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Does your article include research that required ethical approval or permits?:

This article does not present research with ethical considerations

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The TM5 FASST model is accessible at <https://tm5-fasst.jrc.ec.europa.eu/>

The Sentinel 5P L2 products are converted to L3 by the Google Earth Engine. Further data processing (monthly mean, monthly differences etc.) has been made using GEE APIs and code editor. Google Earth Engine was used in full compliance with the terms and conditions imposed by Google Inc. on usage rights.

Conflict of interest

I/We declare we have no competing interests

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Authors' contributions

This paper has multiple authors and our individual contributions were as below

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FD, LE, SG, GC, AI, and MvdB contributed to design and interpretation of results and drafting the paper. RVD performed TM5 FASST simulations, and DM retrieved and processed satellite data. LE, FD, and MvdB can be contacted for inquiries on follow up work in the context of AgMIP O3.

Lower air pollution during COVID-19 lock-down: improving models and methods estimating ozone impacts on crops.

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Summary

We suggest that the unprecedented and unintended decrease of emissions of air pollutants during the COVID-19 lock-down in 2020 could lead to declining seasonal ozone concentrations, and positive impacts on crop yields. An initial assessment of the potential effects of COVID-19 emission reductions was made using a set of six scenarios that variously assumed annual European and global emission reductions of 30 % and 50 % for the energy, industry, road transport and international shipping sectors, and 80 % for the aviation sector. The greatest ozone reductions during the growing season reached up to 12 ppb over crop growing regions in Asia and up to 6 ppb in North America and Europe for the 50 % global reduction scenario. In Europe, ozone responses are more sensitive to emission declines in other continents, international shipping and aviation than to emissions changes within Europe. We demonstrate that for wheat the overall magnitude of ozone precursor emission changes could lead to yield improvements between 2 % and 8 %. The expected magnitude of ozone precursor emission reductions during the Northern Hemisphere growing season in 2020 presents an opportunity to test and improve crop models and experimentally-based exposure response relationships of ozone impacts on crops, under real-world conditions.

1 Introduction

The unprecedented societal response to the on-going COVID-19 pandemic has led to significantly reduced economic activities in the Northern hemisphere since late winter and spring of 2020. Lower levels of air pollution were reported throughout the period as a consequence of the shutdown of numerous activities and shifted or halted mobility and working patterns. Among the decreasing pollutants, NO_x, the sum of nitrogen oxide (NO) and nitrogen dioxide (NO₂), is the most important precursor of tropospheric ozone (O₃), that in turn is toxic to crops, (semi-) natural vegetation, and humans. At mid- and high- latitude regions of the Northern Hemisphere, O₃ photochemical production is low in winter due to low sunlight conditions and temperatures, but increases rapidly in spring and summer. The lock-down has caused a reduction in the NO₂ column by up to 30 % in Europe and North America and by up to 50 % in parts of Asia during spring 2020, as shown by satellite imagery (section 2). Although O₃ is not expected to decrease by the same proportion, such an abatement of NO_x will considerably reduce ground level O₃ concentrations (Section 3) and O₃ impacts on ecosystems, and potentially improve the productivity of crop, forests, and grasslands.

1
2 Extensive evidence of O₃ impacts on crops has been collected through controlled experiments during the past 4 decades
3 (1). These experiments have been used to develop exposure response relationships (ERRs). Application of these ERRs in
4 risk assessment studies suggests that ambient levels of O₃ across important agricultural regions cause yield losses to
5 staple crops (wheat, rice, maize and soybean). In Europe, this scientific evidence has supported the UNECE's Convention
6 on Long Range Transboundary Air Pollution (CLRTAP) to establish critical levels for O₃, which are essentially air
7 quality targets for air pollution emission reduction policies. Despite the reduction of NO_x emissions by as much as 40 %
8 since 1990 in Europe and North America, these critical levels are still frequently exceeded. For instance, the recent
9 CLRTAP assessment report (2) estimates current wheat yield losses due to O₃ in Europe of the order of 13 %.
10 A range of O₃ and associated ERRs metrics exists to estimate crop losses (1). In section 3, we use the simple
11 concentration-based AOT40 metric to demonstrate the potential benefits for crops of emission reductions during the
12 COVID-19 lock-down. In section 4 we explore the opportunity to gain additional insight in the validity of other
13 concentration or flux-based metrics that have been developed to assess O₃ damage (1) as well as more recently developed
14 crop growth models that incorporate O₃ effects.

15 The use of metrics to perform national and international O₃ risk assessments stem mainly from the air quality impact
16 research community, and have not been mainstreamed into agronomic sciences. For instance, to our knowledge, no crop
17 model used for operational crop yield assessments or crop forecasts incorporates the interaction between O₃ and plant
18 physiology. It remains to be determined whether the decrease in O₃ exposure (2), as a consequence to the reductions of its
19 precursor emissions in Europe, has led to increasing crop yields in recent decades. One of the main challenges is to isolate
20 the overall benefits of O₃ reduction on crop yields from other factors such as weather variability and management factors.

21
22 This paper suggests that the unprecedented and unintended COVID-19 lock-down in 2020 provides scientifically relevant
23 information to quantify the actual O₃ impact on crops. These unusual conditions caused an in-vivo atmospheric
24 experiment, whose magnitude could have generated sizeable reductions in surface O₃ levels, and resulting increases in
25 crop production in 2020. The subsequent analysis of agricultural statistics and application of O₃ risk assessment and crop
26 modelling will allow a comparison of the predictive ability of different methodologies to estimate regional-scale crop
27 yield loss due to O₃.

30 2 Are the observed NO₂ air pollution changes exceptional?

31
32 The best near-real-time information on emission changes is available for NO_x. Emission changes of other O₃ precursors
33 are more difficult to derive from observations. The European Environment Agency (EEA) reports declining NO₂
34 concentrations in several cities in Europe (3), as consequence of the reduced activities associated with the COVID-19
35 outbreak. The data show consistent decreases in concentrations registered at road-side and background (sub-)urban
36 monitoring stations from March to May 2020. The Copernicus Atmosphere Services (CAMS) also report reductions in NO₂
37 concentrations (4), but caution that the use of highly variable time series of less than one month may lead to spurious
38 conclusions on emission changes. Therefore, we focus on average values for March, April, and May (MAM), with May the
39 latest month available to us during the revision of this publication.

40
41 Data from TropOMI/Sentinel5P (Figure 1) show that persistent NO₂ reductions in Europe were not confined to cities
42 alone. We provide in the Supplementary Materials maps similar to Figure 1, but separated for March, April and May to
43 provide further insight in the temporal development of the NO₂ reductions. Comparing MAM average NO₂ columns in
44 2020 with 2019, large reductions are visible over extended regions of Europe, amounting to ca. 20% in Germany and the
45 Benelux, 15 % in Italy, 10-15 % in Spain, France, the United Kingdom, Poland and Czech Republic, and 8 % in
46 Romania. Regions of emission reduction largely overlap with regions with extensive wheat production. Urban NO₂
47 column reductions in Brussels, Dusseldorf, and Paris are a few percent higher than countrywide decreases, Milano's
48 reduction of 27% is 10 % higher than for Italy, and the 33 % reductions in Madrid are markedly higher than the average
49 13 % for Spain. There is significant uncertainty in estimating NO_x emission changes from 2020-2019 NO₂ column
50 changes, related to uncertainties in the satellite retrievals (5), the photochemical conditions of the atmosphere, but also
51 due to inter-annual variability related to weather related transport patterns. However, the changes in NO₂ column in urban
52 conglomerations and entire countries between 2020 and 2019 are clearly attributable to lock-down-related emissions
53 variations, while smaller changes in cleaner areas can display residual inter-annual variability, which may obscure
54 changes related to the COVID-19 lockdown.

55 In Asia, significant declines in MAM NO₂ column by more than 50 μmol m⁻² are found over several urban
56 conglomerations (Figure 1), corroborated by a similar analysis by ESA (6). The largest declines in Asia are in March,
57 with levels in April and May more similar to 2019 levels (Supplementary S2). The MAM average emission reductions
58 between 2020-2019 are of ca. 15 % in Wuhan/Shanghai, 20 % in Macao/Guangzhou, 20 % in Tokyo, 18 % in Beijing and
59 Seoul- in March reductions to over 50 % were seen.

1
2
3
4 In North America significant MAM averaged declines of 10-15 % are also found over the Great Lakes, East and West
5 Coast areas. In March declines (up to 30 %) were higher than in April and May (ca. 10 %).

6
7 In Europe, these results can be compared to an earlier analysis of a step-wise emission decline by 20 % in 2010 (7), which
8 was at least in part due to a temporary reduction in emission, resulting from the global economic recession in 2008-2009.
9 Therefore, we note that following this initial survey, which includes data up to the end of May 2020, further analysis over
10 longer periods is needed to corroborate these column and related emission changes, and how these will affect ground
11 level O₃ concentrations. However, the compelling observational evidence of strong emission declines, motivates our call
12 to the wider most research community to collect and analyse data on all related aspects of emissions, air quality and crop
13 production.

14 3 What are the expected impacts on surface O₃ and crop 15 production? 16 17

18
19 Surface O₃ concentration depends on the magnitude and ratio of the emissions of precursor gases (e.g. NO_x and VOCs),
20 photochemical reactions, atmospheric conditions (weather), removal processes at the earth's surface and hence on local,
21 regional, and seasonal factors. In most regions O₃ declines with decreasing NO_x emissions; however, in some traffic-
22 intensive urban regions dominated by high-NO_x emissions, the O₃ response to declining NO_x emissions may be initially
23 positive, as reduced NO concentrations also reduce O₃ titration close to sources, but as the plume of pollutants is
24 transported away from urban areas net O₃ production begins (8). Detailed atmospheric chemistry transport models are
25 generally used to evaluate the variety of regional responses to reductions in the mix of emissions. O₃ can also be
26 transported between regions within Europe and over longer intercontinental distances (9–13). For instance, Jonson et al
27 (13) estimate that for a scenario assuming 20 % reduction in global anthropogenic emissions, up to 60 % change in
28 Phytotoxic Ozone Dose over forests (POD1) in Europe is due to changes in other regions. Therefore, it is likely that
29 strong emission reductions in Asia and North America may also have influenced O₃ in Europe.

30
31 To provide a gross estimate of the effects of the COVID-19 emission reductions on O₃ air quality and its effects on crop
32 production, we develop six illustrative scenarios. In scenario S1, NO_x and NMVOC emissions from transport, energy and
33 industrial sectors are reduced by 30 % in Europe. In scenario S2 the same reductions are applied worldwide. Scenarios S3
34 and S4 assume 50 % lower emissions in Europe and the world, respectively. Scenario S4 is very similar to a recent O₃-
35 carbon cycle impact study (14), in which an emission reduction of 50 % in these sectors were identified to dominate the
36 overall positive impacts on Gross Primary Production of crops with a C3 metabolism (e.g. wheat). Scenario S5 and S6
37 consider that emissions of international shipping were reduced by 30 and 50 %, respectively, while international aviation
38 emissions were down by 80 % in both S5 and S6. As the exact timing of emission reductions is not known, for simplicity
39 we assume in the scenarios year-round reductions, bearing in mind that for wheat the most O₃-sensitive period is
40 approximately during the grain-filling period (approximately end of May and June). We note that emission reductions of
41 this magnitude or even higher are projected by 2050 if aggressive air pollution and climate policies are implemented
42 (15,16), and changes during the COVID-19 lock-down may be informative of the benefits of emission reductions
43 projected over a much longer timescale. After the submission of this paper some more, informal and peer-reviewed
44 analysis on emission reductions have become available, which is now worth mentioning at the revision stage of this
45 paper. The worldwide number of flights was sharply cut by 25 % in March, and by 60 % in April and May 2020 (17).
46 Commercial shipping trade analysis (18) shows that in the 5 weeks after 12 of March 2020 the number of ship departures
47 from major hubs declined by 6 %, of which tanker traffic was mostly affected. Due to a slow response of the shipping
48 sector to changing demand conditions these reductions are likely to become higher in the next months. A recent estimate
49 (19) of impacts of the COVID-19 lock down conditions on regional and global CO₂ emissions, showed that in April 2020
50 about 80 % of the world's CO₂ was emitted in regions affected by lockdown conditions, and the highest daily decline of
51 global CO₂ emissions was estimated for 7 April to range from -11 % to -25 % (central value -17%), with similar
52 declines during the remainder of April 2020. Except residential emissions, all sectors analysed in (19) showed declines
53 ranging from -7 % for power generation to 60 % for aviation, in agreement with the scenarios presented here. Depending
54 on confinement levels (social distancing only, medium or stringent measures), surface transport emissions were reported
55 down (19) by -10 % to -50 %, although numerous web reports also suggest larger reductions in selected cities. An overall
56 annual impact on CO₂ emission in 2020 was estimated (19) to range from -3 % to -13 %, with a central value of -7 %,
57 assuming a return to pre-COVID conditions in the middle of June 2020. Overall, the reported emission reductions support
58 the choice of sensitivity studies presented in this publication, including the assumption that effects could very likely
59 extend through June and July 2020. By a direct comparison with a variety of sources of information available at the time
60 of the revision of this paper, we can conclude that scenario S3, S4 and S6 are probably upper limits for the real-world
impacts.

1
2 Some additional simplifying assumptions have been made in this study. For instance, we have not considered CO
3 emission reductions, which could have some further minor impact on O₃ formation (10). Although the emissions of
4 methane (CH₄), another important O₃ precursor, are probably also affected by the lock-down, and the reduction of air
5 pollutants can influence the CH₄ lifetime, the overall impact on CH₄ and O₃ concentrations is not a-priori clear. As any
6 effect will play out on a timescale of 10 years (CH₄'s lifetime), it will not likely be discernible within 2020, but may
7 become substantial in the following years.

8
9 To estimate possible impacts of such emission reductions on crop yields we use the TM5-FASST global source-receptor
10 model (20). In summary, TM5-FASST considers a set of 56 global regions and 2 global sectors (aviation and shipping),
11 to determine the regional (grid-level) response to emission reduction of air pollutant precursor emissions. For each region
12 and sector the response of hourly O₃ changes and corresponding impacts on crops is calculated using ERR available in the
13 literature (20). In this publication we estimate impacts on crops using AOT40, which is a metric based on the cumulated
14 concentration of hourly surface O₃ above 40 ppb to which crops are exposed during a three-month period in the crop
15 growing season. Comparison of TM5-FASST results with other studies described in (20) show coherent results among
16 models and ERR methods, but the limitations of AOT40 and other ERRs should be noted, and are further discussed in
17 (1).

18
19 Focussing on the scenario S4+S6, the globally 50 % lower emission scenario, seasonal O₃ changes in May-June-July
20 (Figure 2), range from 10-12 ppb O₃ decreases in China and other parts of Asia, 2 to 6 ppb in North America, and less
21 than 2 ppb in north-west Europe to up to 6 ppb in Southern Europe. In particular, in northern Europe, and some other
22 urban conglomerations in North America and Asia, emission reductions caused increases in O₃. Accurate determination
23 of O₃ responses in such regions would need high resolution models as well as high resolution information on emission
24 declines in those regions. For the 30 % global emission reduction case (S2+S5), O₃ decreases were ca. 7 ppb in Asia, 1 to
25 4 ppb in North America and less than 1.5 ppb in Europe, respectively.

26
27 Impacts on wheat yields for the 6 scenarios are presented in Figure 3. Overall improvements of wheat yields range from
28 1-4 % in case of worldwide emission reductions by 30 % (S2+S5), and 2-7 % for reductions by 50 % (S4+S6). The
29 contribution of European emission reductions to yield improvements in a set of European countries is relatively small,
30 ranging from ~0-0.5 % in northern European countries to 3 % in Italy (S1, S3). Shipping and aviation contribute by up to
31 1-3 % for scenario S6. Yield improvements of up to 7 % calculated for Asia and North America (S4+S6).

32 4 There is an opportunity to learn on the real-world impacts of 33 O₃ on crop production 34 35

36
37 Over the past few decades, a wide variety of concentration-based and flux-based O₃ metrics have been used to develop
38 ERRs for use in risk assessment studies. These studies have explored exceedance of critical levels, as well estimated
39 relative and absolute crop yield losses from anthropogenic O₃ concentrations (1). However, substantial differences in
40 estimates of the magnitude as well as of the spatial distribution of yield losses have been found using different methods.
41 For example, differences of up to a factor of two have been found when estimating yield losses using AOT40 versus POD
42 metrics (21). In addition, there are some long-term (5 to 10 years) statistical studies that try to identify the O₃ signal in
43 agricultural yield statistics by performing regression analysis of meteorological and O₃ data. The results are not always
44 consistent with empirically-based risk assessment models (1). This has led to uncertainty on the actual size of effect and
45 spatial distribution of O₃ on crop yields.

46
47 To address these uncertainties in risk assessment modelling, the Agricultural Model Intercomparison and Improvement
48 Project (AgMIP) has started an activity to evaluate and enhance crop models with an O₃ component. Some recent
49 examples of the use of such crop models (22,23) show a good potential to replicate O₃ impacts found in field studies.
50 However, crop growth models used for operational agronomic analyses do not include O₃ impacts. For example, the
51 WOFOST model, currently used by the European Commission Joint Research Centre to provide operational analysis of
52 crop growth development and yield forecasts (24), does not explicitly consider the effect of O₃ on crop phenology and
53 growth. In spite of this, the yield forecasts for which it is used can usually achieve an accuracy within ±3 % (25). This
54 does not rule out the existence of an effect of O₃ on yields, since such signal is likely indirectly hidden in other climatic
55 factors, e.g. air temperature and solar radiation (26), and can be removed during the post-calibration of the model results
56 against a reference of historical yield data. If this is the case, we might expect that the explicit inclusion of O₃ effects on
57 crop development and yield in WOFOST and other crop models would further improve their performance for operational
58 assessments, especially for those locations and years where O₃ impacts can be high and vary between years.
59 Understanding the combined impacts of future climate and air pollution projections, further requires inclusion of O₃
60 impacts in crop models.

COVID-19 has led to a myriad of societal consequences, including a strong decrease of economic activities, with grave impacts on livelihoods and society as a whole. Nonetheless, were the unintended in-vivo atmospheric experiment during COVID-19 to result in substantial reductions in O₃ and subsequent increases in crop productivity, it will allow us to evaluate and compare the different O₃ metrics, risk assessment methods and crop growth models that have been developed. The new insights gained will support future development of operational agronomic analysis. Such analysis would need to be performed on careful consideration of other COVID-19 related factors (i.e. management decisions in response to expected returns) that may co-determine yields. Europe-wide, preliminary information (27) does not provide evidence of large-scale socio-economic responses by farmers, but this information needs to be corroborated at the end of the season.

Specifically, we see the following research opportunities and steps to take related to reduced emissions during the COVID-19 lockdown in 2020 and O₃ impacts:

- The initial submission (5th of May 2020) of this publication intended to alert the research community to collect emerging data on emission and O₃ changes, and prepare atmospheric and crop models to perform an analysis of the role of O₃ in determining 2020 crop yields. At the time of the revision of this publication (24th of June 2020) the latest observations indicated a continued emission reduction through the growing season, albeit with shifting regional importance as the SARS-COV-2 virus spreads around the world. Hence, extension of this analysis to other world regions, would be advisable.
- Accurate estimates of emission changes in 2020 relative to the last 3-5 years, based on observed changes in NO₂, statistical information from activities (e.g. fuel use changes, traffic information), and modelling multiple recent years. Better understanding of emission changes in specific sectors and reductions of other O₃ precursors are important to understand overall impacts on emissions and O₃. This paper showed the important role of intercontinental emissions, including shipping and aviation, which are therefore sectors that need particular attention. The approach to estimating CO₂ emission reductions (19) maybe extended and refined, taking advantage of the satellite observations of NO₂ columns.
- Analysis and estimates of O₃ changes due to lower emissions, focusing on the last 3-5 years, using current best available models, contrasted with available observations.
- Statistical analysis of agricultural yields from long-term experimental sites (to standardise management practices) over the past 3-5 years to assess whether emission reductions were sizeable enough to produce a significant yield anomaly in 2020.
- Evaluation of O₃ risk assessment methods, using both concentration-, and flux-based metrics, and crop models that incorporate an O₃ component to assess their ability to predict changes in crop yields over the past 3-5 years.
- While the examples given in this publication focussed on wheat, evaluation of effects on other crops and ecosystems (e.g. grasslands and forests) known to be susceptible to O₃ damage, needs to be undertaken as well.

Following the methods developed in the UNECE CLRTAP Task Force on Hemispheric Transport of Air Pollution, and ICP Vegetation regarding hemispheric O₃ modelling and impacts of ozone on vegetation and AgMIP modelling of ozone impacts on crops, coordinated modelling activities at the end of the 2020 cropping season can improve process understanding and model quality, ensuring the representation of the variety of modelling methods that currently exist.

Additional Information

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Data Accessibility

The TM5 FASST model is accessible at <https://tm5-fasst.jrc.ec.europa.eu/>

The Sentinel 5P L2 products are converted to L3 by the Google Earth Engine. Further data processing (monthly mean, monthly differences etc.) has been made using GEE APIs and code editor. Google Earth Engine was used in full compliance with the terms and conditions imposed by Google Inc. on usage rights.

Supplementary Material:

Supplementary Material is available via [xxx.xxx.xxx](#)

Competing Interests

We declare no competing interests.

Authors' Contributions

FD, LE, SG, GC, AI, and MvdB contributed to design and interpretation of results and drafting the paper. RVD performed TM5 FASST simulations, and DM retrieved and processed satellite data. LE, FD, and MvdB can be contacted for inquiries on follow up work in the context of AgMIP O₃.

For Review Only

Figure captions

Figure 1: a) TropOMI/Sentinel5P NO_2 tropospheric column [$\mu\text{mol m}^{-2}$] average for March-April-May 2019 over Europe b) for 2020 over Europe c) the difference of March-April-May 2020-2019 over Europe. The green areas indicate soft and durum wheat areas of 500 ha and larger d) the difference of March-April-May 2020-2019 over Asia. e) the difference of March-April-May over North America.

Figure 2: a) Ozone responses (ppbv) calculated by TM5-FASST in Europe and Northern Africa, b) North and middle America and c) Asia (c) to global emission reductions by 50 % in the industry, energy, transport, shipping and aviation (-80 %) sectors, i.e. the sum of scenario S4 and S6. Isolated white regions correspond to near-zero or negative ozone responses due to declining emissions, which can occur in regions with high ratios of NO_x to VOC emissions.

Figure 3 AOT40 based wheat yield increases (%) in selected European countries, USA, China and South Korea due to emission reductions by 30 % and 50 % in the energy, industry and transport sectors in Europe (S1, S3, green), World (S2, S4, blue) and international shipping + aircraft sectors (S5, S6 grey). The upper/lower part of the stacked bar represents the 50 % and 30% emission reduction scenario, respectively, while aviation emissions were down by 80 %. The total yield increase (blue) is the sum of the world and ship/aviation. Reference emissions were taken from the ECLIPSEv5a emission database (28) for the CLE-2020 scenario. Energy, industry and transport emissions amount to 56.6 and 6.2 Tg $\text{NO}_2 \text{ yr}^{-1}$ for the world and Europe, respectively. International shipping and aviation emissions are 23.0 and 3.4 Tg $\text{NO}_2 \text{ yr}^{-1}$, respectively.

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Figure 1

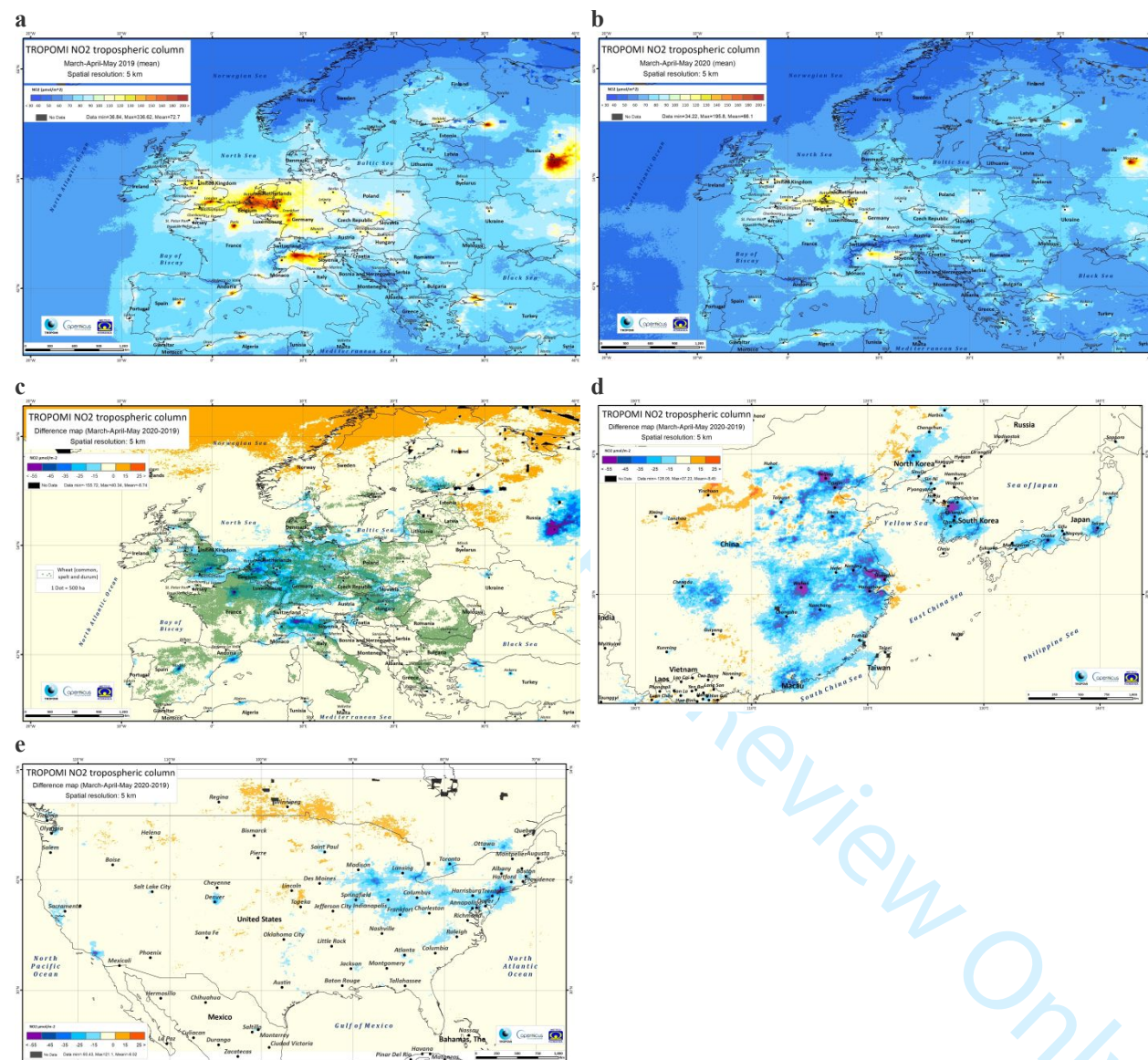
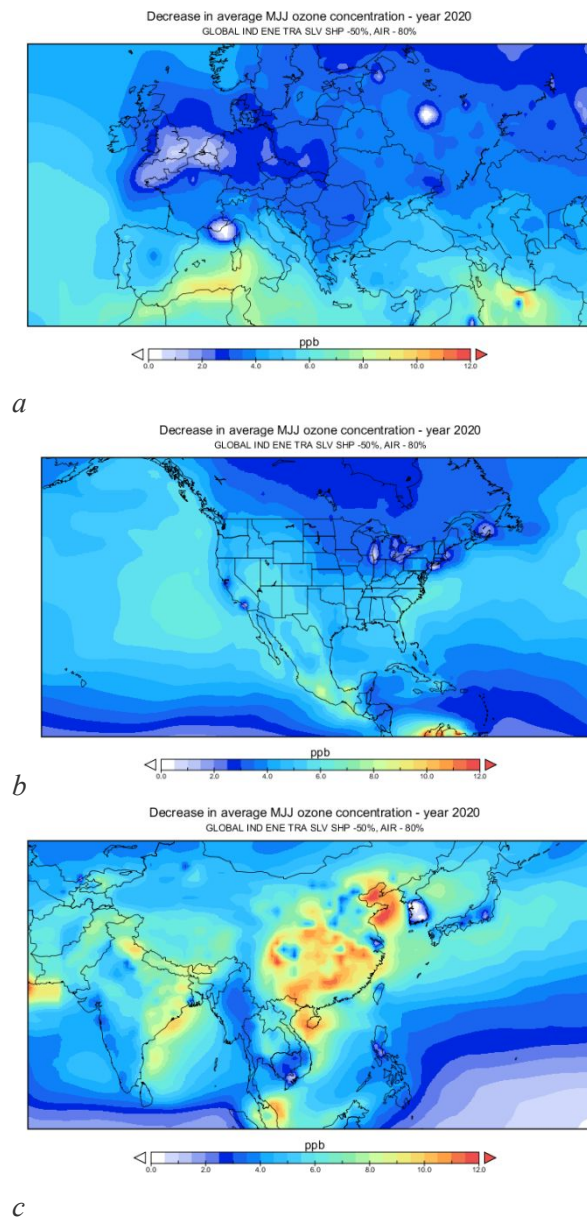


Figure 1: a) TropOMI/Sentinel5P NO₂ tropospheric column [$\mu\text{mol m}^{-2}$] average for March-April-May 2019 over Europe b) for 2020 over Europe c) the difference of March-April-May 2020-2019 over Europe. The green areas indicate soft and durum wheat areas of 500 ha and larger d) the difference of March-April-May 2020-2019 over Asia. e) the difference of March-April-May over North America.

Figure 2



45 *Figure 2: a) Ozone responses (ppbv) calculated by TM5-FASST in Europe and Northern Africa, b) North and middle*
 46 *America and c) Asia (c) to global emission reductions by 50 % in the industry, energy, transport, shipping and aviation (-*
 47 *80 %) sectors, i.e. the sum of scenario S4 and S6. Isolated white regions correspond to near-zero or negative ozone*
 48 *responses due to declining emissions, which can occur in regions with high ratios of NO_x to VOC emissions.*

Figure 3

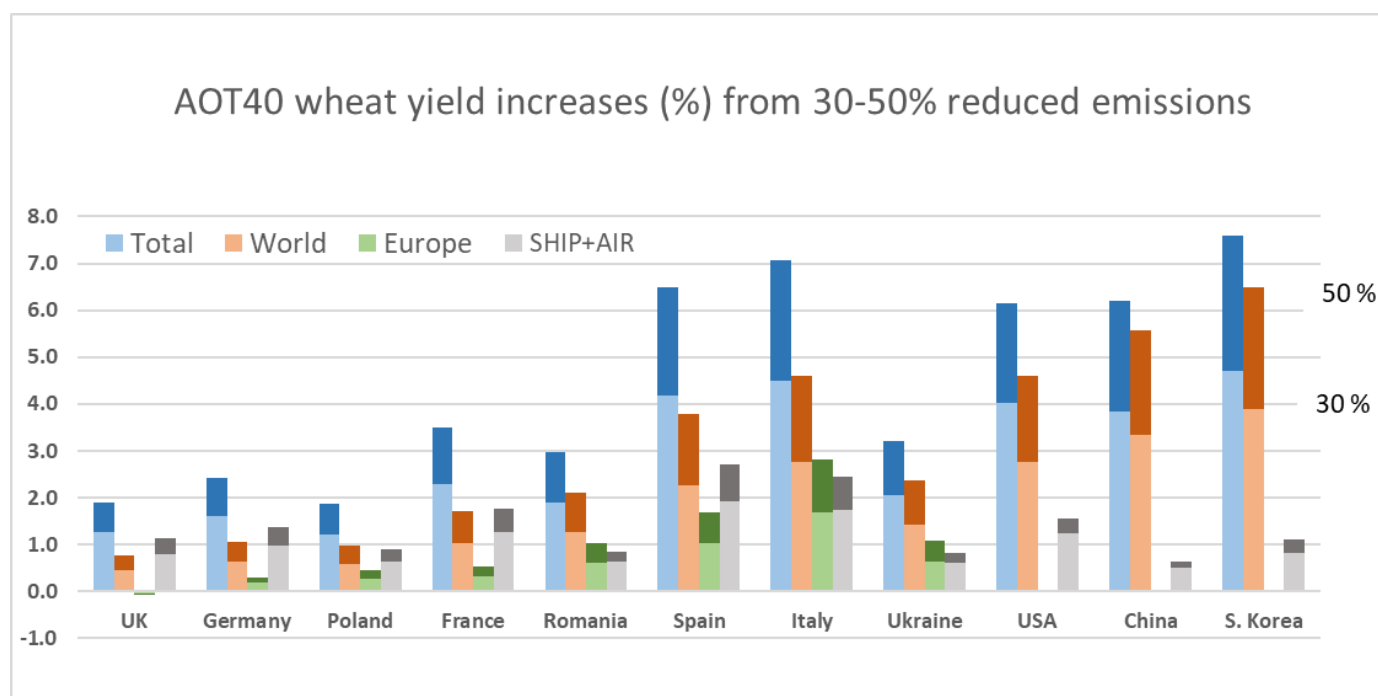


Figure 3 AOT40 based wheat yield increases (%) in selected European countries, USA, China and South Korea due to emission reductions by 30 % and 50 % in the energy, industry and transport sectors in Europe (S1, S3, green), World (S2, S4, blue) and international shipping + aircraft sectors (S5, S6 grey). The upper/lower part of the stacked bar represents the 50 % and 30% emission reduction scenario, respectively, while aviation emissions were down by 80 %. The total yield increase (blue) is the sum of the world and ship/aviation. Reference emissions were taken from the ECLIPSEv5a emission database (28) for the CLE-2020 scenario. Energy, industry and transport emissions amount to 56.6 and 6.2 Tg $\text{NO}_2\text{yr}^{-1}$ for the world and Europe, respectively. International shipping and aviation emissions are 23.0 and 3.4 Tg $\text{NO}_2\text{yr}^{-1}$, respectively.