo, T.; Kondo, A.; Thepanondh,

S. Numerical assessment of $PM_{2.5}$ and O_3 air quality in continental Southeast Asia: Baseline simulation and aerosol direct effects investigation. *Atmos. Environ.* **2019**, *219*, 117054.

19. Daly, A.; Zannetti, P. Air Pollution Modeling - An Overview. 2007.
20. Stevenson, D.S.; Dentener, F.J.; Schultz, M.G.; Ellingsen, K.; van Noije, T.P.C.; Wild, O.; Zeng, G.; Amann, M.; Atherton, C.S.; Bell, N.; Bergmann, D.J.; Bey, I.; Butler, T.; Cofala, J.; Collins, W.J.; Derwent, R.G.; Doherty, R.M.; Drevet, J.; Eskes, H.J.; Fiore, A.M.; Gauss, M.; Hauglustaine, D.A.; Horowitz, L.W.; Isaksen, I.S.A.; Krol, M.C.; Lamarque, J.F.; Lawrence, M.G.; Montanaro, V.; Müller, J.F.; Pitari, G.; Prather, M.J.; Pyle, J.A.; Rast, S.; Rodriguez, J.M.; Sanderson, M.G.; Savage, N.H.; Shindell, D.T.; Strahan, S.E.; Sudo, K.; Szopa, S. Multimodel ensemble simulations of present-day and near-future tropospheric ozone. *J. Geophys. Res. Atmos.* **2006**, *111(D8)*.
21. Sicard, P.; Serra, R.; Rossello, P. Spatiotemporal trends in ground-level ozone concentrations and metrics in France over the time period 1999-2012. *Environ. Res.* **2016**, *149*, 122–144.
22. Statistical Office of Tay Ninh Province. Statistical Yearbook of Tay Ninh Province in 2020, Tay Ninh City, 2021.
23. DARD of Tay Ninh Province. Report on the assessment of the implementation of the first 9 months of 2018 and the key tasks of the last 3 months of 2018 of the Agriculture and Rural Development sector. Tay Ninh City, 2018.
24. Van Dingenen, R.; Dentener, F.J.; Raes, F.; Krol, M.C.; Emberson, L.; Cofala, J. The global impact of ozone on agricultural crop yields under current and future air quality legislation. *Atmos. Environ.* **2009**, *43(3)*, 604–618.
25. Lefohn, A.S.; Laurence, J.A.; Kohut, R.J. A comparison of indices that describe the relationship between exposure to ozone and reduction in the yield of agricultural crops. *Atmos. Environ.* **1988**, *22(6)*, 1229–1240.
26. Emberson, L.D.; Büker, P.; Ashmore, M.R.; Mills, G.; Jackson, L.S.; Atikuzzaman, A.M.; M.D.; Cinderby, S.; Engardt, M.; Jamir, C.; Kobayashi, K.; Oanh, N.T.K.; Quadir, Q.F.; Wahid, A. A comparison of North American and Asian exposure-response data for ozone effects on crop yields. *Atmos. Environ.* **2009**, *43(12)*, 1945–1953.
27. Hu, T.; Liu, S.; Xu, Y.; Feng, Z.; Calatayud V. Assessment of O_3-induced yield and economic losses for wheat in the North China Plain from 2014 to 2017, China. *Environ. Pollut.* **2020**, *258*, 113828.
28. Kumari, S.; Lakhani, A.; Kumari, K.M. First observation-based study on surface O_3 trend in Indo-Gangetic Plain: Assessment of its impact on crop yield. *Chemosphere* **2020**, *255*, 126972
29. Avnery, S.; Mauzerall, D.L.; Liu, J.; Horowitz, L.W. Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage. *Atmos. Environ.* **2011**, *45(13)*, 2284–2296.
30. Dong, C.; Gao, R.; Zhang, X.; Li, H.; Wang, W.; Xue, L. Assessment of O_3-induced crop yield losses in northern China during 2013–2018 using high-resolution air quality reanalysis data. *Atmos. Environ.* **2021**, *259*, 118527.
31. Feng, Z.; Hu, T.; Tai, A.P.K.; Calatayud, V. Yield and economic losses in maize caused by ambient ozone in the North China Plain (2014–2017). *Sci. Total Environ.* **2020**, *722*, 137958.
32. Luecken, D.J.; Yarwood, G.; Hutzell, W.T. Multipollutant modeling of ozone, reactive nitrogen and HAPs across the continental US with CMAQ-CB6. *Atmos. Environ.* **2019**, *201*, 62–72.
33. Ring, A.M.; Canty, T.P.; Anderson, D.C.; Vinciguera, T.P.; He, H.; Goldberg, D.L.;

Ehrman, S.H.; Dickerson, R.R.; Salawitch, R.J. Evaluating commercial marine emissions and their role in air quality policy using observations and the CMAQ model. *Atmos. Environ.* **2018**, *173*, 96–107.

34. Phong, N.H.; Ha, D.T.T.; Duyen, N.C.M.; Long, B.T. Assessment Ground Ozone (O_3) Impacts on Agricultural Crop Yields in Mekong Delta, Vietnam. Proceeding of the International Forum on Green Technology and Management 2021 - Green Pathways Towards a Sustainable Future, 2021, pp. 37.
35. Bui, L.T.; Nguyen, P.H. Ground - level ozone in the Mekong Delta region : precursors , meteorological factors , and regional transport. *Environ. Sci. Pollut. Res.* **2022**, *30*, 23691–23713.
36. Pang, J.; Kobayashi, K.; Zhu, J. Yield and photosynthetic characteristics of flag leaves in Chinese rice (Oryza sativa L.) varieties subjected to free-air release of ozone. *Agric. Ecosyst. Environ.* **2009**, *132(3)*, 203–211.
37. Feng, Z.W.; Jin, M.H.; Zhang, F.Z.; Huang, Y.Z. Effects of ground-level ozone (O_3) pollution on the yields of rice and winter wheat in the Yangtze River Delta. *J. Environ. Sci. (China).* **2003**, *15(3)*, 360–362.
38. Xu, M.; Yao, Q.; Chen, D.; Li, M.; Li, R.; Gao, B.; Zhao, B.; Chen, Z. Estimating the impact of ground ozone concentrations on crop yields across China from 2014 to 2018: A multi-model comparison. *Environ. Pollut.* **2021**, *283*, 117099.
39. Peng, J.; Shang, B.; Xu, Y.; Feng, Z.; Pleijel, H.; Calatayud, V. Ozone exposure- and flux-yield response relationships for maize. *Environ. Pollut.* **2019**, *252*, 1–7.
40. Zhao, H.; Zheng, Y.; Wu, X. Assessment of yield and economic losses for wheat and rice due to ground-level O_3 exposure in the Yangtze River Delta, China. *Atmos. Environ.* **2018**, *191*, 241–248.
41. Statistical Office of Tay Ninh Province. Statistical Yearbook of Tay Ninh Province in 2019. Tay Ninh City, 2020.
42. GSO. National Statistical Yearbook 2019. Statistical Publishing House, Vietnam, Ha Noi Capital, 2019.
43. GSO. National Statistical Yearbook 2020. Statistical Publishing House, Vietnam, Ha Noi Capital, 2020.