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

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## Author-supplied statements

Relevant information will appear here if provided.

***Ethics***

*Does your article include research that required ethical approval or permits?:*
This article does not present research with ethical considerations

*Statement (if applicable):*
CUST_IF_YES_ETHICS :No data available.

***Data***

*It is a condition of publication that data, code and materials supporting your paper are made publicly available. Does your paper present new data?:*
Yes

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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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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.

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

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# Summary

This paper suggests that the unprecedented and unintended decrease of emissions of air pollutants during the COVID-19 lock-down could lead to declining seasonal ozone concentrations, and positive impacts on crop yields. It therefore constitutes an opportunity to test and improve crop models, and experimental exposure-response relationships, under real-world conditions. 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. In Europe, ozone responses are more sensitive to emission declines in other continents, international shipping and aviation than to emissions 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 research community is called to collect emerging data, analyse the emission and ozone changes, and prepare models to perform a systematic analysis of the role of ozone in determining 2020 crop yields.


# 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 are reported 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 ($NO_2$), is the most important precursor of tropospheric ozone ($O_3$), that in turn is toxic to crops, (semi-) natural vegetation, and humans. At mid- and high- latitude regions of the Northern Hemisphere, $O_3$ photochemical production is low in winter due to low sunlight conditions and temperatures, but strengthens in spring and summer. The lock-down may have caused a reduction in $NO_2$ column by up to 30 % Europe and North America and by up to 50 % in parts of Asia during early spring 2020, as shown by satellite imagery (section 2). Although $O_3$ is not expected to decrease by the same proportion, such an abatement of $NO_x$ will considerably affect ground level $O_3$ concentrations (Section 3) and could reduce negative impacts on crops, forests, grasslands and ecosystems.

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Extensive evidence of $O_3$ impacts on crops has been collected through controlled experiments during the past 3 decades (1). These experiments have been used to develop exposure response relationships (ERRs). Application of these ERRs in risk assessment studies suggests that ambient levels of $O_3$ across important agricultural regions cause yield losses to staple crops (wheat, rice, maize and soybean). In Europe, this scientific evidence has supported the UNECE's Convention on Long Range Transboundary Air Pollution (CLRTAP) to establish critical levels for $O_3$, which are essentially air quality targets for air pollution emission reduction policies. Despite the reduction of $NO_x$ emissions by as much as 40 % since 1990 in Europe and North America, these critical levels are still frequently exceeded. For instance, the recent CLRTAP assessment report (2) estimates current wheat yield losses due to $O_3$ in Europe of the order of 13 %.
A range of $O_3$ and associated ERRs metrics exists to estimate crop losses. In section 3, we use the simple concentration-based AOT40 metric to demonstrate the potential benefits for crops of emission reductions during the COVID-19 lock-down. In section 4 we explore the opportunity to gain additional insight in the validity of other concentration or flux-based metrics that have been developed to assess $O_3$ damage (1) as well as more recently developed crop growth models that incorporate $O_3$ effects.

The use of metrics to perform national and international $O_3$ risk assessments stem mainly from the air quality impact research community, and have not been mainstreamed into agronomic sciences. For instance, to our knowledge, no crop model used for operational crop yield assessments or forecasts incorporates the interaction between ozone and plant physiology. It remains to be determined whether the decrease of $O_3$ (2), consequent to the reductions of its precursor in Europe, has favoured increasing crop yields in recent decades. One of the main challenges is to isolate the overall benefits of $O_3$ reduction on crop yields from other factors such as weather variability and management factors.

This paper suggests that the unprecedented and unintended COVID-19 lock-down could provide scientifically relevant information to estimate the actual $O_3$ impact on crops. The current unusual conditions are producing an in-vivo atmospheric experiment, which may be large enough to show sizeable reductions in surface $O_3$ levels, and subsequent increases in crop production. As the unintended experiment is unfolding, the scientific community needs to collect the emerging data and prepare models to perform a systematic analysis of the role of $O_3$ in determining 2020 crop yields. The subsequent analysis of agricultural statistics and application of $O_3$ risk assessment and crop modelling will allow a comparison of the predictive ability of different methodologies to estimate regional-scale crop yield loss due to $O_3$.

# 2 Are the observed $NO_2$ air pollution changes exceptional?

The best near-real-time information on emission changes is available for $NO_x$. Emission changes of other $O_3$ precursors are more difficult to derive from observations. The European Environment Agency (EEA) reports declining NO2 concentrations in several cities in Europe (3), as consequence of the reduced activities associated with the COVID-19 outbreak. The data show consistent decreases in concentrations registered at road-side and background (sub-)urban monitoring stations. The Copernicus Atmosphere Services (CAMS) also report reductions in $NO_2$ concentrations (4), but caution that the use of highly variable time series of less than one month may lead to spurious conclusions on emission changes. Therefore, we focus on average values for March and April.

Data from TropOMI/Sentinel5P (Figure 1) show that persistent $NO_2$ reductions in Europe were not confined to cities alone. Comparing March-April average $NO_2$ columns in 2020 with 2019, large reductions are visible over extended regions of Europe, amounting to ca. 20-25 % in Germany and the Benelux, 20 % in Italy, 10-15 % in Spain, France, Poland and Czech Republic, and 8 % in Romania. Regions of emission reduction largely overlap with regions with extensive wheat production. Urban $NO_2$ column reductions in Brussels, Dusseldorf, and Paris are a few percent higher than countrywide decreases, Milano's reduction of ca. 30% are 10 % higher than for Italy, and the 33 % reductions in Madrid are markedly higher than the average for Spain. There is significant uncertainty in estimating $NO_x$ emission changes from 2020-2019 $NO_2$ column changes, related to substantial uncertainty in the satellite retrievals (5), the photochemical conditions of the atmosphere, but also due to inter-annual variability related to weather related transport patterns. However, the changes in $NO_2$ column in urban conglomerations and entire countries between 2020 and 2019 are clearly attributable to lock-down-related emissions variations, while smaller changes in cleaner areas can display residual inter-annual variability.
A similar analysis over Asia by ESA (6) shows significant declines in $NO_2$ column by more than 100 μmol $m^{-2}$ over several urban conglomerations (Figure 1). The largest declines in Asia are in March, with a recovery to 2019 levels in April. The March-April average emission reductions between 2020-2019 are of ca. 20 % in Wuhan/Shanghai, 25 % in Macao/Guangzhou, 20 % in Tokyo, 22 % in Beijing and Seoul- in March reductions to over 50 % were seen. In North America significant declines of 20 % are also found average for March and April over the Great Lakes, East and West Coast areas. In March declines (ca. 30 %) were higher than in April (ca. 10 %).

In Europe, these results can be compared to an earlier analysis of a step-wise emission decline by 20 % in 2010 (7), which was at least in part due to a temporary reduction in emission, resulting from the global economic recession in 2008-2009. Therefore, we note that following this initial survey, further analysis over longer periods is needed to corroborate these column and related emission changes, and how these will affect ground level $O_3$ concentrations. However, the compelling observational evidence of strong emission declines, motivates our call to the wider most research community to collect data on all related aspects of emissions, air quality and crop production to ensure that this window of opportunity is not missed.

# 3 What are the expected impacts on surface $O_3$ and crop production?

Surface $O_3$ concentration depends on the magnitude and ratio of the emissions of precursor gases (e.g. $NO_x$, and VOCs), photochemical reactions, atmospheric conditions (weather), removal processes at the earth's surface and hence on local, regional, seasonal factors. In most regions $O_3$ declines with decreasing $NO_x$ emissions; however, in some traffic-intensive urban regions dominated by high-$NO_x$ emissions, $O_3$ may initially increase in response to declining $NO_x$ emissions, but after transport of the urban plume to rural areas $O_3$ will eventually decrease (8). Detailed atmospheric chemistry transport models are generally used to evaluate the variety of regional responses to reductions in the mix of emissions. Ozone can also be transported between regions within Europe and over longer intercontinental distances (9–13). For instance, Jonson et al (13) estimate that for a scenario assuming 20 % reduction in global anthropenic emissions, up to 60 % change in Phytotoxic Ozone Dose over forests (POD1) in Europe is due to changes in other regions. Therefore, it is likely that strong emission reductions in Asia and North America can also affect $O_3$ in Europe.

To provide a gross estimate of the effects of the COVID-19 emission reductions on $O_3$ air quality and its effects on crop production, we develop six illustrative scenarios. In scenario S1, $NO_x$, and NMVOC emissions from transport, energy and industrial sectors are reduced by 30 % in Europe. In scenario S2 the same reductions are applied worldwide. Scenarios S3 and S4 assume 50 % lower emissions in Europe and the world, respectively. Scenario S4 is very similar to a recent ozone-carbon cycle impact study (14), in which an emission reduction of 50 % in these sectors were identified to dominate the overall positive impacts on GPP of C3 crops. Scenario S5 and S6 consider that emissions of international shipping were reduced by 30 and 50 %, respectively, while international aviation emissions were down by 80 %. As the exact timing of emission reductions is not known, for simplicity we assume in the scenarios year-round reductions, bearing in mind that for wheat the most $O_3$-sensitive period is approximately during the grain-filling period (approximately end of May and June). We note that emission reductions of this magnitude or even higher are projected by 2050 if aggressive air pollution and climate polices are implemented (15,16), and changes during the COVID-19 lock-down may be informative of the benefits of emission reductions projected over a much longer timescale. Some simplifying assumptions have been made. For instance, we have not considered CO emission reductions, which could have some further minor impact on $O_3$ formation (10). Although the emissions of methane ($CH_4$), another important $O_3$ precursor, are probably also affected by the lock-down, and the reduction of air pollutants can influence the $CH_4$ lifetime, the overall impact on $CH_4$ and $O_3$ concentrations is not a-priori clear. As any effect will play out on a timescale of 10 years ($CH_4$'s lifetime), it will not likely be discernible within this year, but may become substantial in the following years.

To estimate possible impacts of such emission reductions on crop yields we use the TM5-FASST global source-receptor model (17) to calculate hourly $O_3$ changes and corresponding impacts on crops.
Focussing on the scenario S4, the globally 50 % lower emission scenario, seasonal $O_3$ changes in May-June-July (Figure 2), range from 10-12 ppb ozone decreases in China and other parts of Asia, 2 to 6 ppb in North America, <2 ppb in north-west Europe to up to 6 ppb in Southern Europe.

To estimate impacts on crops we use AOT40, which is a metric based on the cumulated concentration of hourly surface $O_3$ above 40 ppb to which crops are exposed during a three month period in the crop growing season; for discussion of other metrics see (1). The results of this preliminary exercise are presented in Figure 3. Overall improvements of wheat yields range from 1-4 % in case of worldwide emission reductions by 30 % (S2+S5), and 2-7 % for reductions by 50 % (S4+S6). The contribution of European emission reductions in a set of European countries is relatively small, ranging from ~0-0.5 % in northern European countries to 3 % in Italy (S1, S3). Shipping and aviation contribute by up to 1-3 % for the 50 % reduction scenario S6. Yield improvements of up to 7 % calculated for Asia and North America (S4+S6).

# 4 There is an opportunity to learn on the real-world impacts of $O_3$ on crop production

Over the past few decades, a wide variety of concentration-based and flux-based $O_3$ metrics have been used to develop ERRs for use in risk assessment studies. These studies have explored exceedance of critical levels, as well estimated relative and absolute crop yield losses from anthropogenic $O_3$ concentrations (1). However, substantial differences in estimates of the magnitude as well as of the spatial distribution of yield losses have been found using different methods. For example, differences of up to a factor of two have been found when estimating yield losses using AOT40 versus POD metrics (18). In addition, there are some long-term (5 to 10 years) statistical studies that try to identify the $O_3$ signal in agricultural yield statistics by performing regression analysis of meteorological and $O_3$ data. The results are not always consistent with empirically-based risk assessment models (1). This has led to uncertainty on the actual size of effect and spatial distribution of $O_3$ on crop yields.

To address these uncertainties in risk assessment modelling, the Agricultural Model Intercomparison and Improvement Project (AgMIP) has started an activity to evaluate and enhance crop models with an $O_3$ component. Some recent examples of the use of such crop models (19,20) show a good potential to replicate $O_3$ impacts found in field studies. However, crop growth models used for operational agronomic analyses do not include $O_3$ impacts. For example, the WOFOST model, currently used by the European Commission Joint Research Centre to provide operational analysis of crop growth development and yield forecasts (21), does not explicitly consider the effect of $O_3$ on crop phenology and growth. In spite of this, the yield forecasts for which it is used can usually achieve an accuracy of <3 % (22). This does not rule out the existence of an effect of $O_3$ on yields, since such signal is likely indirectly hidden in other climatic factors, e.g. air temperature and solar radiation (23), and can be removed during to the post-calibration of the model results against a reference of historical yield data. If this is the case, we might expect that the explicit inclusion of $O_3$ effects on crop development and yield in WOFOST and other crop models would further improve their performance for operational assessments, especially for those locations and years where $O_3$ impacts can be high and vary between years. Understanding the combined impacts of future climate and air pollution projections, further requires inclusion of $O_3$ 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 $O_3$ and subsequent increases in crop productivity, it will allow us to evaluate and compare the different $O_3$ 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 (24) 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:

- Accurate estimates of emission changes in 2020 relative to the last 3-5 years, based on observed changes in $NO_2$, 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 $O_3$ precursors are important to understand overall impacts on emissions and $O_3$. This paper showed the important role of intercontinental emissions, including shipping and aviation, which are therefore sectors that need particular attention.
- Analysis and estimates of $O_3$ 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 $O_3$ risk assessment methods, using both concentration-, and flux-based metrics, and crop models that incorporate an $O_3$ 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 $O_3$ damage, needs to be undertaken as well.

In the light of the current situation, we invite any institution involved in any of the above listed activities to collect detailed, time resolved, data for this extraordinary period, which will be instrumental in the near future to assess the importance of the impact and to calibrate in a more detail way models.
Following the methods used by previous collaborative activities, we call for coordinated modelling activities at the end of this cropping season aimed at improving process understanding and model quality, ensuring the representation of the variety of modelling methods that currently exist. The AgMIP $O_3$ crop modelling activity may in addition to planned work, take such analysis into its core objectives.

# 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.

**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 $O_3$.

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# Figures

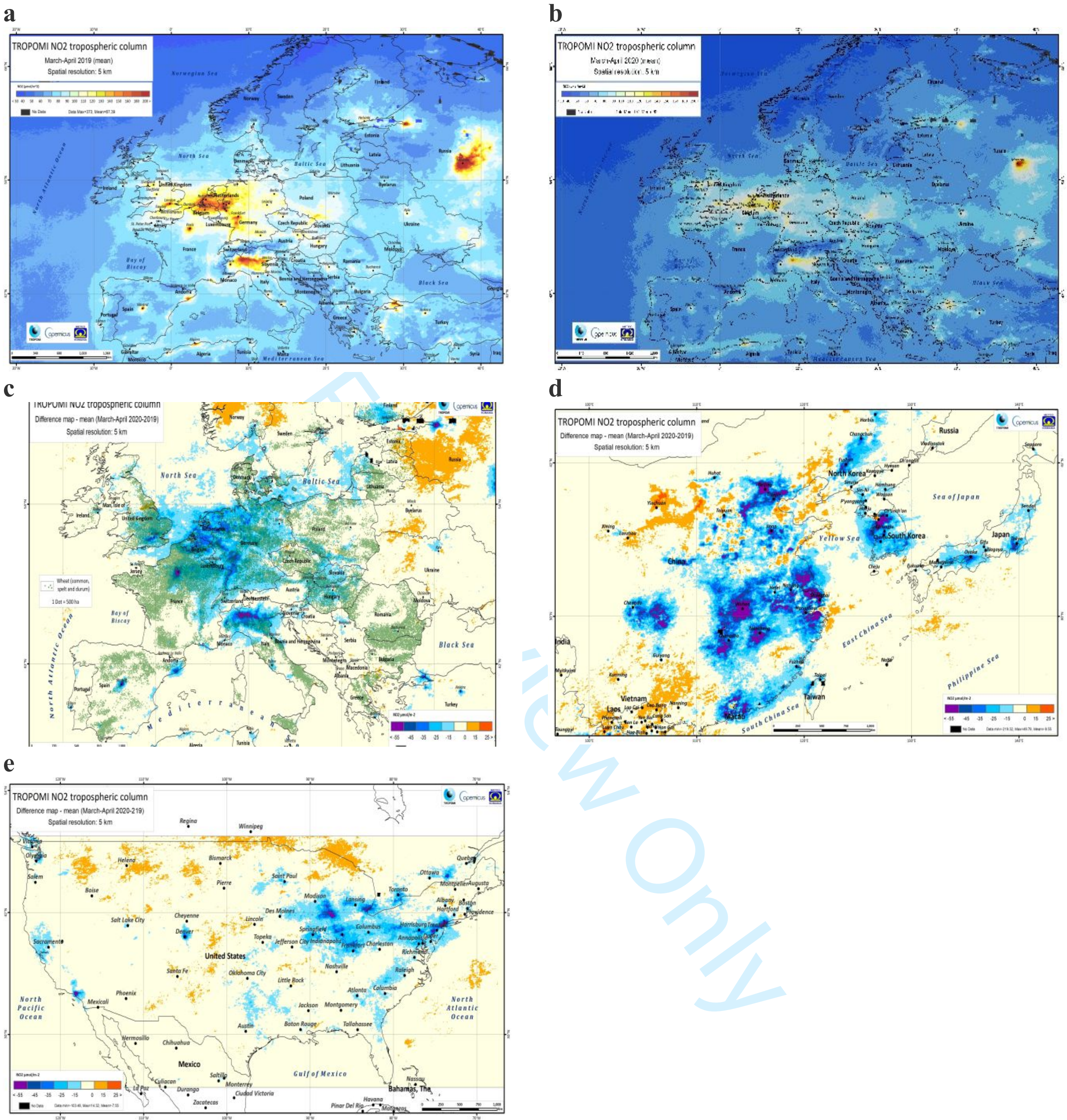


*Figure 1: a) TropOMI/Sentinel5P $NO_2$ tropospheric column [$\mu mol\ m^{-2}$] average for March-April 2019 over Europe b) for 2020 over Europe c) the difference of March-April 2020-2019 over Europe. The green areas indicate soft and durum wheat areas of 500 ha and larger d) the difference of March-April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

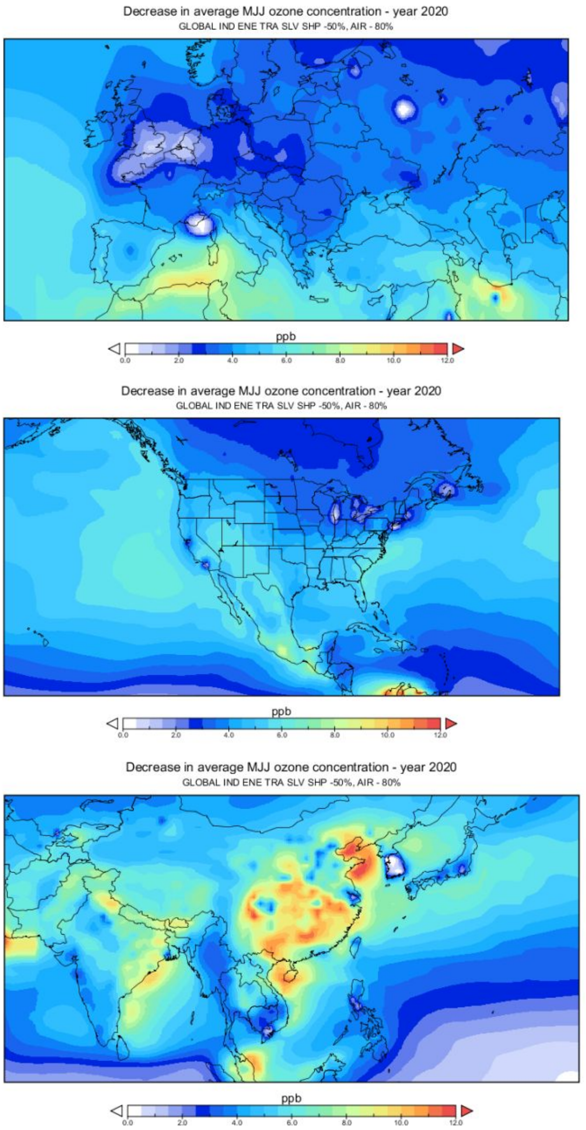


*Figure 2: a) Ozone responses (ppbv) calculated by TM5-FASST in Europe and Northern Africa, b) North and middle America and c) Asia (c) to global emission reductions by 50 % in the industry, energy, transport, shipping and aviation (-80 %) sectors, i.e. the sum of scenario S4 and S6. Isolated white regions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

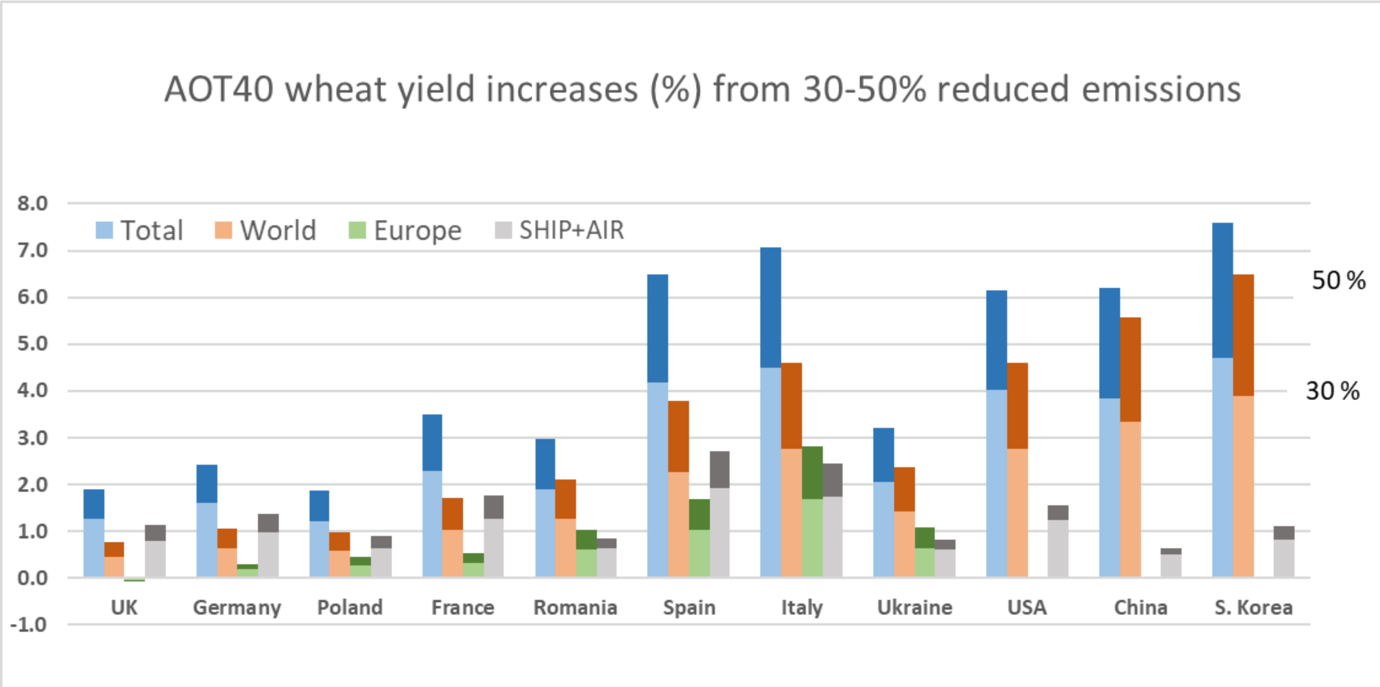


*Figure 3 AOT40 based wheat yield increases (%) in selected European countries, USA, China and South Korea due to emission reductions by 30 % and 50 % in the energy, industry and transport sectors in Europe (S1, S3, green), World (S2, S4, blue) and international shipping + aircraft sectors (S5, S6 grey). 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 ((25) for the CLE-2020 scenario. Energy, industry and transport emissions amount to 56.6 and 6.2 Tg $NO_2$ $yr^{-1}$ for the world and Europe, respectively. International shipping and aviation emissions are 23.0 and 3.4 Tg $NO_2$ $yr^{-1}$, respectively.*