Lee *et al.*
Asian Journal of Atmospheric Environment (2023) 17:21
https://doi.org/10.1007/s44273-023-00021-w

Asian Journal of
Atmospheric Environment

RESEARCH ARTICLE

Open Access

Long-term changes of rice yield loss estimated with AOT40 and M7 metrics using comprehensive ozone and rice cultivation data over South Korea

Jimin Lee[1], Jin-seok Han[2], Jinsu Park[3*], Joon-Yeong Ahn[3] and Gangwoong Lee[1*]

Abstract

This study examines the change in rice yield due to ozone exposure in South Korea using extended air quality monitoring data from 2000 onwards. Notably, the maximum daily 8-h average O_3 (MDA8O3) showed a substantial annual increase of 1 part per billion by volume (ppbv) from 1990 to 2021. AOT40 (accumulated dose of ozone over a threshold of 40 ppb) levels exceeded set thresholds in the early 2010s, and the M7 (mean 7-h ozone mixing ratio) index exhibited a parallel pattern, with a more pronounced increase than the AOT40 during the same period. Spatial variations of AOT40 and M7 metrics have been assessed annually across South Korea since 2000. Both metrics displayed spatial disparities, with higher values in western regions and lower values in the east. In particular, Dangjin and Seosan counties in Chungnam province experienced the greatest rice yield loss due to extensive rice cultivation area and high ozone exposure metrics. The quantified yield loss due to AOT40 increased from 127,000 in 2000 to 230,000 tonnes in 2021 with an increasing rate of 6500 tonnes per year. M7 indicated a rise in yield loss of 3500 tonnes per year, with yield losses growing from 32,000 in 2000 to 92,000 tonnes in 2021. Despite M7's lower loss, it demonstrated a higher percentage increase of 188% over two decades, which was double AOT40's 81%. While the decline in rice production was mainly linked to shrinking cultivation areas, its productivity was improved. Taking both factors into account, there was an unexplained 3% decrease in production over the same period. This discrepancy was close to the 2.5% rice yield loss attributed to the AOT40 metrics, suggesting that the majority of the additional 3% decline in production, surpassing improvements in productivity, could be attributed to the impacts of ozone exposure. We estimated the annual economic loss due to rice yield loss up to around 0.6 billion US dollars, corresponding to an annual rice production loss of 230,000 tonnes using AOT40. It is important to note that this value is expected to steadily worsen as ozone levels increase. This underscores the urgency of taking swift measures to reduce ozone levels, aiming not only to mitigate future economic losses but also to prevent potential health implications.

Keywords Ozone, AOT40, M7, Rice yields, Yield loss

---

*Correspondence:
Jinsu Park
airchemi@korea.kr
Gangwoong Lee
gwlee@hufs.ac.kr
Full list of author information is available at the end of the article

1 Introduction

Tropospheric or ground-level ozone is mainly produced by photochemical oxidation processes of volatile organic compounds (VOCs) with nitrogen oxides (NOx) (Jacob, 2000; Monks et al., 2015). Ozone is a reactive oxidizing reagent and also an important precursor for highly reactive radical species, such as OH and NO_3 radicals. Ozone's oxidizing capacity along with its abundant and ubiquitous presence is a positive aspect of the removal of various air pollutants in the troposphere (Lee et al., 2020). However, due to its strong oxidizing potential, it has also numerous adverse effects on human and vegetation health (Agathokleous et al., 2018; Fleming et al., 2018; Mills et al., 2018). Ozone can cause significant damage to sensitive cells of agricultural crops and plants even with as low as 40 ppbv, which in turn decreases disease tolerance, growth rates, and other essential plant functions. Ozone can permeate to plant leaves through stomata and oxidize the plant tissues disrupting gene expression, photosynthesis, and key metabolism related to protein and chlorophyll production (Fuhrer et al., 1997).

Several metrics for ozone exposure to assess vegetation damages have been developed, including AOT40, M7/M12, W126, and SUM06. Using these metrics, global risks to crops and forests have been assessed for up to 3–16% of crop loss and 11% of forest biomass (Emberson, 2020). The ozone impact analyses on crops have primarily concentrated on four major crops, namely wheat, maize, rice, and soybean (Feng et al., 2022; Li et al., 2022). Avnery et al. (2011) conducted an investigation and projected that global crop losses associated with ozone exposure are anticipated to vary between 4% and 15% for wheat, 9% and 14% for soybean, and 2% to 6% for maize. Furthermore, Tai et al. (2021) determined the current global aggregated crop yield losses to be: 3.6 ± 1.1% for maize, 2.6 ± 0.8% for rice, 6.7 ± 4.1% for soybean, and 7.2 ± 7.3% for wheat. Because rice is a major crop in Asia, the assessment of ozone-induced yield loss in rice has predominantly been conducted in Asia. The rice yield loss by ozone pollution varied widely from 0.04 % up to 15.9% (Debaje, 2014; Qi et al., 2023; Ta Bui & Nguyen, 2023; Tatsumi, 2022; Wang & Mauzerall, 2004).

Although the current background ozone has increased by a factor of 2 until the 1990s and been somewhat stabilized later in Europe, ozone in Asia, particularly in East Asia, continues to grow with the steepest trends and confidence level (Cooper et al., 2014; Marenco et al., 1994). Many studies reported that surface ozone continued to grow at a rate of 2–3% per year or 0.4–0.6 ppbv per year in Korea since the 1990s (Kim et al., 2018; Seo et al., 2014; Shin et al., 2017). This steady increase in ozone was largely attributed to emission reduction of local NOx emission and elevation of regional ozone background concentration (Jaedong, 2018; Nagashima et al., 2010; Tanimoto et al., 2005; Wang et al., 2022). Recently, a new reduction plan for NOx emission has been set to control PM in Korea (KMOE, 2020) and rapid increases in surface ozone have been observed throughout China since the last decade (Lu et al., 2020). Based on these two facts, we anticipate a further increase in surface ozone in Korea.

In Korea, the ozone impact on rice grain yield has remained a persistent concern, prompting scientific investigations over an extended period of time. A study conducted in 2000 indicated that a 20% reduction in ozone concentration resulted in a 7% increase in rice production (Park et al., 2004). In a recent study, it was estimated that rice cultivation in South Korea experienced a relative yield loss of 10.7% (Feng et al., 2022). These observations highlighted the potential impact of ozone levels on rice productivity and underscored the importance of understanding and mitigating such effects in South Korea. However, previous studies have primarily relied on national and provincial-level statistics, potentially overlooking the intricate spatial differences in rice cultivation areas and ozone concentrations at the county level.

In this study, we examined long-term changes in rice yield loss due to the surface ozone increase spanning the last two decades, from 2000 onwards. This analysis incorporated observed ozone concentrations densely populated across the nation, alongside comprehensive statistical data encompassing rice cultivation areas and yields for each county level. Additionally, we discussed the spatial variations of county-level rice yield loss for the year 2021, in conjunction with two ozone metrics, AOT40 and M7 that are the most preferred indices for rice production.

2 Method

Ozone has been monitored on an hourly average basis at 536 air quality monitoring stations as of 2021 in South Korea, which are classified into 4 major types 476 urban, 38 roadside, 16 rural sites, and 6 background sites (Fig. 1).

We computed two common ozone exposure metrics (AOT40 and M7) for every station by utilizing the 1-h ozone data recorded in South Korea since the year 2000. These ozone indices are defined as where $[O_3]$ is the hourly mean O_3 concentration in ppmv.

$$AOT40 = \sum ([O_3] - 0.04) \quad (1)$$

$$M7 = \frac{1}{n} \sum\nolimits_i^n 1000[O_3]_i \quad (2)$$

AOT40 defined in Eq. 1 is a cumulative exposure index in units of ppm-h with hourly ozone concentrations above 0.04 ppmv between local hours of 08:00 and

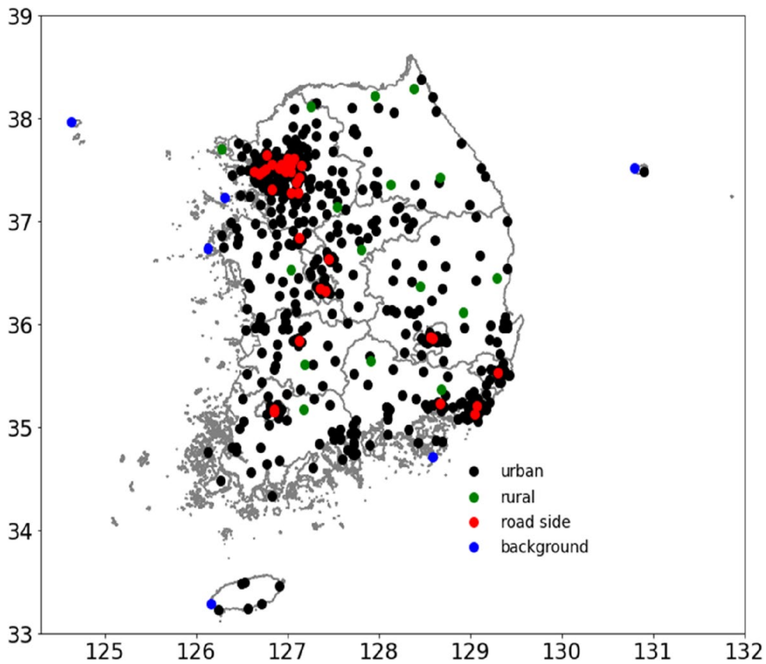

Fig. 1 Locations of the 536 air quality monitoring stations operating in South Korea in 2021 (Song and Lee. 2022)

20:00 in the months of growth season (May, June, and July) (Fuhrer et al., 1997; Mills et al., 2007). M7 in Eq. 2 is a mean exposure index in units of ppbv with hourly mean ozone concentrations with *n* total hours between local times of 09:00 and 16:00 for the same growing months (Hogsett et al., 1988). Using these exposure metrics and concentration-relative yield functions, local rice yield losses can be estimated. Relative yield (RY) is defined as the ratio between the yield affected by observed O_3 exposure and the unaffected yield under conditions of zero O_3 exposure. Relative yields of rice for AOT40 and M7 ozone exposure metrics were calculated below (Adams et al., 1989; Mills et al., 2007; Van Dingenen et al., 2009).

$$RY_{AOT40} = 1 - 0.0415AOT40 \quad (3)$$

$$RY_{M7} = \exp\left[\left(-(M7/202)^{2.47}\right]/\exp\left[-(25/202)^{2.47}\right) \quad (4)$$

South Korea consists of over 500 monitoring stations, but they are mainly concentrated in urban areas. Due to these geographically sparse locations in rural areas, ozone measurements are not available in all administrative counties. To obtain ozone exposure metrics for all counties, the unknown values at counties without observations were interpolated according to proximity with existing monitoring data using the Ordinary Kriging spatial analysis technique.

To compute the loss in rice production resulting from ozone exposure using county-level RYs, it is necessary to find the rice production within each county. The Korea Statistical Information Service (KOSIS, 2023) provides public access to county-level annual cultivation areas and production data since 1965 for major crops in South Korea, including rice. Utilizing this information along with estimated RYs, we were able to analyze the long-term variations of spatially comprehensive rice yield loss in South Korea.

3 Results

3.1 Long-term trends of ozone

The air quality monitoring network's prolonged observations have unveiled a steady upward trend of ozone levels since 1990. Of particular note, the maximum daily 8-h average O_3 (MDA8O3) has exhibited a substantial and noteworthy rise, increasing at a rate of 1 part per billion by volume (ppbv) annually between 1990 and 2021, as depicted in Fig. 2A. It is worth noting that in the last two years, 2020 and 2021, there were sudden and significant decreases in ozone levels, especially at rural and background locations where NOx would act as a limiting factor for ozone production, probably due to the decreasing NOx emissions during the pandemic (Ju et al., 2021; Kim et al., 2022). A more detailed assessment of temporal characteristics of MDA8O3 reveals that its increase rate displayed remarkably fast until the year 2000, subsequently transitioning into a marginal

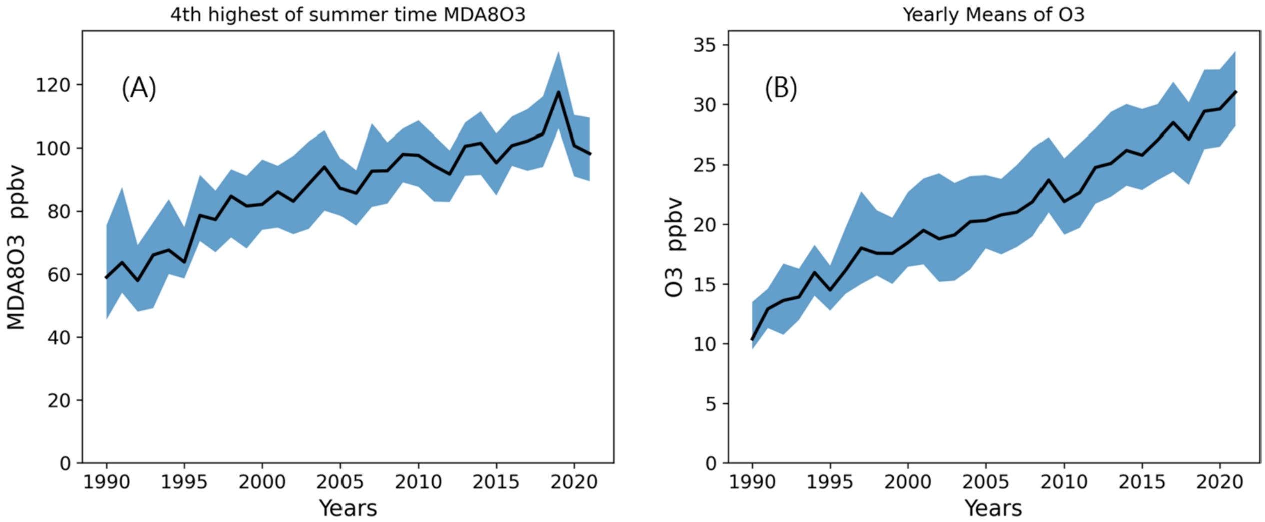

Fig. 2 Long-term variations of **A** maximum daily 8-h average O_3 (MDA8O3) and **B** yearly mean ozone concentrations in South Korea

rate until approximately 2010. Following this interval, a resumption of rapid upsurges in MDA8O3 became discernible, persisting until the last 2 years. Otherwise, the annual changes in the yearly mean ozone concentration, while characterized by a lower increase rate of 0.6 ppbv per year, demonstrate a more persistent pattern (Fig. 2B).

Several factors contribute to this rapid elevation of ozone levels in South Korea. However, the foremost driver behind the increase in ozone can be attributed to the consistent reduction of NOx emissions. Nitric oxide (NO) primarily engages in titrating the existing ozone, especially in urban areas. This diminishing effect of NO's interaction with ozone is intricately linked to the distinct upward trend in ozone concentrations. Other factors contributing to this ozone increase include slower reductions in volatile organic compound (VOC) emissions compared to NOx emissions, the influence of climate change, and rising ozone background by long-range transport (Jaedong, 2018).

3.2 Long-term trends of ozone exposure indices

In conjunction with the ever-increasing ozone concentrations, there also have been consistent upward trends in ozone exposure indices. The long-term trends of the AOT40 and M7 indices in South Korea over the last three decades are depicted in Fig. 3. Among crops, rice exhibits moderately sensitive to ozone with a critical limit of AOT40 12.8 ppm•h (Mills et al., 2007). AOT40 exceeded this threshold in the early 2010s and has been steadily increasing except for the last 2 years influenced by the pandemic.

In general, M7 exhibited a comparable long-term pattern to AOT40. However, the magnitude of its rise from the initial 10 ppbv value in 1990 to the recent 50 ppbv level was more significant than that of AOT40, which varied from 0 ppm•h to 15 ppm•h over the same period. Both metrics show sharp increases to the early 2000s, followed by slowdowns in growth through the late 2000s and then rapid increases again after 2010, which are quite similar to the long-term variation of MDA8O3; otherwise, yearly mean ozone increases monotonously.

3.3 Spatial variations of ozone exposure indices

This study has undertaken an assessment of the annual spatial variations of AOT40 and M7 across South Korea, commencing from the year 2000. Figure 4 illustrates the nationwide variations of these ozone metrics specifically for the year 2021. Notably, both ozone metrics demonstrated substantial spatial variances, displaying elevated values in the western regions overall. The maximum value was found in Dangjin City, an area characterized by extensive industry complexes and coal power plants. The regions surrounding major metropolitan areas, with the exception of Busan, predominantly revealed the high ozone metrics. It is noteworthy that Sangju City, centrally located in South Korea, displayed very high ozone exposure metrics in comparison to its surrounding areas. Sangju City is an elevated basin surrounded by the slopes of the Taebaek Mountains, and its insolation and temperature are higher than the surrounding areas, making it a favorable area for higher ozone production. Across nearly all regions, the two indices exhibited a similar trend. However, in Hapcheon-gun, the M7 index notably surpassed those of the neighboring areas, while its AOT40 value remained comparable to the surrounding regions. This generally indicates that shorter and

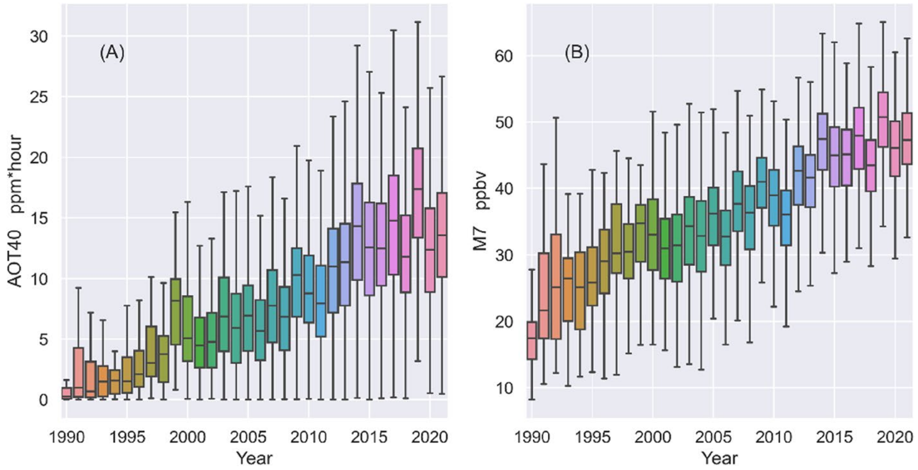

Fig. 3 Box-and-whisker plots for **A** the AOT40 and **B** M7 indices in South Korea over the past thirty years illustrate various parameters, including the yearly minimum value (− 1.5 interquartile range (IQR)), first quartile, median, third quartile, and maximum (+ 1.5 IQR)

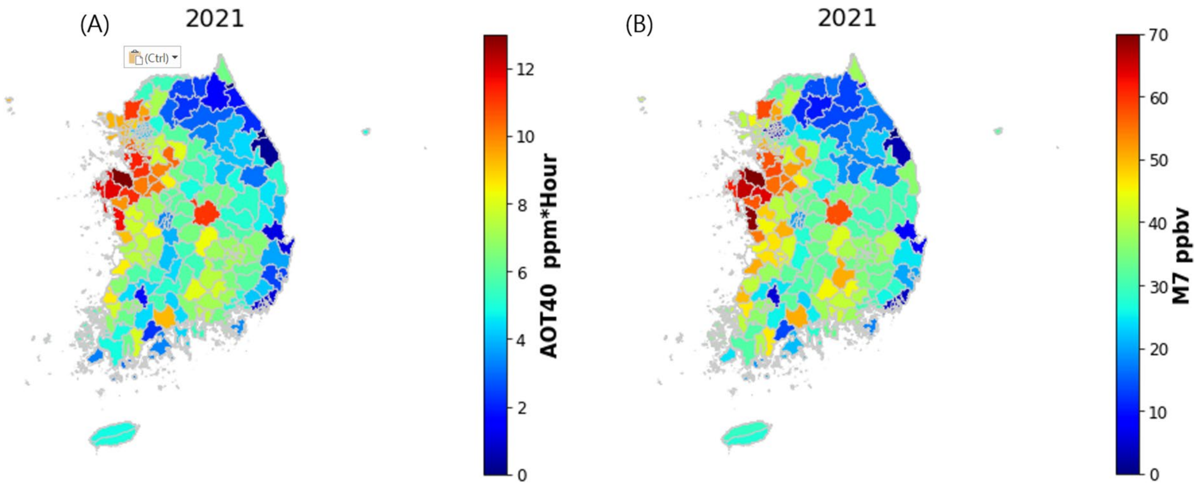

Fig. 4 The spatial distributions of **A** AOT40 and **B** M7 across the South Korea in 2021

high-concentration ozone events contributed significantly to the overall ozone exposure, leading to a higher M7 value compared to AOT40 in Hapcheon-gun.

3.4 Rice cultivation statistics

Virtually all rice cultivation in South Korea (99.9%) is carried out through the paddy farming practice. In 2021, the farming area for rice cultivation within the country has seen a decline of 31.7% in comparison to the year 2000 (Table 1). This decline has been mainly resulted from the decrease in rice consumption and the growing preference for imported non-rice grains. Nevertheless, it is important to note that the overall rice production has decreased by only 26.7% over the past two decades, due to the concurrent increase in rice production yield. The increase in rice production yield in South Korea can be attributed to several factors, including technological advancements in agricultural practice and changing climate conditions on rice cultivation. Kim et al. (2019) identified the monthly mean temperature as the most important variable to determine the changes in annual rice yields in South Korea. According recent study, the peak rice production yield is further projected to be about a 4–5% increase in most rice cultivation areas, but to a slight decrease in the southeastern coastal regions in the near future climate in South Korea (Ahn et al., 2021).

Figure 5 depicts the spatial distribution of rice cultivation areas at the county level in 2021. The rice cultivation area has decreased rather uniformly across all counties throughout the country. Rice cultivation areas are primarily situated in the western and southern coastal regions (Jennam, Jeonbuk, Chungnam province) where low-lying flatlands are abundant in South Korea. These three provinces Jeonnam (789,650 tons), Chungnam (773,013 tons), and Jeonbuk (593,862 tons) produced the majority (55.6%) of the rice production in South Korea. The proportion of agricultural land dedicated to rice cultivation is notably greater in these regions, encompassing counties like Dangjin, Gimje, Iksan, and Muan. In other areas characterized by mountainous terrain or urban environments, the portion of rice cultivation area is relatively limited, except for several centrally located counties, including Sanju, Jaecheon, and Euisung (Fig. 5).

Table 1 Annual rice cultivation area, production, and yields (KOSIS, 2023)

Year	Rice cultivation area (ha)	Production (tonnes)	Rice paddy area (ha)	Yield (tonnes/ha)
2000	1,072,363	5,290,771	1,055,034	4.97
2001	1,083,125	5,514,796	1,055,750	5.16
2002	1,053,186	4,926,746	1,038,577	4.71
2003	1,016,030	4,451,135	1,001,519	4.41
2004	1,001,159	5,000,149	983,560	5.04
2005	979,717	4,768,368	966,838	4.90
2006	955,229	4,679,991	945,403	4.93
2007	950,250	4,407,743	942,223	4.66
2008	935,766	4,843,478	927,995	5.20
2009	924,471	4,916,080	917,990	5.34
2010	892,074	4,295,413	886,516	4.83
2011	853,823	4,224,019	850,798	4.96
2012	849,172	4,006,185	846,870	4.73
2013	832,625	4,230,011	831,355	5.08
2014	815,506	4,240,739	814,334	5.20
2015	799,344	4,326,915	797,957	5.42
2016	778,734	4,196,691	777,872	5.39
2017	754,713	3,972,468	754,339	5.27
2018	737,673	3,868,045	737,408	5.24
2019	729,814	3,744,450	729,585	5.13
2020	726,432	3,506,578	726,180	4.83
2021	732,477	3,881,601	732,070	5.30

3.5 County-level rice yield losses

The county-level RYs were calculated using Eqs. 3 and 4 in conjunction with two ozone exposure metrics. The corresponding yield losses were determined based on the county-level RYs and rice production data, as shown in Fig. 6. While there was a difference in the absolute values of yield losses by two metrics, they were distributed similarly geographically. The AOT40 and M7 regional distributions were comparable but a few differences were observed in some counties, as shown in Fig. 4. Nevertheless, these spatial disparities in yield losses between the two metrics reduced significantly, suggesting that, at the county level, the loss of crop yield was more closely connected to rice cultivation area (Fig. 5) than to ozone metrics (Fig. 4).

Counties with higher yield losses mainly located in the west coastal regions are the most visible feature. In South Korea, the counties of Dangjin and Seosan, located in Chungnam province, experienced the highest yield loss in AOT40 metrics, with above 5 kt and 3 kt per county in M7 metric,

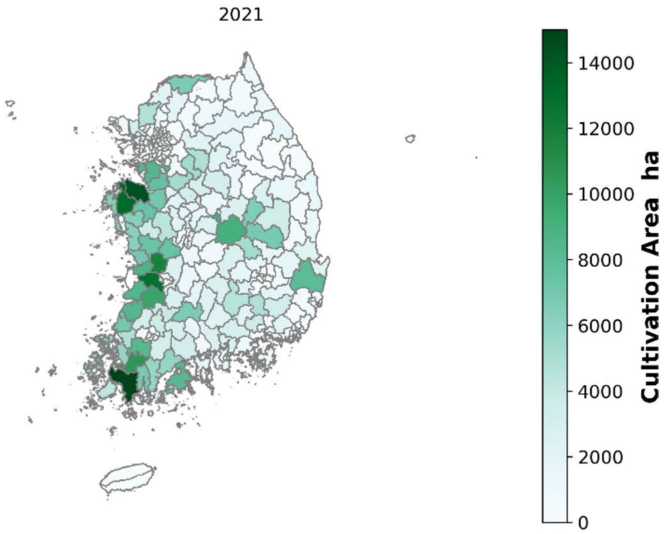

Fig. 5 Rice cultivation area at the county level in South Korea for the year 2021

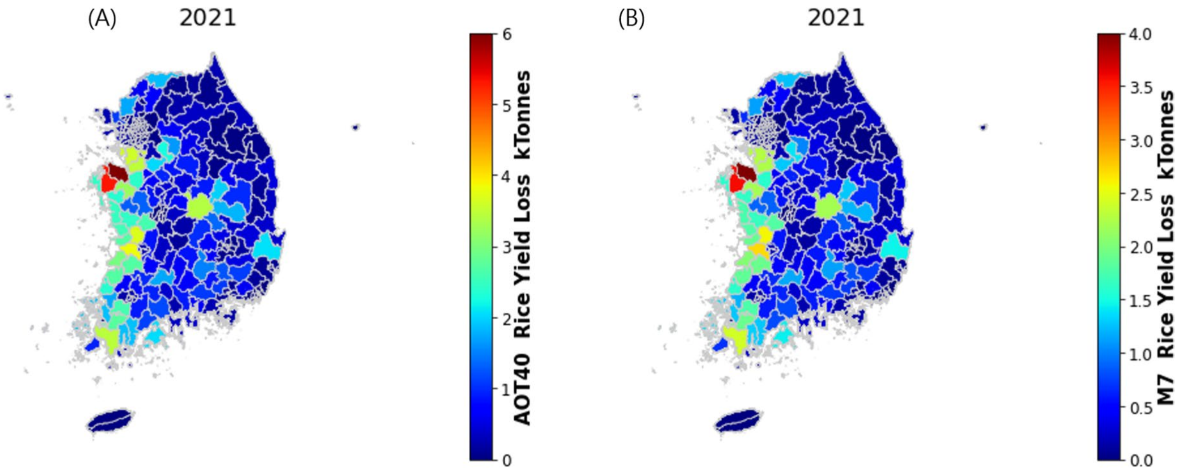

Fig. 6 Rice yield loss by **A** AOT40 and **B** M7 indices per county in kilo tonnes

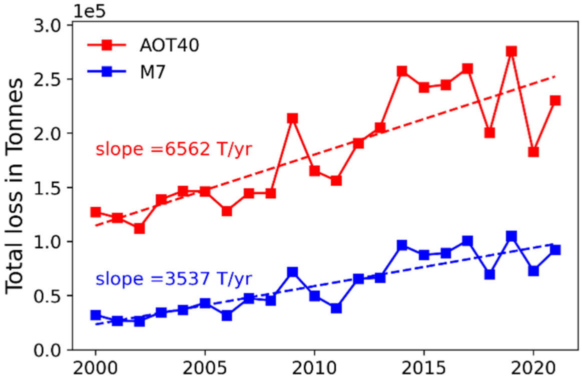

Fig. 7 Yearly changes of total rice yield loss (Tonnes) by **A** AOT40 and **B** M7 indices in South Korea

respectively. These areas are defined by extensive rice cultivation and high ozone exposure metrics. Sangju counties in the central inland regions exhibited higher-than-average levels of ozone concentrations and had large areas cultivated for rice production. Consequently, the loss of crop yield was more prominent in this area than in the surrounding regions. On the other hand, Jeju Island and other mountainous counties had almost no yield loss. This was because the area of rice grown on these counties island were negligible.

3.6 Long-term rice yield losses

The increase in ozone has led to higher exposure metrics and an associated rise in yield losses, as shown in Fig. 7. The amount of yield loss due to AOT40 has risen from 127,000 tonnes in 2000 to 230,000 tonnes in 2021. This meant that there was an annual rise of 6500 tonnes in the losses of rice yield. On the other hand, the M7 estimated a rate of 3500 tonnes per year, with a rise of yield loss from 32,000 tonnes in 2000 to 92,000 tonnes in 2021. Despite having only a third of the yield losses as compared to AOT40, M7 had a higher percentage increase of 188% over the last 20 years, which was two times greater than AOT40's 81% increase. The reason for this difference was that the growth rate of M7 yield loss was significantly higher than that of AOT40, and there were more frequent occurrences of high ozone episodes that happened over a relatively short period of time.

Rice production in South Korea has been steadily declining due to a decrease in rice cultivated areas. As noted above, rice area has declined by 31.7% over the past 20 years, while rice yields have declined by only 26.7% in South Korea. This relatively small decline in rice yield was due to an 8% increase in rice cultivation productivity over the same period. Accounting for this increase in agricultural productivity, the estimated decline in rice production ought to have been approximately 23.7%; however, the actual decline in rice production was 3% higher with 26.7%. The discrepancy is comparable to the 2.5% rice yield loss linked to the AOT40 metric during the same period, which implies that most of the further 3% drop was caused by ozone exposure effects, beyond the enhanced productivity. As a result, the AOT40 was found to be a closer index of the apparent decline in rice production in Korea than the M7, which accounted for a much smaller decline. However, this does not indicate that the AOT40 is a better indicator than the M7 in Korea without a comprehensive understanding of the dynamics of rice production, including local productivity changes with agricultural technology, weather, and plant diseases during the same period.

Production losses at AOT40 amount to 230,000 tonnes, or roughly 6% of the total yearly rice production. This value is notably smaller than the one that Feng et al. (2022) recently calculated, which resulted in a yield loss of 10%. The discrepancy is because Feng's study used an ozone threshold value of 19.4 ppbv, which is compared to 40 ppbv in this study. In our study, economic losses of rice production based on the AOT40 ozone metric are estimated amounting to about 0.6 billion US dollars, which is lower than the lower boundary of the previous study. It is worth noting that this value is expected to rise consistently with increasing ozone, and hence we should take steps to reduce ozone levels immediately to minimize further economic loss as well as human health.

4 Conclusion

Long-term observations from the extensive air quality monitoring network have shown a consistent upward trend in ozone levels since 1990. Of particular note was the significant increase in the maximum daily 8-h average O_3 (MDA8O3), which showed a remarkable annual increase of 1 part per billion by volume (ppbv) between 1990 and 2020. The AOT40 exceeded established thresholds in the early 2010s, and the M7 index showed a long-term pattern parallel to the AOT40, but its rate of increase was more pronounced than that of the AOT40 over the same period.

In this study, the annual spatial variations of both the AOT40 and the M7 metrics were rigorously examined across South Korea starting from the year 2000. Notably, both metrics exhibited considerable spatial disparities, with elevated values prevalent in the western regions and decreased values overall in the eastern regions. Counties with higher yield losses were predominantly located in the western coastal regions, a discernible pattern. Dangjin and Seosan counties in Chungnam Province emerged as the areas with the highest yield losses according to AOT40 and M7 metrics, mainly due to extensive rice cultivation and elevated ozone exposure metrics.

The quantification of yield losses due to AOT40 showed an increase from 127,000 tons in 2000 to 230,000 tons in 2021, representing an annual escalation of 6500 tons in rice yield losses. M7 showed an annual increase of 3500 tons, with yield losses escalating from 32,000 tons in 2000 to 92,000 tons in 2021. Despite the low yield loss compared to AOT40, M7 showed a higher percentage increase of 188% over the last two decades, twice the increase observed in AOT40 (81%). This discrepancy was due to the markedly faster growth rate of yield loss in M7, often associated with frequent occurrences of high ozone episodes within a relatively short period of time.

While the gradual decline in rice production is mainly related to the decrease in rice area, there has been a gradual improvement in productivity in South Korea over the past decades. Taking into account both the increase in productivity and the decrease in rice area, there was an unexplained 3% decrease in rice production over the same period. This discrepancy was consistent with the 2.5% rice yield loss attributed to the AOT40 metrics during the corresponding interval, suggesting that most of the additional 3% production decline, beyond productivity improvements, could be attributed to the effects of ozone exposure.

In this study, economic losses in rice production of 230,000 tons per year amounted to approximately US$0.6 billion. It is important to note that this value is expected to increase steadily as ozone levels rise. Therefore, there is an urgent need to take immediate action to reduce ozone levels in order to limit not only further economic losses but also the potential impact on human health.

Acknowledgements
This study was supported by research grants from the National Institute of Environmental Research, South Korea (NIER-2022-01-02-081) and the National Research Foundation of Korea (NRF) (Grant No. 2022R1A2C201017911).

Authors' contributions

Jimin Lee: visualization, writing—review and editing. Jin-seok Han: funding acquisition, resources. Joon-Yeong Ahn: data curation, conceptualization, validation. Jinsu Park: project administration, supervision. Gangwoong Lee: conceptualization, methodology, writing—original draft, review, and editing. All authors read and approved the final manuscript.

Availability of data and materials

The authors declare that the data supporting the findings of this study are available within the paper. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

Author details
[1]Department of Environmental Science, Hankuk University of Foreign Studies, Yongin, Republic of Korea. [2]Department of Environmental and Energy Engineering, Anyang University, Anyang, Republic of Korea. [3]Air Quality Research Division, Climate and Air Quality Research Department, National Institute of Environmental Research, Incheon, Republic of Korea.

Received: 30 August 2023 Accepted: 30 November 2023

References

Adams, R. M., Glyer, J. D., Johnson, S. L., & McCarl, B. A. (1989). A reassessment of the economic effects of ozone on U.S. agriculture. *JAPCA, 39*, 960–968. https://doi.org/10.1080/08940630.1989.10466583

Agathokleous, E., Kitao, M., & Kinose, Y. (2018). A review study on ozone phytotoxicity metrics for setting critical levels in Asia. *Asian Journal of Atmospheric Environment, 12*, 1–16. https://doi.org/10.5572/ajae.2018.12.1.001

Ahn, J.-B., Kim, Y.-H., Shim, K.-M., Suh, M.-S., Cha, D.-H., Lee, D.-K., Hong, S.-Y., Min, S.-K., Park, S.-C., & Kang, H.-S. (2021). Climatic yield potential of Japonica-type rice in the Korean Peninsula under RCP scenarios using the ensemble of multi-GCM and multi-RCM chains. *International Journal of Climatology, 41*, E1287–E1302. https://doi.org/10.1002/joc.6767

Avnery, S., Mauzerall, D. L., Liu, J., & Horowitz, L. W. (2011). Global crop yield reductions due to surface ozone exposure: 2. Year 2030 potential crop production losses and economic damage under two scenarios of O3 pollution. *Atmospheric Environment, 45*, 2297–2309. https://doi.org/10.1016/j.atmosenv.2011.01.002

Cooper, O. R., Parrish, D. D., Ziemke, J., Balashov, N. V., Cupeiro, M., Galbally, I. E., Gilge, S., Horowitz, L., Jensen, N. R., Lamarque, J. F., Naik, V., Oltmans,

S. J., Schwab, J., Shindell, D. T., Thompson, A. M., Thouret, V., Wang, Y., & Zbinden, R. M. (2014). Global distribution and trends of tropospheric ozone: An observation-based review. *Elementa, 2*, 1–28. https://doi.org/10.12952/journal.elementa.000029

Debaje, S. B. (2014). Estimated crop yield losses due to surface ozone exposure and economic damage in India. *Environmental Science and Pollution Research, 21*, 7329–7338. https://doi.org/10.1007/s11356-014-2657-6

Emberson, L. (2020). Effects of ozone on agriculture, forests and grasslands. *Philosophical Transactions of the Royal Society A - Mathematical Physical and Engineering Sciences, 378*, 20190327. https://doi.org/10.1098/rsta.2019.0327

Feng, Z., Xu, Y., Kobayashi, K., Dai, L., Zhang, T., Agathokleous, E., Calatayud, V., Paoletti, E., Mukherjee, A., Agrawal, M., Park, R. J., Oak, Y. J., & Yue, X. (2022). Ozone pollution threatens the production of major staple crops in East Asia. *Nature Food, 3*, 47–56. https://doi.org/10.1038/s43016-021-00422-6

Fleming, Z. L., Doherty, R. M., von Schneidemesser, E., Malley, C. S., Cooper, O. R., Pinto, J. P., Colette, A., Xu, X., Simpson, D., Schultz, M. G., Lefohn, A. S., Hamad, S., Moolla, R., Solberg, S., & Feng, Z. (2018). Tropospheric ozone assessment report: present-day ozone distribution and trends relevant to human health. *Elementa: Science of the Anthropocene, 6*. https://doi.org/10.1525/elementa.273

Fuhrer, J., Skärby, L., & Ashmore, M. R. (1997). Critical levels for ozone effects on vegetation in Europe. *Environmental Pollution, 97*, 91–106. https://doi.org/10.1016/S0269-7491(97)00067-5

Hogsett, W. E., Tingey, D. T., & Lee, E. H. (1988). Ozone exposure indices: concepts for development and evaluation of their use. In W. Heck (Ed.), *Assessment of Crop Loss From Air Pollutants*. Elsevier. Elsevier Applied Science.

Jacob, D. J. (2000). Heterogeneous chemistry and tropospheric ozone. *Atmospheric Environment, 34*, 2131–2159. https://doi.org/10.1016/S1352-2310(99)00462-8

Jaedong. (2018). Trend of air quality in Seoul: Policy and science. *Aerosol and Air Quality Research, 18*, 2141–2156. https://doi.org/10.4209/aaqr.2018.03.0081

Ju, M. J., Oh, J., & Choi, Y. H. (2021). Changes in air pollution levels after COVID-19 outbreak in Korea. *The Science of the Total Environment, 750*, 141521. https://doi.org/10.1016/j.scitotenv.2020.141521

Kim, J., Lee, J., Sang, W., Shin, P., Cho, H., & Seo, M. (2019). Rice yield prediction in South Korea by using random forest. *Korean Journal of Agricultural and Forest Meteorology, 21*, 75–84.

Kim, J., Ghim, Y. S., Han, J.-S., Park, S.-M., Shin, H.-J., Lee, S.-B., Kim, J., & Lee, G. (2018). Long-term trend analysis of korean air quality and its implication to current air quality policy on ozone and PM10. *Journal of Korean Society of Atmospheric Environment*. https://doi.org/10.5572/KOSAE.2018.34.1.001

Kim, S.-W., Kim, K.-M., Jeong, Y., Seo, S., Park, Y., & Kim, J. (2023). Changes in surface ozone in South Korea on diurnal to decadal timescales for the period of 2001–2021. *Atmos Chem Phys*, 23, 12867–12886. https://doi.org/10.5194/acp-23-12867-2023

KMOE. (2020). *The study for basic plan for regional air quality management*. Ministry of Environment.

KOSIS, 2023. Korean Statistical Information Service(KOSIS) [WWW Document]. 2023. https://kosis.kr/index/index.do. Accessed 1 June 2023

Lee, G., Park, J. H., Kim, D. G., Koh, M. S., Lee, M., Han, J. S., & Kim, J. C. (2020). Current Status and Future Directions of Tropospheric Photochemical Ozone Studies in Korea. *Journal of Korean Society of Atmospheric Environment, 36*, 419–441. https://doi.org/10.5572/KOSAE.2020.36.4.419

Li, D., Shindell, D., Ding, D., Lu, X., Zhang, L., & Zhang, Y. (2022). Surface ozone impacts on major crop production in China from 2010 to 2017. *Atmospheric Chemistry and Physics, 22*, 2625–2638. https://doi.org/10.5194/acp-22-2625-2022

Lu, X., Zhang, L., Wang, X., Gao, M., Li, K., Zhang, Y., Yue, X., & Zhang, Y. (2020). Rapid increases in warm-season surface ozone and resulting health impact in China since 2013. *Environmental Science & Technology Letters, 7*, 240–247. https://doi.org/10.1021/acs.estlett.0c00171

Marenco, A., Gouget, H., Nédélec, P., Pagés, J.-P., & Karcher, F. (1994). Evidence of a long-term increase in tropospheric ozone from Pic du Midi data series: Consequences: Positive radiative forcing. *Journal of Geophysical Research – Atmospheres, 99*, 16617–16632. https://doi.org/10.1029/94JD00021

Mills, G., Buse, A., Gimeno, B., Bermejo, V., Holland, M., Emberson, L., & Pleijel, H. (2007). A synthesis of AOT40-based response functions and critical levels of ozone for agricultural and horticultural crops. *Atmospheric Environment, 41*, 2630–2643. https://doi.org/10.1016/j.atmosenv.2006.11.016

Mills, G., Pleijel, H., Malley, C. S., Sinha, B., Cooper, O. R., Schultz, M. G., Neufeld, H. S., Simpson, D., Sharps, K., Feng, Z., Gerosa, G., Harmens, H., Kobayashi, K., Saxena, P., Paoletti, E., Sinha, V., & Xu, X. (2018). Tropospheric Ozone Assessment Report: Present-day tropospheric ozone distribution and trends relevant to vegetation. *Elementa: Science of the Anthropocene, 6*. https://doi.org/10.1525/elementa.302

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. (2015). Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer. *Atmospheric Chemistry and Physics, 15*, 8889–8973. https://doi.org/10.5194/acp-15-8889-2015

Nagashima, T., Ohara, T., Sudo, K., & Akimoto, H. (2010). The relative importance of various source regions on East Asian surface ozone. *Atmospheric Chemistry and Physics Discussions, 10*, 9077–9120. https://doi.org/10.5194/acpd-10-9077-2010

Park, Y., Lee, Y., & Cho, Y. (2004). Estimating social benefits of reduced ozone air pollution : focused on rice yield TT - estimating social benefits of reduced ozone air pollution : Focused on Rice Yield. *Korean Journal of Agricultural Management and Policy, 31*, 143–164.

Qi, Q., Wang, S., Zhao, H., Kota, S. H., & Zhang, H. (2023). Rice yield losses due to O3 pollution in China from 2013 to 2020 based on the WRF-CMAQ model. *Journal of Cleaner Production, 401*, 136801. https://doi.org/10.1016/j.jclepro.2023.136801

Seo, J., Youn, D., Kim, J. Y., & Lee, H. (2014). Extensive spatiotemporal analyses of surface ozone and related meteorological variables in South Korea for the period 1999-2010. *Atmospheric Chemistry and Physics, 14*, 6395–6415. https://doi.org/10.5194/acp-14-6395-2014

Shin, H. J., Park, J. H., Park, J. S., Song, I. H., Park, S. M., Roh, S. A., Son, J. S., & Hong, Y. D. (2017). The long term trends of tropospheric ozone in major regions in Korea. *Asian Journal of Atmospheric Environment, 11*, 235–253. https://doi.org/10.5572/ajae.2017.11.4.235

Song, CK., Lee, G. (2022). Regional and Urban Air Quality in East Asia: South Korea. In: Akimoto, H., Tanimoto, H. (Eds.), *Handbook of Air Quality and Climate Change*. Springer, Singapore. https://doi.org/10.1007/978-981-15-2527-8_70-1

Ta Bui, L., & Nguyen, P. H. (2023). Assessment of rice yield and economic losses caused by ground-level O(3) exposure in the Mekong delta region, Vietnam. *Heliyon, 9*, e17883. https://doi.org/10.1016/j.heliyon.2023.e17883

Tai, A. P. K., Sadiq, M., Pang, J. Y. S., Yung, D. H. Y., & Feng, Z. (2021). Impacts of surface ozone pollution on global crop yields: comparing different ozone exposure metrics and incorporating co-effects of CO2. *Frontiers in Sustainable Food Systems, 5*, 1–18. https://doi.org/10.3389/fsufs.2021.534616

Tanimoto, H., Sawa, Y., Matsueda, H., Uno, I., Ohara, T., Yamaji, K., Kurokawa, J., & Yonemura, S. (2005). Significant latitudinal gradient in the surface ozone spring maximum over East Asia. *Geophysical Research Letters, 32*. https://doi.org/10.1029/2005GL023514

Tatsumi, K. (2022). Rice yield reductions due to ozone exposure and the roles of VOCs and NOx in ozone production in Japan. *Journal of Agricultural Meteorology, 78*, 89–100. https://doi.org/10.2480/agrmet.D-21-00051

Van Dingenen, R., Dentener, F. J., Raes, F., Krol, M. C., Emberson, L., & Cofala, J. (2009). The global impact of ozone on agricultural crop yields under current and future air quality legislation. *Atmospheric Environment, 43*, 604–618. https://doi.org/10.1016/j.atmosenv.2008.10.033

Wang, T., Xue, L., Feng, Z., Dai, J., Zhang, Y., & Tan, Y. (2022). Ground-level ozone pollution in China: a synthesis of recent findings on influencing factors and impacts. *Environmental Research Letters, 17*, 63003. https://doi.org/10.1088/1748-9326/ac69fe

Wang, X., & Mauzerall, D. L. (2004). Characterizing distributions of surface ozone and its impact on grain production in China, Japan and South Korea: 1990 and 2020. *Atmospheric Environment, 38*, 4383–4402. https://doi.org/10.1016/j.atmosenv.2004.03.067

Publisher's Note