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Quantifying the impact of ozone on crops in Sub-Saharan Africa demonstrates regional and local hotspots of production loss.

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Abstract

Tropospheric ozone can have a detrimental effect on vegetation, including reducing the quantity of crop yield. This study uses modelled ozone flux values (POD_3IAM; phytotoxic ozone dose above 3 nmol m^{-2} s^{-1}, parameterised for integrated assessment modelling) for 2015, together with species-specific flux-effect relationships, spatial data on production and growing season dates to quantify the impact of ozone on the production of common wheat (*Triticum aestivum*) and common beans (*Phaseolus vulgaris*) across Sub-Saharan Africa (SSA). A case study for South Africa was also done using detailed data per province. Results suggest that ozone pollution could decrease wheat yield by between 2 and 13%, with a total annual loss of 453,000 tonnes across SSA. The impact on bean production depended on the season, however estimated yield losses were up to 21% in some areas of SSA, with an annual loss of ~300,000 tonnes for each of the two main growing seasons. Production losses tended to be greater in countries with the highest production, for example Ethiopia (wheat) and Tanzania (beans). This study provides an indication of the location of areas at high risk of crop losses due to ozone. Results emphasise that efforts to reduce ozone precursors could contribute to reducing the yield gap in SSA. More stringent air pollution abatement policies are required to reduce crop losses to ozone in the future.

Keywords: Wheat, beans, Africa, crop production, ozone, yield loss.

1. Introduction

Tropospheric (ground-level) ozone is a secondary air pollutant, formed from sunlight-driven reactions between precursor molecules including carbon monoxide (CO), methane (CH4), non-methane hydrocarbons and nitrogen oxides (NO_x) (Monks *et al*., 2015). Surface ozone concentrations vary spatially at the global scale. Data from ozone measurement stations around the globe for 1995 – 2014 showed that while ozone levels had become more stable in Europe and declined in North America, levels in rapidly developing regions such as East Asia continued to rise

(Mills *et al*., 2018a). As a powerful oxidant, ozone can have a detrimental effect on vegetation, entering the leaves via the stomata and disrupting metabolic pathways (Emberson *et al*., 2018), which can lead to physiological changes, including decreased photosynthesis and early leaf senescence (Ainsworth *et al*., 2012).

For the continent of Africa, there is little measured data on ozone concentrations, however model simulations suggest that ozone increased over the last four decades in central Africa (Ziemke *et al*., 2019). In South Africa, ozone monitoring is carried out across a network of air quality monitoring stations (https://saaqis.environment.gov.za/). Data for 2019/2020 (accessed 1st June 2020) shows high maximum daily ozone concentrations (above 100ppb) during the crop growing season (for common wheat and beans) in states with high crop production (FAOSTAT, 2017). During biomass burning season, surface O_3 concentrations can reach peaks of up to 70 ppb in Rwanda (DeWitt *et al.,* 2019).

There are a number of sources of ozone precursors in Africa, including emissions from biomass burning, biogenic VOCs, lightning (NO_x), and anthropogenic activities (Bouarar *et al*., 2011). Large amounts of CO, NO_x and VOCs are emitted from burning biomass associated with savanna and forest fires, which takes place during dry and monsoon periods over West and Central Africa, respectively (Sauvage *et al*., 2005). Ozone is also a transboundary pollutant as precursors can travel far from their point of production before ozone is formed (Cooper & Derwent 2013). For example, dry season ozone concentrations in Rwanda are increased by transport of precursor gases from biomass burning in northern and southern Africa (DeWitt *et al*., 2019). Increasing application of fertiliser to crops is also predicted to lead to an increase in NO_x emissions in Sub-Saharan Africa (SSA), and in turn lead to an increase in ozone concentrations (Huang *et al*., 2018). Ozone concentrations are predicted to continue to increase in developing regions around the world in the future (Turnock *et al*., 2018) unless precursor emissions are further controlled.

Tropospheric ozone can have a negative effect on the quality and quantity of crop yield in sensitive species. A number of experimental studies on African crop species show a decrease in yield with elevated ozone. For example, Hayes *et al*. (2019) reported reductions in total yield and 1,000-grain weight for African cultivars of common wheat (*Triticum aestivum*) and widely grown cultivars of common bean (*Phaseolus vulgaris)* in high treatment levels of ozone (mean daily max concentration of 84.0 ± 4.5ppb and 93.0 ± 4.3ppb respectively). Exposure to elevated ozone led to a reduction in 100-seed weight and seeds per pod for the two most widely cultivated varieties of cowpea (*Vigna unguiculata* L.) grown in Ghana (Tetteh *et al*., 2015).

Modelling studies are particularly useful for providing estimates of potential ozone impacts for regions with few physical ozone measurements and/or where it may be difficult or impractical to carry out field experiments. Previous modelling studies, using ozone concentration based metrics, estimated that 4–15% of wheat yields, 3–4% of rice yields, 2–5% of maize yields and 5–15% of soybean yields are lost globally due to ozone pollution (Van Dingenen *et al*., 2009; Avnery *et al*., 2011). An alternative method is the flux-based approach (Emberson *et al*., 2000, Pleijel *et al*., 2007), which calculates ozone uptake via the stomata and takes into account environmental conditions that may influence uptake, for example, temperature, humidity and light. Flux-based models have been found to perform better than concentration-based models (Pleijel *et al*., 2007) and to be better predictors of the distribution of ozone damage (Mills *et al*., 2011). A recent global flux-modelling study estimated that ozone had reduced the annual global yield of soybean (12.4%), wheat (7.1%), maize (6.1%), and rice (4.4%), leading to a total of 227 million tonnes of lost yield (Mills *et al*., 2018c).

The aim of this study is to quantify the impact of ozone on common wheat and common bean across SSA using spatial data on crop production, modelled ozone flux values and flux-effect relationships from experimental data. In 2017, wheat was among the top ten crops produced in Africa (FAOSTAT, 2017). Common beans were the most common legume produced in East Africa in 2017 (FAOSTAT, 2017), providing an important source of dietary protein. While global flux modelling studies have been carried out for soybean, wheat, maize and rice (e.g. Mills *et al*., 2018b,c), this new study focuses on SSA, using finer resolution data (~0.33 by 0.33°), and a new crop (common bean), using a species-specific flux relationship for widely grown bean cultivars from experimental data. A more detailed case study for South Africa was also carried out, using spatial data per province.

2. Materials and Methods

2.1 The EMEP-WRF model

The EMEP MSC-W (European Monitoring and Evaluation Programme, Meteorological Synthesising Centre-West) chemical transport model (Simpson *et al.*, 2012) has been used for air quality assessments for more than 30 years. For this study, EMEP-WRF Africa version rv4.33 (Vieno *et al.,* 2016), which is based on the official EMEP MSC-W model (Simpson *et al.*, 2012) was used. While the EMEP MSC-W model uses data from the European Centre for Medium Range Weather Forecasting integrated Forecasting System (ECMWF-IFS) model, EMEP-WRF Africa uses the Weather Research and Forecast (WRF) model (Skamarock *et al*., 2019). The EMEP-WRF Africa model uses a latitude-longitude grid and 21 vertical layers with thickness varying from ~40 m at the surface to ~2 km at the top of the vertical boundary (~16 km). The WRF version 3.9.1.1 was used to calculate hourly 3D meteorological data used to drive the EMEP-WRF Africa model for the year 2015. The WRF model is initialised and nudges every six hours using the Global Forecast system final reanalysis (GFS-FNL) data (National Centres for Environmental Prediction, 2015). Nudging is a method for ensuring that model simulations resemble observed values. For further details on the WRF model methodology, including different types of nudging, see Skamarock *et al.,* (2019). The model domain covers the globe with a horizontal resolution of 1.0 x 1.0° and a nested domain covering the African continent with a horizontal resolution of ~0.33 x 0.33° (~37 x 37 km at the equator). The emissions used were based on the IIASA ECLIPSE v6a (Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants) GAINS (Greenhouse gas – Air pollution Interactions and Synergies) model for the year

2015 (Stohl *et al*., 2015). The WRF model output is not compatible with the convection parametrisation used in the EMEP MSC-W model, so this feature has not been included in this work. Model output data went through a process of quality assurance/control before use in subsequent analyses.

The EMEP-WRF Africa model was used to provide daily surface ozone concentrations (ppb) and ozone flux (POD_3IAM; phytotoxic ozone dose above 3 nmol m^{-2} s^{-1}, parameterised for integrated assessment modelling) values for Africa with a 0.33 x 0.33° grid cell resolution for 2015. The DO_3SE (Deposition of O_3 for Stomatal Exchange) model, originally developed in 2000 (Emberson *et al.* 2000, 2001) for estimating ozone deposition and stomatal flux, has been embedded within the EMEP model. The DO_3SE modelling approach is based on the multiplicative stomatal conductance (gs) model originally established by Jarvis (1976). The DO_3SE model simulates the effect of phenology, light, temperature, vapour, pressure deficit (VPD) and soil moisture deficit on stomatal conductance. These factors are considered most important in determining the opening and closing of stomatal pores. The model has been developed to allow the evaluation of species-specific stomatal conductance (gs) if appropriate experimental data are available to parameterise the model. The DO_3SE model has been continuously improved and updated since the original modelling approach was first developed by Emberson *et al.,* (2000). For further details on the equations used by the DO_3SE model within the EMEP model, see Simpson *et al*., (2012).

Within the EMEP model (via DO_3SE), the estimation of stomatal ozone flux follows the assumption that the concentration of ozone at the canopy top represents a reasonable estimate of the concentration near the sunlit upper canopy leaves (or flag leaf for wheat), at the upper surface of the laminar layer. The model uses (hourly mean modelled) ozone concentration at canopy height, deposition rate of ozone (allowing for boundary layer and leaf surface resistance), and the fraction of ozone taken up by the stomata to calculate ozone uptake i.e. flux. For further details and full equations, see the Modelling and Mapping Manual (CLRTAP, 2017). Daily flux values are calculated from modelled hourly stomatal uptake and accumulated during daylight hours.

For this study, POD_3IAM was calculated with the model parameterised for Integrated Assessment Modelling (IAM). This involves using simplified flux models for a vegetation type (e.g. crops) rather than one species, which allow estimates to be provided at a larger scale than POD_YSPEC (values for a specific species). There are difficulties in estimating ozone flux at higher values of Y (e.g. Y = 6 nmol m^{-2} s^{-1}) due to the increase in uncertainty with increasing Y (CLRTAP, 2017). The simplified models used for IAM do not include the modifying effect of phenology or soil moisture as inputs to calculate ozone flux. When used within the EMEP model (Simpson *et al.,* 2012) however, a simplified soil moisture index is included in the final calculations of ozone flux. The EMEP model outputs both irrigated (calculated without soil moisture limitation) and non-irrigated (calculated using a modelled soil moisture index) POD_3IAM values per grid cell. For crops, POD_3IAM is calculated over 90 days, centred on the timing of mid-anthesis (flowering) and example model parameterisation values are already available (CLRTAP, 2017), based on European wheat.

The EMEP-WRF Africa model was parameterised using the POD_3IAM crop inputs, but these were adjusted for African wheat and common beans using published experimental data (for example, g_{max}, optimal temperature) from work carried out on African crops in the UK CEH Bangor solardomes 2017 – 2019 (Hayes *et al*., 2019, 2020). See Supplementary Material, Tables S1 and S2 for the model input values. Hayes *et al.* (2020) provide further details on the experimental set up.

2.2 Crop production data

Crop production data were obtained from the Spatial Production Allocation Model (SPAM; You *et al.,* 2014), resolution 0.0833 by 0.0833° for the year 2010. Both irrigated and non-irrigated production (tonnes) data for SSA were downloaded for wheat and beans.

Using ArcGIS (version 10.6), a 0.33 x 0.33° fishnet grid (aligned with the EMEP data grid) was created and for each crop, production per cell was summed. Cells were designated a SSA country, based on the area of the country within the cell. For each country, a conversion factor was calculated using national production data from the Food and Agriculture Organisation of the United Nations (FAO) (2015 production/2010 production), then the production per grid cell was multiplied by this value to provide an estimate of production in 2015.

Similarly, for the South African case study, each grid cell was designated a province, based on the area of the province within the cell. For each province, a conversion factor was calculated using crop production data for 2010 and 2015 published by the South African government (Directorate of Statistics and Economic Analysis 2018) (2015 production/2010 production), then the production per grid cell was multiplied by this value to provide an estimate of production in 2015.

2.3 Calculating 90-day POD_3IAM

For each crop, a 90-day period before harvest was designated for the SSA countries listed in the SPAM data as crop producers (Tables S3 & S4). This time-period includes the ozone-sensitive period between anthesis and end of grain fill (Soja *et al.*, 2000). Growing season information was taken from the FAO crop calendar (http://www.fao.org/agriculture/seed/cropcalendar/welcome.do) and the FAO Global Information and Early Warning System country profiles (http://www.fao.org/giews/country-analysis/en/). If there was no information available for a particular country, then the growing season for the nearest country with the crop growing in the same climate zone was used, based on the global "Climatic Zone" GIS raster layer produced by the European Soil Data Centre (ESDAC) at JRC (Joint Research Centre).

The POD_3IAM over the designated 90-day period was calculated for each 0.33 by 0.33° grid cell in SSA and mapped for each crop. Due to the variation in climate zone and altitude across Africa, crops are grown throughout the year and beans can have more than one growing season in a year in some African countries. The POD_3IAM was therefore calculated for two growing seasons for beans, a) growing seasons spanning March – July (spring - summer in Northern Hemisphere); b) growing seasons spanning August to February (autumn - winter in Northern Hemisphere; Table S4). Irrigated and non-irrigated accumulated POD_3IAM per grid cell were calculated. Grid cells were classed as irrigated (>75% irrigated production per cell) and non-irrigated (<75% irrigated production per cell). For irrigated grid cells, irrigated POD_3IAM values were used, for non-irrigated cells, non-irrigated POD_3IAM values were used.

The start and end of the growing season for each crop may vary within a country, for example, due to weather conditions or elevation. Hence, we used South Africa as a case study to allow detailed information on growing seasons for crops in each province to be used. The growing season for wheat production in South Africa varies depending on province and irrigation practices. Growing season information for irrigated and rainfed wheat was taken from the USDA Major World Crop Areas and Climate Profiles (http://www.usda.gov/oce/weather/pubs/Other/MWCACP/index.htm), the Abstract of Agricultural Statistics (Directorate of Statistics and Economic Analysis, 2018) and Guidelines for the Production of Small Grains in the Summer Rainfall Region (ARC-Small Grain, 2019). Using the SPAM production data for 2010, wheat production totals (irrigated and non-irrigated) were calculated for each South African province (Table S5) and subsequently converted to 2015 production data as described above.

For South African provinces with the majority of production being rainfed (Western Cape, Free State, North West, KwaZulu-Natal, Mpumalanga and Gauteng), non-irrigated ozone data were used to calculate the 90-day POD_3IAM. For provinces with >40% irrigated production overall (Northern Cape, Limpopo and Eastern Cape), grid cells were split into irrigated (with >75% irrigated production per grid cell) and non-irrigated (<75% irrigated production per grid cell). For irrigated grid cells in these provinces, the irrigated growing period and ozone data were used to calculate POD_3IAM. For non-irrigated cells, non-irrigated ozone data and growing period were used. See Table S6 for the wheat growing seasons used for each South African province.

Bean planting times per province were taken from https://www.horticulture.org.za/green-bean-planting-times/. Production data per province (SPAM 2010 spatial data) indicated that while irrigation of beans varied per state, the majority of beans produced were rainfed (Table S7). No specific information on growth periods for irrigated and non-irrigated beans could be sourced, therefore the primary growing periods for each province were used for all grid cells. When irrigated production per grid cell was >75%, irrigated ozone data were used to calculate the POD_3IAM over 90 days, otherwise non-irrigated ozone data were used. Bean growing period information also indicated that the growing season varied depending on the presence of frost in the winter. South Africa has areas known as the Highveld, (1500m < elevation < 2100m) and the Lowveld (150m < elevation < 600 m). Beans growing in the Highveld (exposed to winter frost) grow at a different time of year from beans growing in the Lowveld (hot summers and frost-free winters). Using SRTM (Shuttle Radar Topography Mission, v4.1) elevation data (90m resolution) to calculate the average elevation per grid cell, cells in the provinces of Mpumalanga, Limpopo and Kwazulu-Natal were split into 'Highveld' and 'Lowveld' and assigned 90-day accumulation periods based on this classification (Table S8).

2.4 Yield loss calculations

Using the POD_3IAM values per grid cell, the percentage yield loss due to ozone for each crop was calculated. For wheat, the African wheat yield data collected in the solardome experiments was not a large enough sample to calculate a robust flux effect relationship (Hayes *et al.,* 2020). However, Hayes *et al*. (2019) show that the African wheat cultivars tested have a similar ozone sensitivity as European cultivars. Therefore, the POD_3IAM flux-effect relationship for European wheat from the Modelling and Mapping Manual (CLRTAP, 2017) was used, using the most up to date methodology adopted by the convention:

$$\% \text{ yield loss} = (POD_3IAM - 0.1) * 0.64 \qquad \textbf{Equation 1}$$

where 0.1 is a reference value used to represent ozone uptake at pre-industrial or natural ozone levels and subtracted before yield loss is calculated and 0.64 is the slope of the relationship between

POD_3IAM and percentage yield reduction (Fig. S1), and represents the percentage reduction per mmol m^{-2} POD_3IAM.

For beans, experimental data from the UK CEH Bangor solardomes (2017-2019) was used to calculate a flux-effect relationship (Fig. S2). POD_3IAM was estimated using the DO_3SE model stomatal algorithm (Emberson *et al*., 2000, 2001, CLRTAP, 2017). Following Zuur *et al*. (2009), generalised least squares (gls) regression (using the R 'nlme' package (Pinheiro *et al.*, 2018)) was used to model the relationship between relative yield and POD_3IAM, to allow for the spread in the data as POD_3IAM increased. The reference value was calculated for the experimental conditions under which the flux-effect relationship data were collected, assuming constant 10 ppb ozone across the 90-day period. For the bean experiment, this reference value was zero.

Therefore the equation for the bean flux-effect relationship was:

$$\% \text{ yield loss} = POD_3IAM * 1.175 \qquad \textbf{Equation 2}$$

2.5 Production loss calculations

Following Mills *et al*., (2018b), production loss due to ozone was calculated using the following equation:

Production loss = (Total production/(Relative yield))- Total production) **Equation 3**

Where 'relative yield' = 1 - (% yield loss/100) **Equation 4**

For SSA countries where beans were grown in two seasons, annual production was divided by two before calculating production loss for each season.

3. Results

3.1 Surface ozone concentrations in Africa

Daily mean ozone concentrations varied with season (Fig. 1). During the first three months of the year, concentrations in SSA were highest in western and central areas, including the Democratic Republic of the Congo (DR Congo) and the Central African Republic (Fig. 1a). During April to June, ozone concentrations in SSA were slightly lower, with the highest values still in central/western areas, including Chad, Nigeria, Cameroon, Burkina Faso and the Central African Republic (Fig. 1b). Between July and September 2015, the highest ozone concentrations were found slightly further south, particularly in DR Congo and Angola (Fig. 1c). The final period, October to December 2015, showed the lowest ozone concentrations, with pockets of slightly higher values across SSA, for example in Nigeria, Botswana and Ethiopia (Fig. 1d).

3.2 Ozone impact on wheat production in Sub-Saharan Africa

Wheat is produced across SSA, with production levels highest in Ethiopia, South Africa and Sudan (Fig. 2a, Table 1). FAO national data suggested that wheat production increased for many countries between 2010 and 2015, particularly Rwanda and Mali (Table 1). In 2015, average ozone flux (POD_3IAM) values were highest in Cameroon (20.2 mmol m^{-2} ± 7.9sd) and Zambia (14.3 mmol m^{-2} ± 3.3sd) (Fig. 2b, Table S9). In the countries with the highest wheat production, average POD_3IAM values were lower, for example, in Ethiopia (9.7 mmol m^{-2} ± 3.8sd) and South Africa (4.3 mmol m^{-2} ± 2.5sd) (Table 1). Average percentage yield loss estimates for wheat varied between 2 and 13%, with high losses in Cameroon (13.0% ± 5.0sd) and Zambia (9.1% ± 2.1sd) (Fig. 2c, Table S9). Figure 2b&c also show that there were pockets of high ozone flux and yield loss estimated within some countries, for example in northern and western areas of Ethiopia and southern areas of South Sudan.
Production losses in SSA due to ozone, which account for the combination of the total amount of wheat grown and the % yield loss, were highest in the countries with the highest wheat production, including Ethiopia and Sudan (Fig. 2d, Table 1). Rwanda also had a relatively high production loss of 46,000 tonnes. The total estimate for wheat production loss due to ozone for SSA in 2015 was 453,000 tonnes (Table S9).

Table 1. Wheat production and ozone-induced losses per country in Sub-Saharan Africa for the 10 countries with the highest estimated production loss in 2015. SPAM production data are used for 2010, values for production in 2015 have been estimated using conversion factors from FAO national totals.

Country	2010 prod. (Th. t)	2015 prod. (Th. t)	Av. POD_3IAM (mmol m^{-2})	±sd	Av. % yield loss	±sd	Total prod. loss (Th. t)
Ethiopia	2950	4805	9.7	3.8	6.1	2.4	233
Sudan	442	853	7.5	4.5	4.7	2.9	69
Rwanda	72	758	10.8	2.4	6.9	1.5	46
South Africa	1792	1826	4.3	2.5	2.7	1.6	46
Zambia	201	250	14.3	3.3	9.1	2.1	27
Mali	24	87	9.2	3.6	5.8	2.3	7
Tanzania	88	102	10.3	3.0	6.5	1.9	5
Kenya	331	154	6.9	3.6	4.4	2.3	4
Nigeria	115	63	4.1	3.8	2.5	2.4	3
Zimbabwe	19	49	5.8	3.7	3.7	2.4	3

3.3 Ozone impact on bean production in Sub-Saharan Africa

3.3.1 Season 1

Common beans are widely grown across SSA. Countries with the highest production include Tanzania, Kenya and Uganda (Fig. 3a, Table 2). FAO national data suggested that bean production increased for the majority of countries between 2010 and 2015, particularly Togo, DR Congo and Kenya (Table 2). In season 1, ozone flux values in 2015 were highest in the central countries of SSA (Fig. 3b), with the highest average values in Congo (17.9mmol m^{-2} ± 3.1sd) and DR Congo (15.8mmol m^{-2} ± 4sd) (Table S10). In countries with the highest bean production, average flux values were lower, for example, Tanzania (10.1 mmol m^{-2} ± 2.9sd) and Kenya (11.3 mmol m^{-2} ± 4.6sd) (Table 2). Estimated (average) percentage yield losses due to ozone were again highest in the central area of SSA, with values ranging from 0.9% ± 0.7sd (Mauritania) to 21.0% ± 3.7sd (Congo) (Fig. 3c, Table S10). Other countries with high estimates for average yield loss included DR Congo (18.6% ± 4.7sd), Togo (17.5% ± 3sd) and Uganda (16.5% ± 5.1sd) (Table 2). Countries with the highest bean production showed slightly lower estimates for average percentage loss, for example Tanzania (11.9% ± 3.4sd) and Kenya (13.3% ± 5.4sd). Production losses due to ozone were generally highest in the countries with the highest bean production, for example Tanzania (55,000 tonnes), and Kenya (47,000 tonnes) (Fig. 3d, Table 2). As Uganda had a high estimate for percentage yield loss (16.5%), estimated production loss was also high (43, 500 tonnes), despite the country not being one of the top producers. Total estimated production loss for beans due to ozone in season 1 was 370,000 tonnes (Table S10).

Table 2. Bean production and ozone-induced losses (season 1) per country in Sub-Saharan Africa for the 10 countries with the highest estimated production loss in 2015. SPAM production data are used for 2010, values for 2015 have been estimated using conversion factors from FAO national totals. For countries where beans were grown in two seasons, annual production and estimated production losses were divided by two.

Country	2010 prod. (Th. t)	2015 prod. (Th. t)	Av. POD_3IAM (mmol m^{-2})	± sd	Av. % yield loss	± sd	Total prod. loss (Th. t)
Tanzania	382	529	10.1	2.9	11.9	3.4	54.86
Kenya	240	469	11.3	4.6	13.3	5.4	47.05
Uganda	249	266	14.0	4.3	16.5	5.1	43.49
Ethiopia	182	318	11.5	4.2	13.5	4.9	37.62
Cameroon	170	175	13.7	7.3	16.1	8.6	34.81
Ghana	210	212	12.9	2.5	15.1	2.9	31.64
Togo	76	177	14.9	2.5	17.5	3.0	28.33
Rwanda	156	207	8.9	2.5	10.4	3.0	20.05
DR Congo	75	156	15.8	4.0	18.6	4.7	18.13
Benin	110	101	12.1	5.0	14.2	5.9	16.77

3.3.2 Season 2

Bean production in the second growing season was more focused on the central area of SSA (whereas in the first growing season, there was more production in Western Africa) (Fig. S3). Countries with the highest production include Tanzania, Kenya and Angola (Fig. S3a, Table S11). FAO national data suggested that bean production increased for the majority of countries between 2010 and 2015 (Tables S11, S12). Ozone flux values were generally highest in the central part of SSA, however high values were also seen in South Africa (Fig. S3b). Countries with the highest average flux values in season 2 included Cameroon (13.4 mmol m^{-2} ± 6.4sd), DR Congo (12.6 mmol m^{-2} ± 3.0sd) and Angola (12.1 mmol m^{-2} ± 3.1sd) (Table S11). In this second growing season, some countries with high bean production had relatively high average flux values, for example Angola, however values were lower in Tanzania (5.3 mmol m^{-2} ± 3.0sd) and Kenya (6.7 mmol m^{-2} ±3.6sd) (Table S11). Similarly, estimated percent yield losses due to ozone were highest in central areas of SSA, with high values also seen in South Africa (Fig S3c). The highest estimated average percentage yield losses were seen in Cameroon (15.7% ± 7.5sd), DR Congo (14.8% ± 3.5sd) and Mozambique (14.4% ± 1.8sd) (Table S12). Some countries with high bean production, had relatively high average yield loss values, for example Angola, however values were lower in Tanzania (6.3% ± 3.5sd) and Kenya (7.8% ± 4.3sd) (Table S11). The highest production losses due to ozone were estimated for Angola (60,000 tonnes), Uganda (42,500 tonnes) and Tanzania (41,500 tonnes) (Fig. S3d, Table S11). While Uganda was not one of the highest producing countries, the relatively high yield loss led to a high estimate of production loss. Total estimated production loss for beans due to ozone in season 2 was 337,000 tonnes (Table S12).

3.4 South Africa case study

3.4.1 Ozone impact on wheat production

Key wheat production areas in South Africa were the Western Cape, Free State and Northern Cape provinces (Fig. 4a), with 37%, 28% and 15% production respectively in 2010 (Table 3). Government data per province show that in 2015 wheat production had increased in some states (e.g. Western Cape and Northern Cape) but decreased in others (e.g. Free State) (Table 3). In 2015, ozone flux (POD_3IAM) values for wheat were highest in the north of the country, in Limpopo province, with values >12 mmol m^{-2} (Fig. 4b). The highest average flux value was for the Free State (8.8 mmol m^{-2} ± 2.0sd; Table 3), where 28% of South African wheat was produced in 2010. In the Western Cape, the province with the highest wheat production in 2010 (and 2015), ozone flux values were low. The average flux for South Africa was 6.6 mmol m^{-2} (**±** 3.3sd). Figure S4 shows where irrigated wheat cells were located in the Northern Cape, Limpopo and the Eastern Cape. It can be seen that ozone flux values for irrigated cells were higher than other cells within these provinces, particularly in Limpopo. Irrigated wheat is grown later in the season when ozone concentrations are slightly higher and irrigation increases the ozone uptake by the plants.

Estimates of (average) wheat yield loss due to ozone in 2015 varied between <2 and >8%, with grid cell values highest in the north of the country, in Limpopo province (Fig. 4c). The highest average yield loss was seen in the Free State (5.6% ± 1.3sd; Table 3). In the provinces with the greatest levels of wheat production, yield loss varied between primarily <2% for the Western Cape, areas of 6-8% loss for the Free State and primarily 4-6% yield loss for the Northern Cape. Across South Africa, the average yield loss for wheat was 4.2% (± 2.1sd). Wheat production losses due to ozone in 2015 were highest in the Northern and Western Cape provinces of South Africa (Fig. 4d, Table 3), with 15, 700 and 14, 000 tonnes lost respectively. The Free State (13, 700 tonnes) and Limpopo (10, 700 tonnes) also showed relatively high losses. The total estimated wheat production loss due to ozone for 2015 in South Africa was 61,700 tonnes (Table 3).

Table 3. Wheat production and ozone-induced losses per province in South Africa in 2015. Production data are from the SPAM 2010 model. Production was estimated for 2015 using a conversion factor value, calculated per province from South African government production data for the years 2010 and 2015.

Province	**2010 prod. (Th. T)**	**2015 prod. (Th. T)**	**Av. POD_3IAM (mmol m^{-2})**	**± sd**	**Av. % yield loss**	**± sd**	**Total prod. loss (Th. T)**
Western Cape	670	881	2.5	0.8	1.6	0.5	14.04
Northern Cape	272	279	8.2	1.2	5.2	0.7	15.68
Free State	520	242	8.8	2.0	5.6	1.3	13.65
Limpopo	109	240	7.0	4.9	4.4	3.2	10.69
North West	123	85.97	4.0	2.1	2.5	1.4	2.39
KwaZulu-Natal	39.88	54.50	7.2	3.5	4.6	2.2	2.94
Mpumalanga	38.65	32.21	4.7	3.0	2.9	1.9	1.21

Eastern Cape	22.99	19.16	7.8	1.6	5.0	1.0	0.97
Gauteng	11.27	2.25	7.9	1.4	5.0	0.9	0.12
South Africa	1,806	1,837	6.6	3.3	4.2	2.1	61.69

3.4.2 Ozone impact on bean production

The majority of bean production was in the Free State, Mpumalanga and the Eastern Cape (Fig. 5a), with small amounts of production in the other provinces (Table 4). Bean production in 2015 increased in the Free State and Eastern Cape compared to in 2010, however decreased in other provinces, particularly in Mpumalanga and KwaZulu-Natal (Table 4). In 2015, ozone flux (POD_3IAM) values for bean were highest in the north of the country, particularly in Limpopo and also parts of the North West, Gauteng and Mpumalanga provinces (Fig. 5b). The highest average flux value was for Gauteng province (14.3 mmol m^{-2} ± 1.9sd; Table 4). Flux values were also relatively high in the Free State (up to 15-18 mmol m^{-2}), which is where the majority of bean production in South Africa occurs. The average flux for South Africa for beans was 11.3 mmol m^{-2} (± 3.9sd). Figure S5 shows where Lowveld cells are located in Limpopo, Mpumalanga and KwaZulu-Natal. It can be seen that ozone flux values for Lowveld cells were generally low compared to other cells within these provinces. Beans in the Lowveld region are grown at a different time in the season (planted in March-April compared to Dec-Jan) when ozone concentrations are slightly lower, ozone concentrations also tend to increase with altitude.

Estimated yield loss for beans in 2015 was considerably higher than for wheat, with maximum values >20% (Fig. 5c). Losses were highest for grid cells in the northern part of South Africa, particularly in Limpopo and Gauteng. The highest average yield loss was seen in Gauteng (16.8% ± 2.2sd, Table 4). Areas of losses >20% were also seen in the North West, Mpumalanga and KwaZulu-Natal provinces. In the Free State, the province with the greatest bean production in South Africa, estimated yield losses were relatively high, particularly in the eastern half of the province, with estimates of 17.5-20% yield losses. The Lowveld grid cells showed the lowest estimated yield loss, <5% (See Fig. S5 for map of Lowveld cells). The average yield loss across South Africa for beans was 13.3% (± 4.6sd). In 2015, bean production losses due to ozone were lower than estimates for wheat. The highest production losses were seen in the Free State (6,591 tonnes) and Mpumalanga (1,542 tonnes) (Fig. 5d, Table 4). The total estimated bean production loss due to ozone for South Africa was 11,800 tonnes.

Table 4. Bean production and ozone-induced losses per province in South Africa in 2015. Production data are from the SPAM 2010 model. Production was estimated for 2015 using a conversion factor value, calculated per province from South African government production data for the years 2010 and 2015.

Province	**2010 prod. (T)**	**2015 prod. (T)**	**Av. POD_3IAM (mmol m^{-2})**	**± sd**	**Av. % yield loss**	**± sd**	**Total prod. loss (T)**
Free State	20568	33300	13.7	2.3	16.2	2.7	6591
Mpumalanga	11789	8322	11.6	5.3	13.7	6.2	1542
Eastern Cape	1800	7201	10.9	1.7	12.8	2.0	1070
Gauteng	3288	4326	14.3	1.9	16.8	2.2	889
KwaZulu-Natal	6837	3703	10.2	5.1	12.0	6.1	522
Limpopo	7894	3107	13.5	5.1	15.9	6.0	650
North West	4957	2163	13.4	2.9	15.8	3.4	459
Northern Cape	1023	614	8.8	1.9	10.4	2.2	69.4
Western Cape	630	420	8.6	2.4	10.1	2.8	41.5
South Africa	58,786	63,156	11.3	3.9	13.3	4.6	11,833

4. Discussion

4.1 Spatial and seasonal variation in ozone impacts

This study indicates that ground-level ozone can have a substantial negative impact on the production of both wheat and beans in SSA. However, the spatial patterns and the location of the highest losses varied for the two crops. Results indicated that the areas with the highest estimated percentage losses do not necessarily have the highest production losses, because the highest ozone flux values might occur where production is low. For wheat, the greatest production losses were estimated for countries with the most production, including Ethiopia and Sudan. For beans in season 1, production losses due to ozone were generally highest in the countries with the highest production, while in season 2, not all of the countries with the greatest production loss were those with the greatest production (for example, Uganda).

For South Africa, average yield loss due to ozone for wheat and beans was 4.2% and 13.3% respectively, however as more wheat is produced in South Africa than beans, the overall production losses for wheat were higher than for beans. The region with high ozone flux and percentage yield loss values for beans (north-east) is the largest industrial area of South Africa with emissions of atmospheric pollutants from anthropogenic activities (Lourens *et al*. 2011, 2012). Spring maximum ozone concentrations (the key growing season for beans), can also be attributed to regional biomass burning (Laban *et al.,* 2018). Due to their high protein content, it is predicted that efforts may be made to increase bean yield in the future. Estimates of percentage yield loss provide important information on where production loss due to ozone could become a significant problem, if crop production were to increase in the future.

Results for South Africa in the broad-scale and more detailed study differed slightly. For example, for wheat, although estimated total production losses were similar, the case study using finer scale data identified additional areas 'at risk,' which were not detected at a coarser resolution. A small difference in growing season could be important if this causes a greater overlap with the time-period of highest ozone flux. Detailed studies for individual countries can be more informative, particularly if data are also available on ozone flux-effect relationships with local crop cultivars. However if detailed data are difficult to source, broad-scale studies are a useful first step to provide an overview of the potential risk of ozone impacts. These studies highlight high risk areas, which could then be followed up with further investigation, including the placement of relatively low cost methods of measuring local ozone concentrations, for example, passive (diffusion) samplers (Saitanis *et al.,* 2020).

The South African study shows that crops sown in slightly different growing seasons, due to timing of irrigation or elevation, can be exposed to differing levels of ozone flux. For example, for wheat, ozone flux values for irrigated grid cells tended to be higher than other neighbouring cells. Irrigated wheat is grown later in the season when ozone concentrations are slightly higher and irrigation can increase ozone uptake as leaf stomata open to allow water intake. Increased ozone flux and yield loss were demonstrated for irrigated wheat in a recent global modelling study (Mills *et al.,* 2018b). There may be potential for crop growers to mitigate the impact of ozone on yield by practicing irrigation and crop management (e.g. sowing date) strategies. Harmens *et al.* (2019) investigated the effect of irrigation regimes on Kenyan wheat growing in low (30 ppb) and high (80 ppb) ozone treatments. Reduced irrigation stimulated grain weight and harvest index, which compensated for ozone induced reductions in well-watered plants.

4. 2 Sources of variation in modelling results

4.2.1 Comparison with other global modelling studies

Mills *et al*. (2018b) evaluated the POD_3IAM modelling approach (at the global scale) using the EMEP-MSC West model, finding that the model captured spatial and temporal variations when modelled and measured ozone data were compared. In the current study, the EMEP-WRF model (Vieno *et al.,* 2016) was used, which works with a different source of meteorological data. Also more up to date crop production data (SPAM 2010, You *et al*., 2014) were used in the current study. A comparison of wheat yield loss estimates for SSA between Mills *et al*. (2018b, c) and the current study does show higher estimates in some countries for the latter. Further differences between the studies include the resolution and the years of ozone flux data used. Due to computational constraints, the EMEP-WRF model was run for only one year (2015), while Mills *et al*. (2018b, c) ran the EMEP-MSC West model for the years 2010-2012. Due to the lack of measured ozone data for SSA, it was difficult to test if differences in model output were due to the time-periods used. Ozone concentrations (and flux values) can be expected to vary between years (e.g. Balashov *et al.*, 2014), primarily due to variations in weather and emissions of precursors. To build on the current results, future modelling should be carried out with further years of data (or an average across years) to allow for annual variation in ozone levels.

Modelling studies using concentration-based metrics to estimate yield loss (e.g. Van Dingenen *et al*., 2009, Avnery *et al*., 2011) show varying results for SSA, depending on the model and metric used. Van Dingenen *et al.* (2009) estimate wheat yield loss (in year 2000) for some areas of SSA, e.g. Zambia, at ~30%, however the model used was found to overestimate ozone levels for some African areas and model resolution was reduced over Africa. Avnery *et al*. (2011) present national relative yield loss for wheat (year 2000), for example 2-4% (M12) and 6-8% (AOT40) in South Africa, which are more similar to the results for the current study.

4.2.2 Influence of growing season and crop cultivar

The growing seasons used for wheat and bean in this study were chosen to cover the majority of the production of each crop. However suggested planting times for beans can span several months. The optimum planting time for each country/province was chosen where possible, however the 90-day ozone flux for beans planted in October would differ from those planted in December. Other factors, including temperature, may also influence growing season length. An additional factor to include if possible is how planting times for irrigated crops vary from rainfed crops. There are many different wheat cultivars grown across SSA. Within South Africa, wheat cultivars have slight variations in optimum planting time (ARC-Small Grain, 2019). This could become increasingly important into the future if new cultivars are developed that might be selected to grow in a slightly different growing season to account for changes in climate.

Different cultivars of a crop can show differing sensitivity to ozone, for example, different bean cultivars showed varying effects on yield after ozone exposure (Hayes *et al.,* 2019). Flux-effect relationships are calculated using as many cultivars as possible to allow for this variation. However, for particularly sensitive cultivars, losses could be higher than estimated in this study. The flux-effect relationship used to calculate yield loss for African wheat (CLRTAP, 2017) uses data compiled from 13 experiments on five wheat cultivars, carried out in four European countries (Pleijel et al., 2007). Data were collected on the response of African wheat yield to ozone (Hayes *et al.,* 2020) however there were not enough data points for a robust relationship. Studies have indicated that the ozone sensitivity of crop cultivars could vary between continents (e.g. Emberson *et al.,* 2009, Osborne *et al*., 2016). However, Hayes *et al*. (2019) report that the African wheat cultivars tested had a similar ozone sensitivity as European cultivars. Further experimental work is required to develop a flux-effect relationship specifically for African wheat cultivars to improve the predictions of potential production losses. This should include as many cultivars of varying ozone sensitivity as possible to provide a robust estimate of ozone impact on African crop production. For crop cultivars that are used widely and/or of particular economic importance in a region or country, it would also be beneficial to gather enough data to develop individual flux-effect relationships.

4.2.3 Crop production estimates

The SPAM crop production data are estimated using a combination of regional/national production data and spatial modelling (You *et al.,* 2014). When compared with South African government data (totals per province), values were in the same order of magnitude, however totals were not identical. Conversion factors (national or per province for South Africa) were used to convert between 2010 and 2015 production data. This method does not allow for any changes in distribution of production between 2010 and 2015, for example, new areas of production. The SPAM data may also not include all countries producing the crops of interest, for example, there are no data for bean production in Mali however, FAOSTAT (2017) provides a national production total for this country. Studies such as this could be used to highlight regions where it may be possible to expand production of a crop into a new area, but could also show where expansion of production areas should be treated with caution, as the potential yield losses due to ozone might outweigh the benefits of changing to a different crop. Additional factors must be taken into account however, for example, Rippke *et al*. (2016) report that 60% of the present suitable areas for common beans in SSA are likely to require a “transformational change,” for example switching crop types or moving away from agriculture, by 2100 due to predicted changes in climate.

4.3 Measured vs. modelled values

Due to the potential reduction in crop production reported in this study, it is important to validate the predictions. There is a focus on air pollution monitoring in cities, but this study shows that it is important to carry out more standardised ozone monitoring measure in agricultural areas, for example, in central countries of SSA. The estimated values of surface concentration from the EMEP-WRF model can be compared with measured ozone data from monitoring stations in South Africa (Laban *et al.,* 2018). Both the observed and modelled data show higher values towards the end of the year (spring-summer). However, the modelled EMEP data also show high values at the start of the year, which are not seen so clearly in the measured data. The mapped EMEP data are daily mean values (between 6am and 6am) presented for every 3 month period in 2015, while the observed data are hourly median values for each month, spanning a period of 2006 – 2015, therefore the outputs can't be directly compared. Further comparison between modelled and measured data (across SSA) would be useful. Laban *et al.* (2020) highlight how regional-scale ozone precursors and meteorological conditions can both influence daily ozone levels in South Africa. The EMEP model uses emissions of precursors as input data. While emission inventories are well developed for Europe, there are less up to date data available for Africa (including on how annual emissions are distributed across the year), which shows that it is very important to have improved information on the emission of precursors, such as from biomass burning, which has been shown to be an important local/regional source.

4.4 Future work

This study highlights that tropospheric ozone has the potential to reduce the production of staple food crops in Africa. In 2015, the total requirement for wheat in South Africa was higher than the total production (Department of Agriculture, Forestry and Fisheries, 2016), leading to importation of wheat from other countries. Van Ittersum *et al*. (2016) demonstrate the threat to food security in SSA due to the contrast between rapidly increasing population and demand and slow growing cereal yields, highlighting the need to focus on methods of closing the yield gap. To build on current knowledge and understanding, future studies should test the impact of ozone on a wider variety of tropical and temperate crop species, under realistic growing conditions if possible. As different cultivars of the same crop can show varying levels of ozone sensitivity, (demonstrated for African crops by Hayes *et al*. 2019, 2020), it would be beneficial to carry out screening of crop cultivars, including further commonly used cultivars of African wheat and common bean and other important SSA crop types for relative ozone sensitivity. This variation in response to ozone also highlights the potential scope for breeding ozone tolerant cultivars. Mills *et al.* (2018c) present an ideotype for an ozone tolerant crop but highlight the need to balance ozone tolerance with other favourable crop characteristics, such as high yield and disease resistance. It would therefore be useful to aim to include ozone as a factor in future regional SSA crop breeding programs. Lastly, measurements of ozone (for example, using passive samplers) from areas of SSA where models predict a high risk of crop production losses would be beneficial to validate model outputs and provide supporting evidence for policy makers.

5. Conclusions

Overall, while the methodology does contain some sources of variation, this study is the first to quantify the impact of ozone on two important SSA crops using finer resolution data than previous global studies and species-specific flux-effect relationships. The results demonstrate that efforts to reduce ozone precursors could contribute to reducing the yield gap in SSA, which would be particularly useful as ozone stress often occurs in areas where other stresses (such as pests & diseases or heat stress) are also a problem (Mills *et al.,* 2018c). More stringent air pollution abatement policies are required to achieve this in the future. In the shorter term, approaches based on crop management (e.g. irrigation, sowing date) and breeding ozone tolerant cultivars could provide potential solutions for reducing ozone impact on yield.

Figures

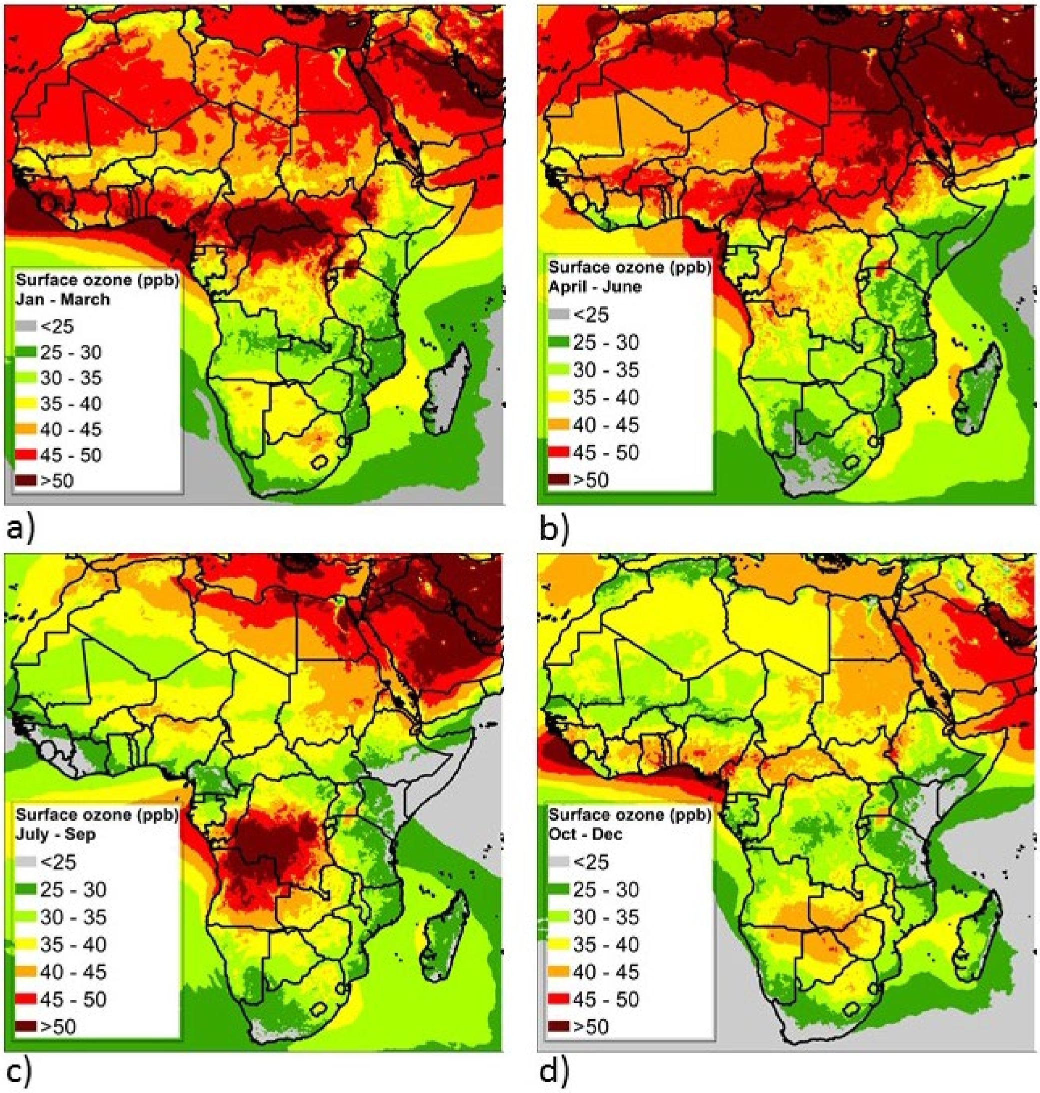

Fig. 1 EMEP-WRF Africa model output for surface ozone (ppb) daily mean (6am – 6am), averaged across 3 month periods for 2015; a) Jan – March, max = 68.7ppb; b) April – June, max = 66.9ppb; c) July – September, max = 84.2 ppb; d) October – December, max = 62.4ppb.

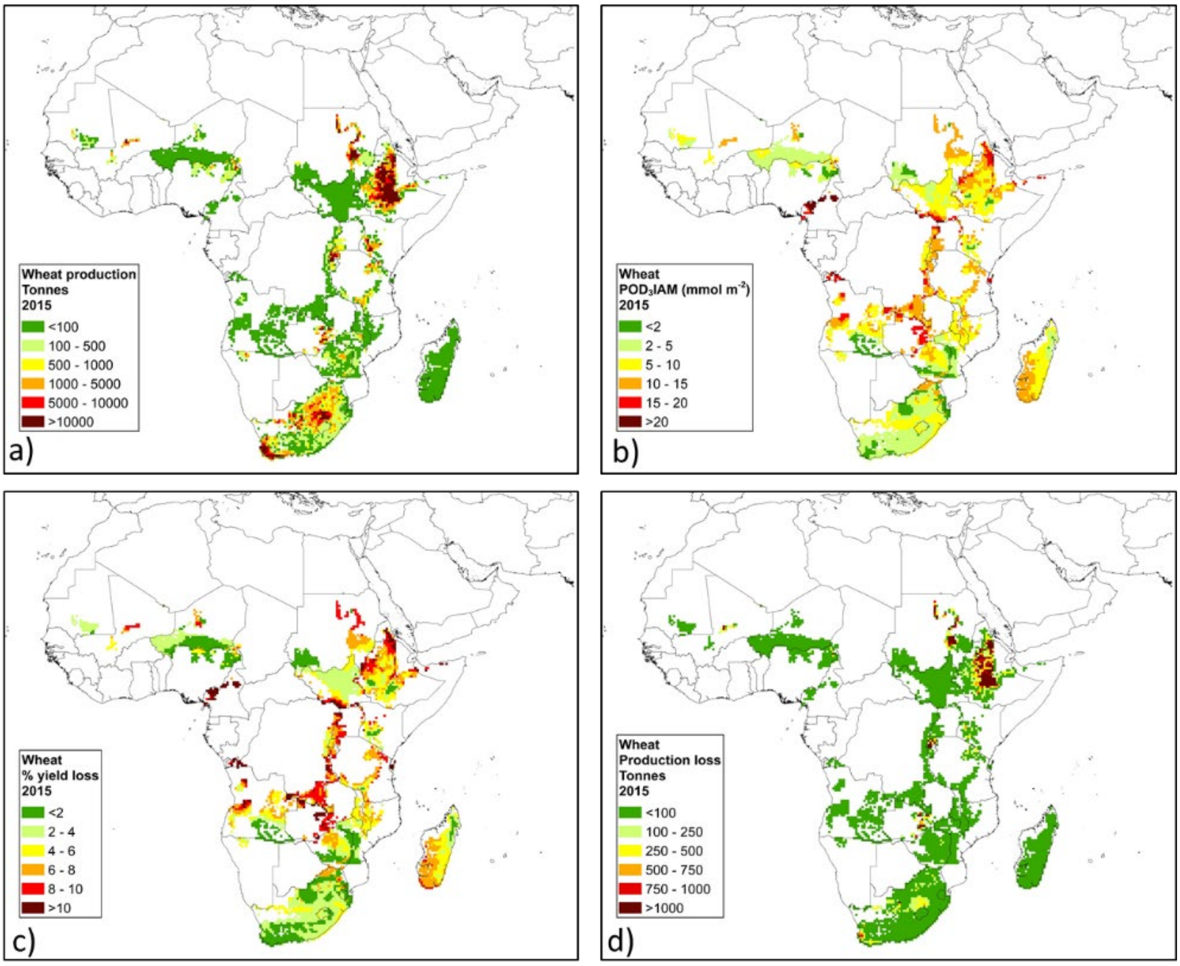

Fig. 2 Ozone impact on wheat production in Sub-Saharan Africa for the year 2015. a) Wheat production for 2015, using spatial data from the SPAM dataset for 2010 and FAO national conversion factors for 2015; b) POD_3IAM (mmol m^{-2}) for wheat, accumulated over a 90-day period during the growing season; c) Percentage yield loss for wheat due to ozone; d) Production loss (tonnes) in 2015 for wheat due to ozone.

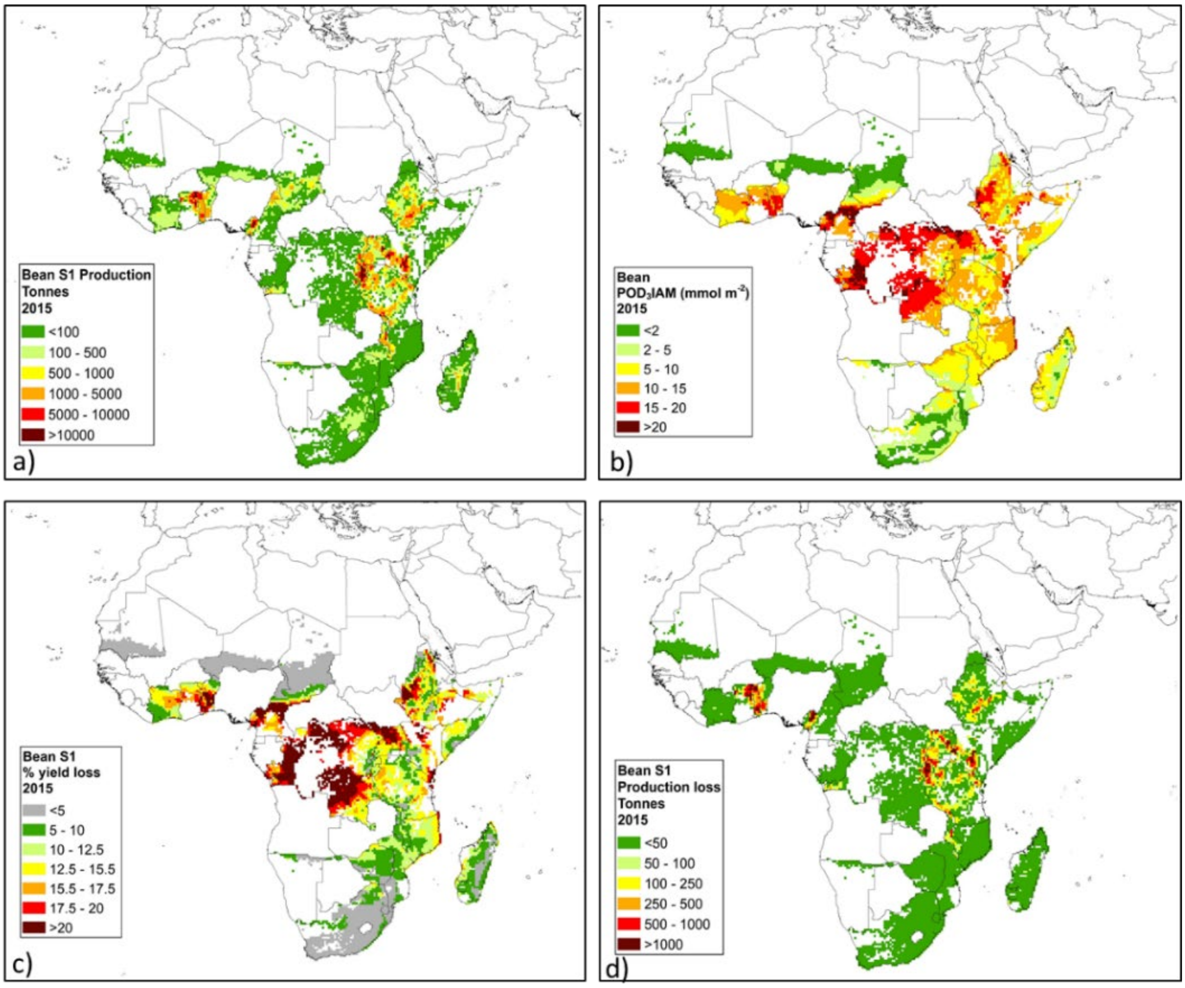

Fig. 3 Ozone impact on bean production in Sub-Saharan Africa for the year 2015 (season 1). a) Bean production for 2015, using spatial data from the SPAM dataset for 2010 and FAO national conversion factors for 2015; b) POD_3IAM (mmol m^{-2}) for bean, accumulated over a 90-day period during the growing season; c) Percentage yield loss for bean due to ozone; d) Production loss (tonnes) in 2015 for beans due to ozone. For countries where beans were grown in two seasons, annual production and estimated production losses were divided by two.

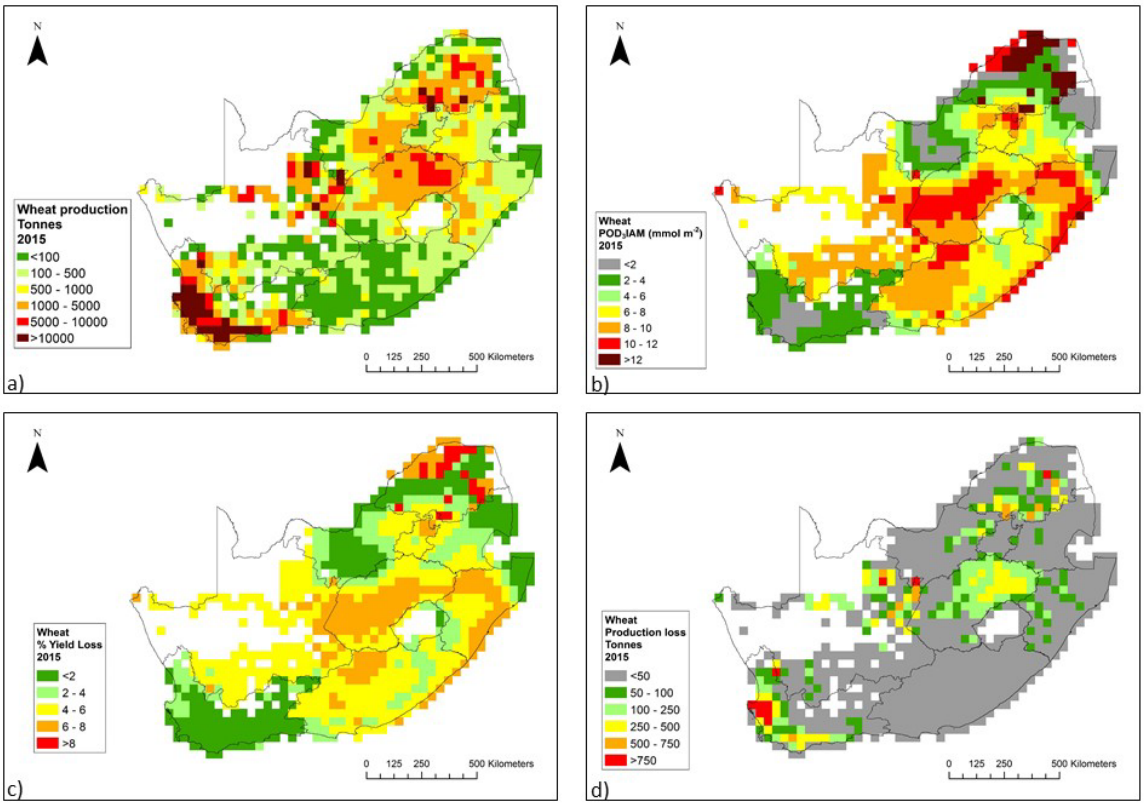

Fig. 4 Ozone impact on wheat in South Africa (a) 2015 wheat production (using SPAM 2010 spatial data, converted per province using Government data for 2015; b) POD_3IAM (mmol m^{-2}); c) Percentage yield loss due to ozone and d) Wheat production loss in 2015 due to ozone.

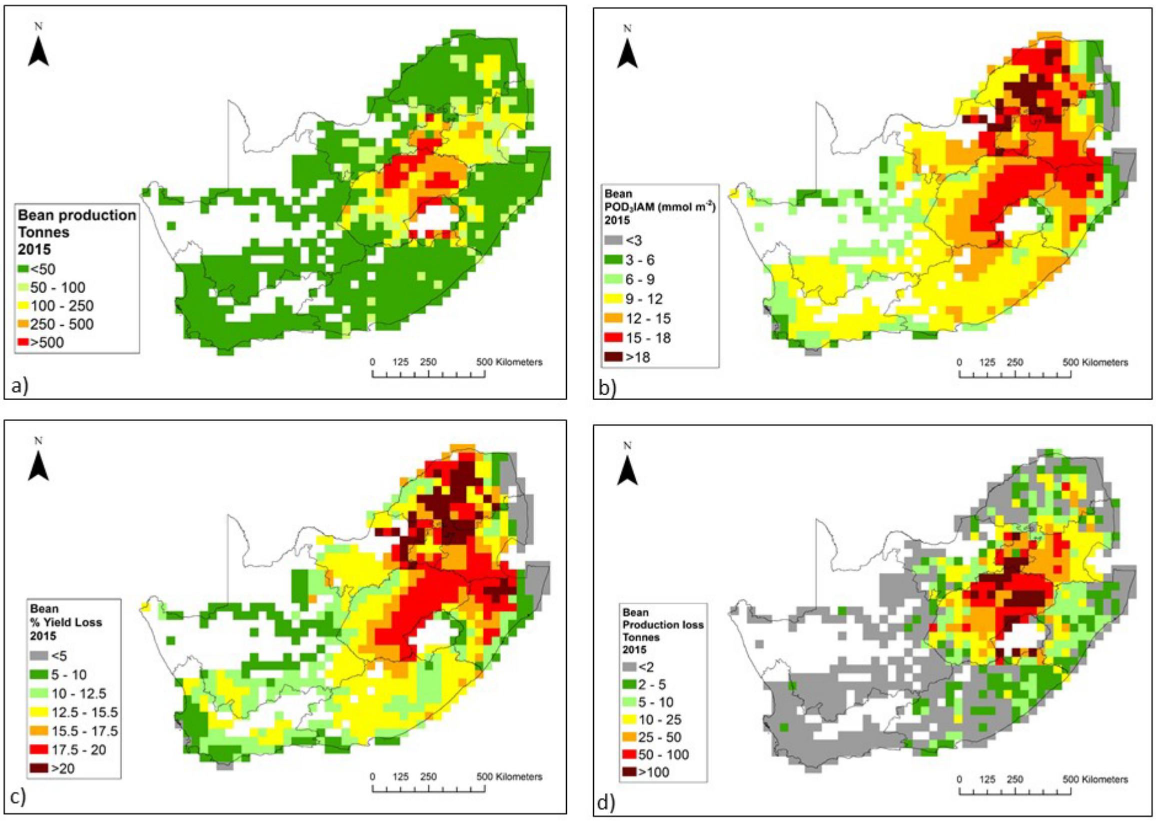

Fig. 5 Ozone impact on beans in South Africa (a) 2015 production (using SPAM 2010 spatial data, converted per province using Government data for 2015; b) POD_3IAM (mmol m^{-2}); c) Percentage yield loss due to ozone and d) Bean production loss in 2015 due to ozone.

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Declarations

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Not applicable.

Consent for publication:

Not applicable.

Availability of data and materials:

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request. Due to requirements of the NERC funding body, if requested, data would be made available via the Environmental Information Data Centre (EIDC), where data could be downloaded.

Competing interests:

The authors declare that they have no competing interests.

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Authors' contributions:

KS, FH and HH contributed to the study conception and design. Material preparation, data collection and analysis were performed by KS and FH. MM and RB ran the EMEP-WRF model, performed quality assurance/control and provided ozone flux data for further analysis/mapping by KS. The first draft of the manuscript was written by KS and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.