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Wheat yield loss in 2019 in Europe due to ozone exposure

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Summary

Tropospheric ozone impacts agricultural crop and timber production (yield, quality) entailing significant economic effects for the sector. This report assesses the impact of tropospheric ozone on wheat production in Europe in 2019. To this effect it uses the ozone impact indicator PODy (phytotoxic ozone dose above a threshold y), developed since the early 2000s by the IPC-Vegetation working in support of the Air Convention([1]) in connection with the Working Group on Effects (WGE). Contrary to AOT40, the earlier indicator used in the Air Convention and actually used in the Ambient Air Quality Directive (EU, 2008), PODy takes into account the conditions of hydrological stress the plant may be exposed to, which differs across Europe, and induces the plant to reduce its stomatal flows and thus its exposure to ozone. PODy thus allows for more satisfactory dose-response relationships, and reduces uncertainty in the assessment of ozone impacts on agricultural yields compared to the AOT40 indicator.

Following the development of an ozone flux calculation tool at Ineris (Schucht et al., 2019a, b), which applies the methodology described in the Manual for modelling and mapping critical loads & levels of the Air Convention (hereafter referred to as 'Mapping Manual') in its most recent available revision (CLRTAP, 2017), the PODy approach was implemented by the ETC/ACM([2]) in 2018 in the context of a trend assessment (Colette et al., 2018). In 2019, the ETC/ATNI started implementing the PODy calculation in the framework of the indicator mapping (Horálek et al., 2019). Annual production of PODy maps has started in 2020 (cf. Horálek et al., 2020). 2021 is the first year in which this work is included in the air quality assessment. For this, the objective of the present report is to translate the ozone flux calculations into yield losses expressed in %, in terms of quantity and in terms of economic value. This year's work focusses on ozone impacts on wheat for which methodological uncertainties are lowest.

We have implemented an impact modelling chain to quantify and monetize the loss in wheat production due to tropospheric ozone exposure for 2019 (the latest reporting year for which ozone data were available at the time of writing this report). To the extent possible, all input data are for this same year: meteorology, ozone concentrations, PODy maps, ozone fluxes, wheat production and wheat prices.

An additional objective consisted in studying the sensitivity of the results to the degree of spatialization of the input data. Reasons for this are (i) the EEA's request to identify possibilities of simplification and automation, thus reducing resources necessary and (ii) the wish to assess the additional uncertainty of an aggregated approach as it is applied in other tasks within the ETC/ATNI work.

In response to this additional objective, we have calculated a reference case for which we quantify ozone impacts on wheat at the highest spatial resolution possible. This reference case uses wheat production data provided at NUTS 2 (regional) level, then spatialized at the grid with a resolution of 2 km using information from Corine Land Cover (CLC). Ozone impacts on wheat are then calculated at grid level, combining production data and ozone fluxes at this high spatial resolution. The losses are then aggregated at NUTS 2 level and then at country level where they are monetized using wheat selling prices.

We have furthermore calculated results for two sensitivity cases where we reduce the spatial resolution of the input data. The first alternative case uses wheat production data provided at country level, which again is spatialized at the grid using CLC. Ozone impacts on wheat are then calculated at

([1]) Convention on Long-Range Transboundary Air Pollution (CLRTAP).
([2]) Predecessor of the ETC/ATNI.

grid level, combining production data and ozone fluxes at this high spatial resolution. Then losses are aggregated at country level. The second sensitivity case does not at all spatialize wheat production data. It aggregates average POD levels at the country level and calculates wheat production losses directly at the country level.

In the report the ozone flux approach is introduced and the ozone maps are compared to those for the AOT40 indicator. The statistical data available is presented and their spatialization at the grid explained, as well as the calculation of yield loss and economic damage. The report finishes with a presentation and discussion of the results and of uncertainties.

PODy levels in 2019 appear low compared to earlier years. One reason for this might be the draughts that affected large areas of Europe in 2019. Despite this, the results for our reference case show important losses of wheat production in 2019. Expressed in percentage, they reach levels of up to 9% in Greece, and levels between 8% and 9 % in Portugal, Cyprus, Albania and Czechia. For 17 countries the loss exceeded 5 %. In terms of quantities and monetary equivalent, losses were highest in France (almost 2 million tonnes or 350 million €), Germany (1.6 million tonnes or 280 million €), Poland (about 800 thousand tonnes or 140 million €) and Turkey (almost 750 thousand tonnes or 130 million €). Economic losses amounted to several millions of € in the majority of countries.

When comparing the percentage loss results of the reference case to the two sensitivity cases no clear pattern can be detected. Depending on the country, either of the three cases can show the highest percentage loss. When comparing these results to the two sensitivity cases, on a country level, percentage losses differed up to 2.8 percent. Aggregated at a European level, the differences were less than expected, but this is possibly related to the low ozone levels in 2019. It is suggested that the sensitivity study should therefore be repeated for a year with average PODy levels, before drawing final conclusions.

Monetary valuation of crop losses by gross production value or sales prices implicitly assumes that pollutant damage is not sufficient to affect the price of crops, although this approach is followed in many European and non-European studies, and it represents an approximation. However, the use of more complex models for the economic evaluation of crop loss may be considered disproportionate given that the associated impacts correspond to only a few percentage points of the monetary health damage due to air pollution. This simplification also needs to be seen in the context of further uncertainties, which accumulate at each step of the calculation chain of ozone impacts on crops. Altogether, this implies that the uncertainties in the economic results for ozone impacts on crops must be considered as high, with a tendency to overestimation due to the PODy calculation methodology which uses low end limitation functions of the stomatal conductance which favour ozone absorption. In addition, the use of flux-effect relationships and critical levels for crops gives, according to the Mapping Manual, a potential maximum rate of reduction which can be understood as a high end estimate of the impact.

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Ingress

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Acronyms

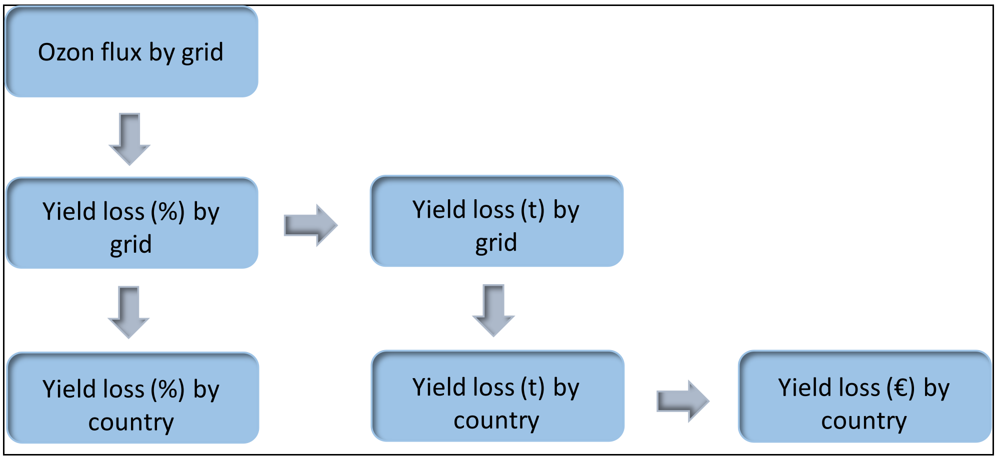
AOT40	Accumulated Ozone over Threshold of 40 ppb
CLC	Corine Land Cover database
CLRTAP	Convention on Long-Range Transboundary Air pollution (also: Air Convention)
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Programme
EMEP model	Chemistry-transport model developed by the Meteorological Synthesizing Centre - West (MSC-W)
ETC/ACM	European Topic Centre on Air Pollution and Climate Change Mitigation
ETC/ATNI	European Topic Centre on Air Pollution, transport, noise and industrial pollution
EUROSTAT	European Statistical Office
FAO	United Nations' Food and Agriculture Organization
HICP	Harmonised Index of Consumer Prices
ICP Vegetation	International Cooperative Programme on Vegetation
NUTS	Nomenclature of Territorial Units for Statistics (abbreviated from the French version "Nomenclature des Unités Territoriales Statistiques")
O_3	Ozone
OECD	Organisation for Economic Co-operation and Development
PODy	Phytotoxic Ozone Dose above a threshold y
ppb	Parts per billion
PPP	Purchasing Power Parities
SRM	Source Receptor Matrix
UNECE	United Nations Economic Commission for Europe
WGE	Working Group on Effects

1 Introduction

Tropospheric ozone impacts agricultural crop and timber production (yield, quality) entailing significant economic effects for the sector. In line with the European Regulation (EU, 2008) these impacts of ozone on vegetation are currently quantified based on an indicator of annual Accumulated Ozone over a Threshold (AOT)([3]) for May-July. However, this indicator does not take into account the conditions of hydrological stress the plant may be exposed to, which often occurs during ozone episodes. The hydrological stress differs across Europe, and induces the plant to reduce its stomatal flows and thus its exposure to ozone. The use of the AOT indicator, therefore, hinders the development of satisfactory dose-response relationships, and introduces important uncertainty into the assessment of ozone impacts on agricultural yields and, hence, into the economic analysis of this impact. To cope with such limitations, an alternative indicator (Emberson et al., 2000a & b), based on stomatal fluxes (the phytotoxic ozone dose above a threshold y, PODy) has been proposed since early 2000s by the expert group IPC-Vegetation working in support of the Air Convention([4]) in connection with the Working Group on Effects (WGE).

The PODy approach was implemented by the ETC/ACM (predecessor of the ETC/ATNI) in 2018 in the context of a trend assessment (Colette et al., 2018). This followed the development of an ozone flux calculation tool at Ineris (Schucht et al., 2019a, b), which applies the methodology described in the Manual for modelling and mapping critical loads & levels of the Air Convention (hereafter referred to as 'Mapping Manual') in its most recent available revision (CLRTAP, 2017). In the 2018 ETC/ACM assessment, yield losses were calculated over all grids of the European domain and further aggregated at country level (cf. left column in Figure 1). The assessment led to the conclusion that wheat crop yield was reduced by about 14% due to exposure to ozone in Europe in 2010.

Figure 1: Steps of ozone impact calculation



In 2019, the ETC/ATNI started implementing the PODy calculation in the framework of the indicator mapping (Horálek et al., 2019). Annual production of PODy maps has started in 2020 (cf. Horálek et al., 2020). It was then decided to include this work also in the air quality assessment, starting with ozone

([3]) AOT40 is the sum of the differences between hourly ozone concentrations greater than 80 µg/m^3 (= 40 ppb) and 80 µg/m^3 over a given period (for instance, a relevant growing season, e.g. for forest and crops) using only the one-hour values measured between 8.00 and 20.00 Central European Time (CET) each day.
([4]) Convention on Long-Range Transboundary Air Pollution (CLRTAP).

impacts on wheat for which methodological uncertainties are lowest and possibly extending the work to other crops in later years. ([5])

In order to include this work in the air quality assessment there is, however, a need to translate the ozone flux calculations not only into yield losses in %, but also into yield losses expressed in terms of quantity and economic value (cf. second and third column in Figure 1).

This has been the objective of this year's work. We have implemented an impact modelling chain to quantify and monetize the loss in wheat production due to tropospheric ozone exposure for 2019 (the latest reporting year for which ozone data are available). To the extent possible, all input data are for this same year: meteorology, ozone concentrations, PODy maps, ozone fluxes, wheat production and wheat prices.

An additional objective consisted in studying the sensitivity of the results to the degree of spatialization of the input data. A first reason for this is the EEA's request to identify possibilities of simplification and automation, thus reducing resources necessary. A second reason is to assess the additional uncertainty of an aggregated approach as it is applied in other tasks within the ETC/ATNI work (notably the work calculating marginal damage costs per tonne of pollutant emitted in the framework of the environmental externalities task).

To this end we have calculated a reference for which we quantify ozone impacts on wheat at the highest spatial resolution possible. This reference case uses wheat production data provided at NUTS 2 level ([6]),which is then spatialized at the grid with a resolution of 2 km using information from Corine Land Cover (CLC). Ozone impacts on wheat are then calculated at grid level, combining production data and ozone fluxes at this high spatial resolution. The losses are then aggregated at NUTS 2 level and then at country level where they are monetized using wheat selling prices.

We have furthermore calculated results for two alternative cases where we reduce the spatial resolution of the input data. The first alternative case uses wheat production data provided at NUTS 0 (i.e. country) level, which again is spatialized at the grid using CLC. Ozone impacts on wheat are then calculated at grid level, combining production data and ozone fluxes at this high spatial resolution. Then losses are aggregated at country level. The second alternative case does not at all spatialize wheat production data. It aggregates average POD levels at the country level and calculates wheat production losses directly at the country level.

This report is structured as follows. Chapter 2 introduces the approach and calculation of the ozone fluxes. Chapter 3 shows the ozone map provided by CHMI on which the subsequent impact calculations are based. It also compares this map to that for other years and to the alternative ozone impact indicator AOT40. Chapter 4 presents the available statistical data on wheat production and shows how these data were spatialized at the grid. Gap filling approaches are also presented. Chapter 5 presents the available statistical data for wheat prices. In chapter 6 the calculation of yield loss and economic damage is explained. Chapter 7 presents the results in terms of crops losses in %, quantity and economic damage for the reference and the two sensitivity cases. Chapter 8 summarizes the conclusions.

([5]) There remains considerable uncertainty with respect to the dates defining the accumulation periods for tomato and potato, notably with respect to the dates for tuber initiation for potato and the transfer into the field dates for tomato. For tomato, the current PODy methodology and associated flux-effect relationships are also not applicable to tomato grown under greenhouse conditions, which account for a significant proportion of tomato crops in several countries, including France (2/3 of the French production is under glass). In theory, greenhouse cultivated tomatoes have a different phenology, a different accumulation period and different factors limiting ozone absorption in one direction or the other…
([6]) The level of European regions is known as NUTS level 2.

2 Overall approach

2.1 Calculation steps

The quantification and subsequent monetisation of crop losses as implemented here involves the following steps (cf. also Holland et al., 2015a, b, Schucht et al., 2019a, b):

1. Choose exposure-response functions,
2. Define the geographic resolution,
3. Obtain ozone data,
4. Calculate PODy fluxes,
5. Obtain crop production data,
6. Obtain landcover data for the assessed crop species,
7. Spatialize production data at the grid,
8. Apply response functions to ozone and production data (at grid or country level) to calculate impacts,
9. Obtain crop price data,
10. Convert price data from international $ to euro,
11. Apply price data to impacts to calculate economic losses.

In the approach presented here, the parameterization of the ozone flux calculation as well as the choice of the flux-effect function follow the latest version of the Mapping Manual (CLRTAP, 2017). The geographic domain covers the 41 following countries: Albania, Andorra, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Monaco, Montenegro, Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, San Marino, Serbia (incl. Kosovo), Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom. The spatial resolution of the ozone flux calculation is 2 km and the ozone data were obtained from multiple linear regression followed by the kriging of its residuals based on measurement data, EMEP model output, altitude and the surface solar radiation.

These first four steps of the quantification applied here are further detailed in earlier reports of the European Topic Centre (Colette et al., 2018, Horálek et al., 2019).

Concerning the following steps, data on crop production quantities and economic indicators (production volume, prices) are collected for the year for which ozone data are available (2019) and applied to ozone fluxes calculated for the same year. This choice appears as justified as 2019 was the latest year for which environmental data were available when writing this report.

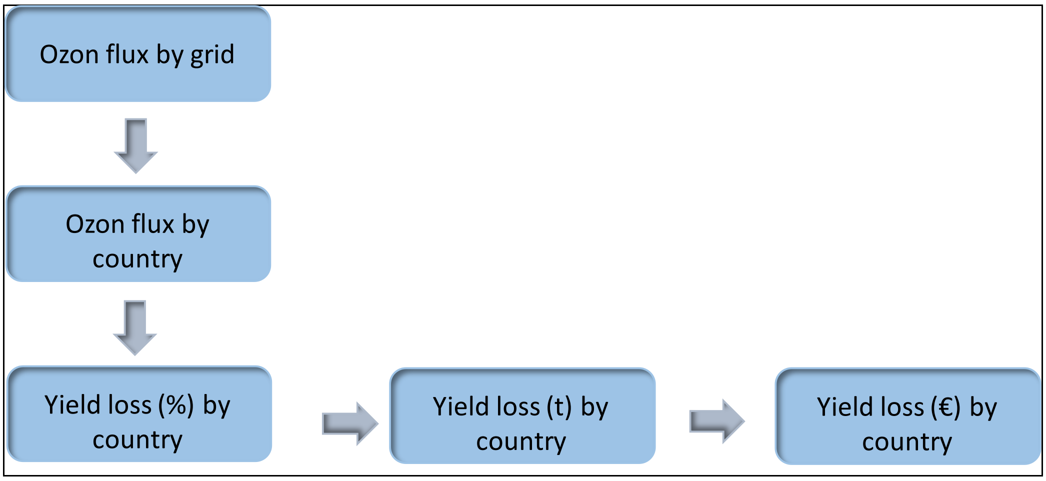
Following the EEA's request to identify possibilities of simplification and automation, we test different levels of spatial resolution of data and the effect on the results in terms of crop losses.

In our reference calculation (hereafter denoted as "NUTS 2_{agg}") we aim at quantifying ozone impacts on wheat at the highest spatial resolution possible. For this reference case, wheat production data at NUTS 2 level are used. These are subsequently spatialized at the grid using information from Corine Land Cover (CLC). Ozone impacts on wheat are then calculated at grid level, combining production data and ozone fluxes at this high spatial resolution. The losses are then aggregated first at NUTS 2 and then at country level where they are transformed into their monetary equivalent using wheat selling prices. In this assessment, all steps of the ozone impact calculation as presented in Figure 1 were followed, as well as all steps indicated in the list above, with an additional intermediate aggregation of results at regional level. This is also the approach applied in an earlier study by Ineris (Schucht et al., 2019a, b).

This is also the case for our first sensitivity case, hereafter referred to as "NUTS 0". In this case production data is still spatialized at the grid and ozone impacts are calculated at grid level and then aggregated to region and country level. However, the statistical input data used for production here is initially available only at country level.

The second sensitivity case applies a shortcut by not spatializing crop production data, thus avoiding steps 6 and 7 in the list above (cf. also Figure 2). It aggregates average POD levels at the country level and calculates wheat production losses directly at the country level. This case is hereafter referred to as "$PODy_{agg}$". This shortcut approach was developed in the European research project ECLAIRE (Effects of Climate Change on Air Pollution Impacts and Response Strategies for European Ecosystems, Holland et al., 2015a, b) and applied in a recent ETC/ATNI report assessing marginal damage costs for airborne pollutants and calculating externalities of European industrial facilities (Schucht et al., 2021).

Figure 2: Shortcut ozone impact calculation



2.2 The PODy indicator calculation

The calculation tool for phytotoxic ozone doses developed by Ineris (Colette et al., 2018, Schucht et al., 2019a, b) uses the methodology described in the Mapping Manual (CLRTAP, 2017, Mills et al., 2017). The tool is developed as an offline POD module, allowing an application to both surface observations of ozone and modelled ozone fields as primary input variables. The aim of this work was not to improve the formulation of the current PODy methodology defined in the latest version of the Mapping Manual but to apply the tool and the current methodologies developed by the Air Convention.

This involves calculating the dry deposition of ozone through a stomatal conductance for each species where the variation parameters are irradiance, temperature, water vapour deficit in the leaves, soil humidity, premature ageing and the different plant growth stages (phenology). Following this, to calculate the dose, the ozone flux assimilated by the plants and exceeding a Y threshold value is cumulated over a period that is dependent on each species.

More in detail, the basis of the model for calculating phytotoxic doses of ozone is the calculation of a stomatal conductance g_{sto} defined from a species-specific maximum conductance value g_{max}. Concerning g_{max}, the Mapping Manual provides literature references which provide values for several species or vegetation types.

The final equation for calculating the stomatal conductance has the following multiplicative form:

$$g_{sto} = g_{max} * [min(f_{phen}, f_{O3})] * f_{light} * max\{f_{min}, (f_{temp} * f_{VPD} * f_{SW})\} \quad (1)$$

g_{sto} and g_{max} being defined in mmol O_3 m^{-2} Projected Leaf Area (PLA) s^{-1}. The parameters f_{phen}, f_{O3}, f_{light}, f_{temp}, f_{VPD}, f_{SW} and f_{min} are expressed in relative proportions and therefore take values between 0 and 1. These parameters allow environmental factors such as irradiance (fl_{ight}), temperature (f_{temp}), leaf water vapour deficit (f_{VPD}) and soil moisture (f_{SW}) to be taken into account, as well as premature ageing (f_{O3}) and the different stages of plant growth through the phenological function (f_{phen}), with f_{min} reflecting the relative minimum value of stomatal conductance during the hours of the day.

The Mapping Manual provides direct parameterisations or references for each of these functions, which will not be detailed here. Parameter values for the calculation of the functions f_{phen}, f_{O3}, f_{light}, f_{temp}, f_{VPD}, f_{SW} and f_{min} are given in the Mapping Manual (CLRTAP, 2017). Some of these parameter values may depend on the biogeographical regions defined in the manual.

The general formulation for the calculation of the stomatal flux of ozone assimilated by the plant is given by analogy with the resistance method used for electricity (Wesely, 1989).

$$F_{sto} = C(z_1) * \frac{1}{r_b + r_c} * \frac{g_{sto}}{g_{sto} + g_{ext}} \quad (2)$$

Where C is the level of ozone at canopy height z_1. The term 1 / (r_b + r_c) thus represents the deposition rate on the leaf through the resistances r_b (quasi laminar resistance) and r_c (leaf surface resistance). The fraction of ozone absorbed by the stomata is given by g_{sto} / (g_{sto} + g_{ext}), where g_{sto} is the stomatal conductance, and g_{ext} is the cuticular resistance.

Since the leaf surface resistance, r_c, is given by r_c = 1 / (g_{sto}+ g_{ext}), we can also write :

$$F_{sto} = C(z_1) * g_{sto} * \frac{r_c}{r_b + r_c} \quad (3)$$

The resistance r_b is calculated following the original formulation of the CHIMERE model, (Menut et al, 2013).

$$r_b = \frac{2\nu}{k * DH2Ow * Pr} * DH2Og^{2/3} \quad (4)$$

With u representing the cinematic viscosity, k the Von Karman constant, DH2Ow and DH2Og respectively the molecular diffusivity of water and gaseous species (calculated here for ozone), and Pr the Prandl number.
Subsequently and for each grid cell, the ozone flux per second F_{sto} assimilated by plants and exceeding a threshold value Y is calculated over the accumulation period at an hourly time step (*3600) and in mmol m^{-2} PLA, (factor $*10^6$), depending on each species as follows:

$$PODY = \Sigma[(Fst - Y) \cdot (3600/10^6)] \ (mmol\ m^{-2}\ PLA) \quad (5)$$

The Y-value is therefore subtracted from the hourly averaged stomatal flux and only values for which F_{sto} is higher than the Y-threshold during daylight are taken into account in the calculation of the ozone flux accumulation. The phytotoxic dose of ozone above the threshold "Y" is then calculated over the accumulation period defined for each of the species considered. Once the PODy has been calculated for the target species and year, an estimation of the yield losses cross-referenced with production data makes it possible to calculate the losses in quantity, yield percentage and price, at the resolution of a grid cell, a region or country.

The PODy tool was developed using the methodology described above. The development was carried out with the open source R language. The application of this module requires two input files:

- A file containing hourly ozone concentrations near the surface over the period of interest and over the target domain. This file may result from simulation with any chemistry transport model like the CHIMERE model.
- The meteorological file containing all the necessary hourly meteorological parameters (ambient temperature, relative humidity, irradiance, humidity in the different soil layers) over the period of interest and the target domain.

The output of the tool is a two-dimensional field representing the values of a so-called "potential" PODy because it is calculated considering that the target species for which it is applied is present in the whole domain. Additional information is available in Horálek et al. (2019), Colette et al. (2018) and Schucht et al. (2019a, b).

For this study, the bread wheat species was selected in relation to the availability of flux-effect functions, its sensitivity to ozone and its importance and representativeness in terms of agriculture. Table 1 presents information on the estimation of the accumulation period, the PODy threshold value, and the nature of the damage caused by ozone. Use of these values and associated uncertainty are discussed in the Mapping Manual and in Emberson (2000a & b).

Table 1: Y thresholds used for wheat to calculate the phytotoxic ozone dose, accumulation period and nature of damage

	Damage indicators	**Determining the accumulation period**	**Y threshold** (nmol m-2 PLA s^{-1})
Wheat	Kernel yield Weight of 1000 kernels Protein yield	Accumulation period defined using the degree days method (Mapping Manual). Mid-anthesis (mid-flowering) is estimated to be a temperature sum of 1075 °C days for the European area. Once this date identified, the accumulation period is then defined in each grid cell starting 200 degree days before the mid-anthesis and finishing 700 degree days after (900 degree days in total).	Y = 6 (POD6SPEC)

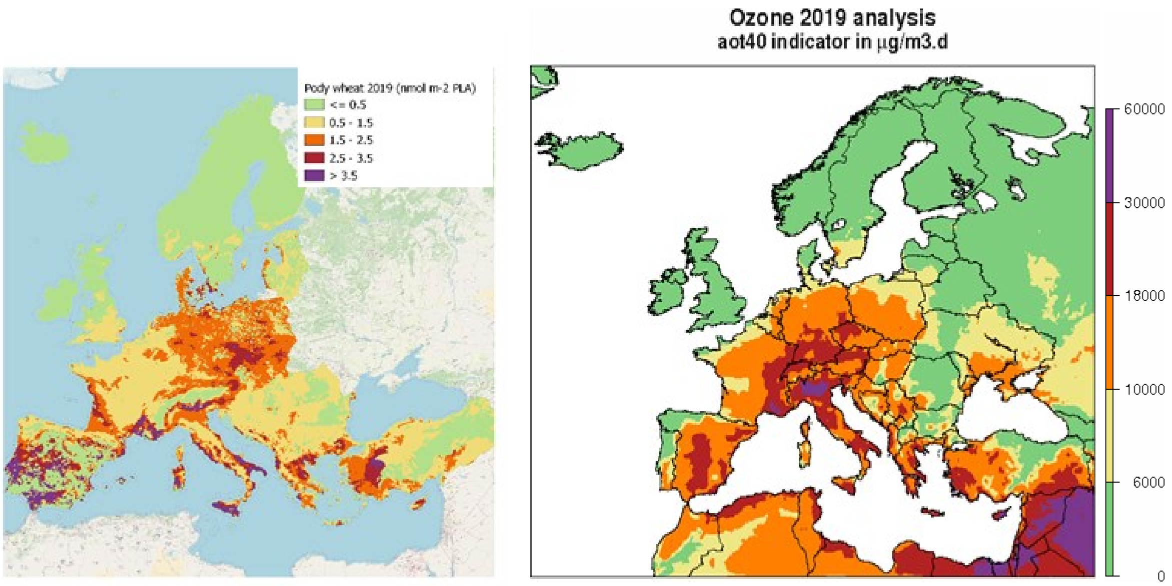
Source: Schucht et al. (2019b), following CLRTAP (2017).

Note that we have attempted to be as consistent as possible in the use of statistical data. However, in the remainder of the text we apply the denominations of wheat type as used in the respective statistics. The PODy function used refers to bread wheat, EUROSTAT production data is available for common wheat and EUROSTAT wheat prices for soft wheat. These three categories refer to similar wheat types. However, for reasons of data limitations, EUROSTAT price data could not be used, instead data from FAO were used. FAO data are just labelled “wheat” without any further specification of the wheat type. A comparison between the FAO price for wheat and the EUROSTAT price for soft wheat shows that the FAO price is within the range of soft wheat prices from EUROSTAT.

3 Ozone maps – PODy and AOT40

The POD6 values for wheat were computed by CHMI (cf. ETC/ATNI, 2021) using the PODy tool developed by Ineris for the year 2019. The POD6 was calculated for 41 countries (cf. chapter 2.1).
The POD6 map for bread wheat is presented here and compared with the AOT40 values for the same year, AOT 40 being the alternative and older indicator of Ozone accumulation (see description in footnote 3) (Figure 3).

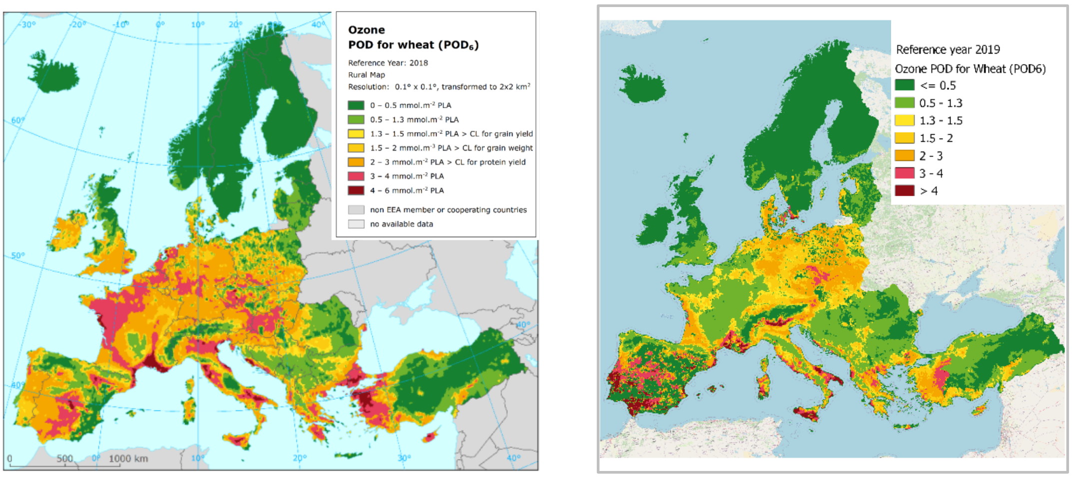
Figure 3: Ozone indicators wheat POD6 (left) and AOT40 for vegetation protection (right) maps for Europe in 2019



The comparison of the two maps shows obvious differences in the patterns. The high value areas of POD6 (red colour) are dispatched between central Europe, Spain, the Atlantic coast and the south of France, while high values of AOT40 (red colour) are located mainly in the centre of the map. Particularly, the south and centre of Spain and the south of Portugal show high values of POD6 that are less corroborated with the AOT40 indicator. However, the highest values (purple) of both indicators show some similarities in their location (north of Italy, south of France).

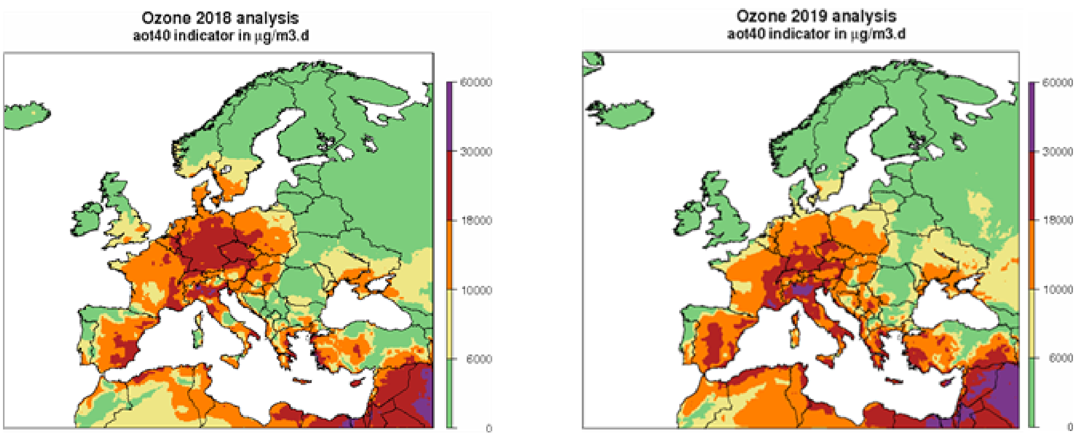
In Figure 4, the bread wheat POD6 map for 2019 is compared with the bread wheat POD6 maps for 2018 (Horálek et al., 2020) using the same methodology and the same colour scale. It can be noted that the 2019 POD6 values are significantly lower than the values for 2018, especially in France, Hungary, Ireland, the United Kingdom and some specific areas in Croatia, Spain and Turkey. There might be several reasons for this, depending on the area of interest. For example, the unusual spring of the year 2019, which was subject to severe drought in France. Indeed, the POD methodology for wheat takes into account the water stress of the vegetation which results in the closure of the stomata and a lower absorption of ozone explaining these low values for the POD6 in this region.

Figure 4: Bread wheat POD6 for 2018 (left) compared to bread wheat POD6 for 2019 (right)



A comparison between the years 2018 and 2019 for AOT 40 shows that the year 2019 is rather similar to 2018 in terms of ozone AOT40 levels (Figure 5) even if lower levels of AOT 40 may be noted in the south of the United Kingdom, north of France, Poland and Germany, and south of Scandinavia. Thus, the differences in the PODy values between the two years can result from ozone levels in some areas and/or meteorological parameters which lead to significant differences in the limitation functions and different levels for the stomatal conductance.

Figure 5: AOT40 for vegetation protection for year 2018 (left) and 2019 (right)



4 Available wheat production statistics and spatialization of the data

4.1 Crop production data

Wheat production data for Europe is available both from the European statistical office EUROSTAT and from the statistics of the international Food and Agricultural Organisation FAOSTAT. However, only EUROSTAT data are available at a subnational level, and this is, therefore, the source used here. The exact data set is indicated in Table 2 and gives the quantity (in kT) of wheat produced for 38 countries([7]): Albania, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Kosovo under UN Security Council Resolution 1244/99([8]), Latvia, Lithuania, Luxembourg, Malta, Montenegro, Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom. We, therefore, have not calculated losses in wheat production for Liechtenstein, San Marino, Monaco and Andorra.

Table 2: Data sources used for crop production in Europe

Crops	Crop sub-category	Production data
Wheat	Common wheat	Crop production in EU standard humidity by NUTS 2 regions [apro_cpshr]

Source: (https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=apro_cpshr&lang=en).

In our reference case, the quantification of the impact of ozone on wheat is based on production quantities reported at the level of European regions, known as level 2 of the Nomenclature of Territorial Units for Statistics (NUTS).

The data for common wheat are available from the EUROSTAT statistics aggregated at country level (Crop production in EU standard humidity (apro_cpsh1)) and by NUTS 2 region (Crop production in EU standard humidity by NUTS 2 regions (apro_cpshr)) and expressed as « Crop production in EU standard humidity », « Harvested production in EU standard humidity (1000 t) ». These data are currently available up until 2021.

However, data are not available at a NUTS 2 level for all countries. For some countries, production is available only by NUTS 1 (larger regions than NUTS 2) or at national level. For Bulgaria, Germany, Portugal and the United Kingdom, the finest spatial resolution available is by NUTS 1 regions and for Norway, Albania, Bosnia & Herzegovina and Kosovo the production is provided only at the national level.

4.1.1 Gap filling for NUTS 2 using the number and size of wheat holdings

With the aim, in our reference case, to start spatialization from the most detailed level of European production statistics possible, gap filling was therefore necessary to estimate the missing NUTS 2 values. In all cases in which regional data were not available, the respective countries had however reported the quantity produced at national level. In order to distribute this national production over the missing NUTS 2 regions, another data source from EUROSTAT was used as proxy: the number of holdings by area category (ha) by NUTS 2 region (ef_lac_cerealsr, cf. Table 3). These statistics are detailed by type of crops. The type 'Common wheat and spelt' was selected.

([7]) https://ec.europa.eu/eurostat/web/main/data/database.

([8]) The wheat loss calculations are done for Serbia including Kosovo. But some statistics present data separately for Serbia and for Kosovo under UN Security Council Resolution 1244/99.

Table 3: Data sources used for number of holdings in Europe

Crops	Holdings data
Common wheat and spelt	Cereals by NUTS 2 regions [ef_lac_cerealsr] : number of holdings by area category

Source: (https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ef_lac_cerealsr&lang=en).

Table 4 shows the different area categories of the wheat and spelt holdings distinguished in the data set (left column).

Table 4: Area categories of holdings

Area category	Mean calculated area (ha)
Less than 1 ha	1
From 1 to 1.9 ha	1.45
From 2 to 4.9 ha	3.45
From 5 to 9.9 ha	7.45
From 10 to 19.9 ha	14.95
From 20 to 29.9 ha	24.95
From 30 to 79.9 ha	55
80 ha or over	100

The number of holdings in a given NUTS 2 area was re-evaluated by summing all classes weighted by their mean area. This was done for all NUTS 2 areas.

We assumed that a linear relationship might exist between wheat areas and the produced quantity of wheat. These areas were calculated in each NUTS 2 using the data shown in Table 3. The mean area of a holding category was estimated as mean of minimum and maximum area of this category (right column in Table 4).

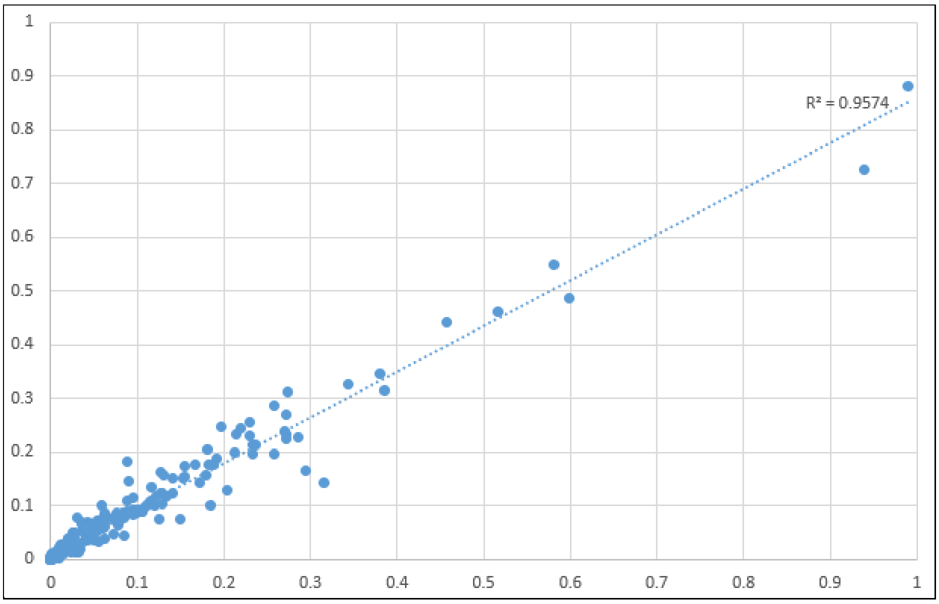
The wheat areas by NUTS2 were evaluated by summing number of holding multiplied by their mean area

$$Wheat\ area_{\ NUTS\ 2} = \sum_m (Number\ of\ holding_{category,NUTS2} * Mean\ area_{category}) \qquad (6)$$

The areas assed by NUTS 2 were then aggregated at country level, and the share of each NUTS 2 in the country aggregate calculated. These shares were then multiplied by the country level production data to dispatch the national wheat production over the NUTS 2 regions. This method was applied for gap filling in Bulgaria, Germany, Portugal and the United Kingdom.

Figure 6 confirms the assumption that there exists a strong relationship between the quantity of wheat produced in a NUTS 2 region and the number of holdings weighted by their area category. In order to evaluate the validity of our assumption, 20 countries were selected for which both types of data, production and number of holdings, were available at NUTS 2 level. For these the wheat production shares at NUTS 2 level in the country production as given in the EUROSTAT statistics were compared to the wheat production shares calculated via the "adapted number of holdings" variable. The result is presented in Figure 6.

Figure 6: Comparison of the production share of NUTS 2 between production data and estimated wheat areas



4.1.2 Gap filling for NUTS 2 using earlier data

For Norway, wheat production data for earlier years was available at NUTS 2 level. The ratios of wheat production at each NUTS 2 level to production at country level were calculated for the year 2018 and then applied to the wheat production at country level available in 2019 to estimate the corresponding NUTS 2 production levels.

4.1.3 Countries for which no NUTS 2 data were estimated

For three countries, Albania, Bosnia-Herzegovina and Kosovo, no earlier production data nor data on holding numbers were available at NUTS 2 level. For these countries, only the national production level data was used.

4.2 Landcover data and geolocation of crop production

The objective of the geolocation of crop production is to allocate the production data available at relatively large scale (NUTS 2 level for Europe, with the exception of some countries for which data are limited to the national level, cf. section 4.1) over the grid used by the ozone flux tool. The cell size of the grid is 2 km x 2 km. Spatialization of production data uses the Corine Land Cover (CLC) database (CLC - https://land.copernicus.eu/pan-european/corine-land-cover). The CLC database is broken down into 44 land-use positions, and allows the location of areas likely to accommodate the crops studied on a high geographical resolution (up to infra-municipal scale). Urban, industrial, forest and marshland areas are excluded from the analysis.

Four land-use classes were selected for being used to distribute the wheat production data to the grid. These are indicated in Table 5. Class 211 (Non-irrigated arable land) is the only category representing only soils of arable land type. The other three selected classes are of mixed land use categories. When using these CLC classes to distribute wheat production over the grid we have assumed that a weight should be assigned to each of them and that the share of class 211 should be higher than the other selected classes because it is the only pure arable land category. This class was assigned a weight of 1, the other classes were assigned weights of 0.2 each.

Table 5 CLC codes used to spatialize crop data

Crops	CLC codes	Weight for spatialization
Wheat	***211*** *Non-irrigated arable land*	1
	241 *Annual crops associated with permanent crops*	0.2
	242 *Complex cultivation patterns*	0.2
	243 *Land principally occupied by agriculture, with significant areas of natural vegetation*	0.2

To give an example, assume a NUTS 2 administrative region producing wheat in which m CLC surface entities of the type 211, 241, 242 and 243 are included. The share of production of the administrative area that will be allocated to each CLC entity (Sn) of the area is weighted by the surface of Sn and the weight of the CLC type. It will follow the following equation:

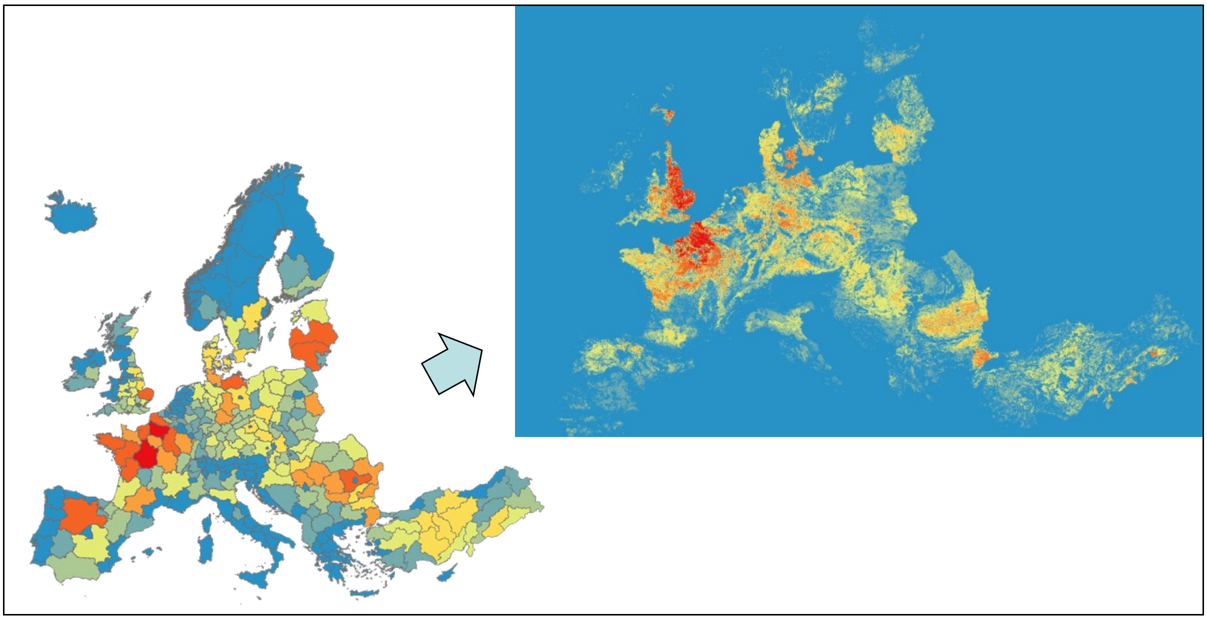
$$Share\ of\ production_{Sn} = \frac{Weight_n * Surface_n}{\sum_m (Weight_m * Surface_m)} \quad (7)$$

With $Weight_n$ representing the spatialization weight of the CLC type of entity n as given in Table 5.

The latest available update of the CLC data base is for 2018. It is updated every 6 years. Annual variations of crop location are not considered as critical to the work.

The result of this spatialization approach for our reference case NUTS 2_{agg} is illustrated in Figure 7. The left hand side shows the production data at NUTS 2 level, the right hand site shows the data at the grid resolution.

Figure 7: Spatialization of the wheat production - from Nuts 2 level to grid (reference case)



In our first sensitivity case (NUTS 0), CLC is again used to spatialize production data over the grid. However, in this case the starting point is wheat production data at the country level (and not at NUTS 2 level).

Figure 8 illustrates the spatialization approach of NUTS 0.

Figure 8: Spatialization of the wheat production - from country level to grid (sensitivity case NUTS 0)

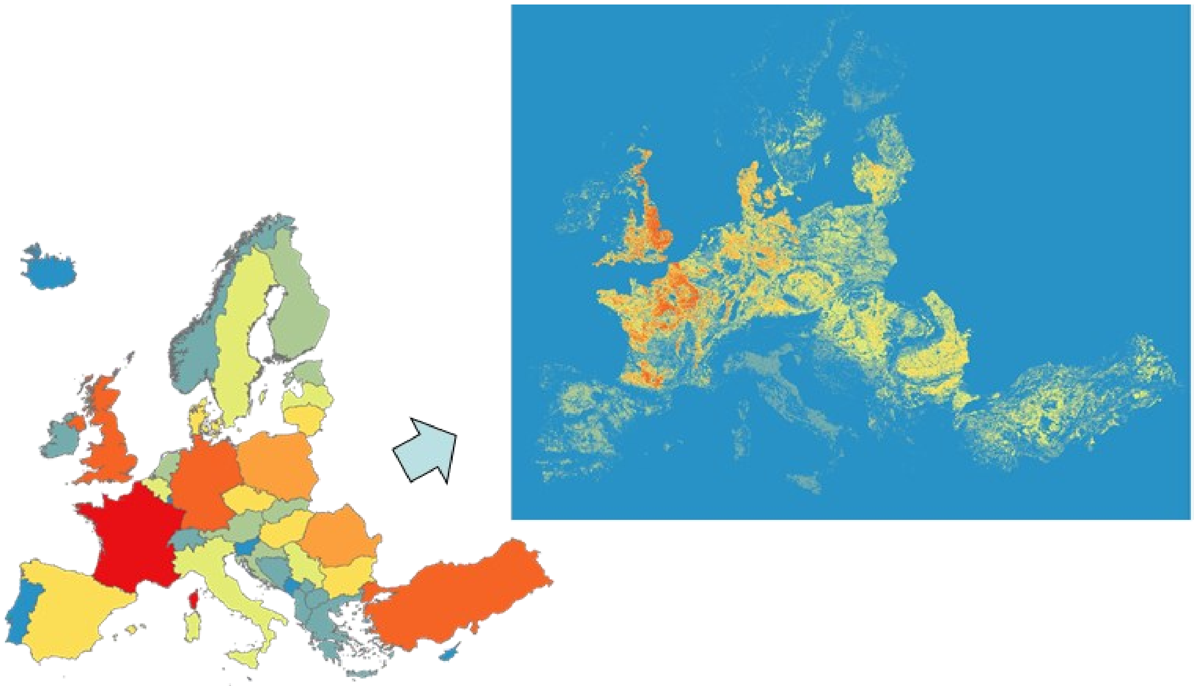
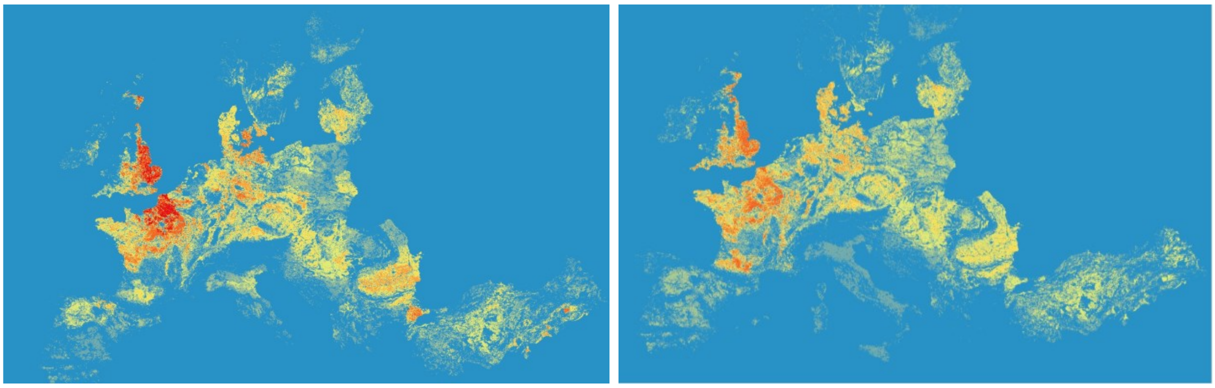


Figure 9 shows the results of the spatialization in a direct comparison between the reference case starting from wheat production at NUTS 2 level (left), and the first sensitivity case, starting from wheat production at national level (right). As was to be expected, in the sensitivity case the production is distributed more evenly over the country, because the information about the biggest producer regions in each country were not available in this case.

Figure 9: Results of the spatialization of wheat production over the grid starting from NUTS 2 (left) and from country level (right)



In our second sensitivity case, the wheat production is not spatialized. Data provided at country level as shown in the left part of Figure 8 are directly used.

5 Available wheat price data

Using crop price or gross production value data to calculate the monetary value of crop yield losses due to ozone pollution implicitly assumes that prices do not change as a result of ozone pollution. This is the approach used also by the ICP Vegetation (Mills and Harmens, 2011), Holland et al. (2015a, b) and Schucht et al. (2019a,b, 2021); in EEA (2011, 2014), Avnery et al. (2013) and Van Dingenen et al. (2009); and also by numerous studies outside Europe (e.g. Feng et al., 2019, Ren et al., 2020). For a survey, cf. Castell and Le Thiec (2016). This approximation is further discussed in chapter 8.

Economic data for crops is available from EUROSTAT and from the UN Food and Agriculture Organization (FAO([9])).
Data available from EUROSTAT are Selling prices of soft (bread) wheat (prices given per 100 kg) in the data set apri_ap_crpouta. The data are defined as output prices received by farmers for their products measured at farm gate. These statistics are limited to 37 countries, with values available only for 23 amongst these (cf. Table 6). Iceland and Malta do not produce wheat.

Table 6: Selling prices of soft (bread) wheat in 2019, in €$_{2019}$

Country name	**Price (€$_{2019}$/t)**
Austria	146
Belgium	156
Bosnia and Herzegovina	
Bulgaria	152
Croatia	150
Cyprus	
Czechia	170
Denmark	180
Estonia	168
Finland	184
France	
Germany	
Greece	191
Hungary	155
Iceland	
Ireland	
Italy	199
Kosovo (under United Nations Security Council Resolution 1244/99)	
Latvia	163
Lithuania	163
Luxembourg	158
Malta	
Montenegro	
Netherlands	162
North Macedonia	

([9]) http://www.fao.org/faostat/en/#data/QV.

Country name	Price (€$_{2019}$/t)
Norway	
Poland	168
Portugal	207
Romania	154
Serbia	
Slovenia	163
Slovakia	153
Spain	187
Sweden	139
Switzerland	
Turkey	
United Kingdom	181

The values in the table range from a minimum of 139 €$_{2019}$/t, in Sweden, to a maximum of 207 €$_{2019}$/t, in Portugal, and imply a mean of 167 €$_{2019}$/t. Amongst the countries missing is the biggest European wheat producer France, for which last reported prices (2016) were the highest in Europe.

Data available from FAOSTAT are gross production value for wheat (expressed in 2014-2016 constant 100 international $) and representing output prices at farm gate. These are available for 34 countries (no data is available for Kosovo). Data provided in international $ require conversion to € using PPP (Purchasing Power Parity) exchange rates([10]) from OECD, and correction for inflation using HICP([11]) (Harmonised Index of Consumer Prices) data from EUROSTAT to convert them to a specific price base. This was done here. The average PPP exchange rate for the years 2014 to 2016 to convert international $$_{2014-2016}$ into €$_{2014-2016}$([12]) is 0.709916. The HICP coefficient converting €$_{2014-2016}$ to €$_{2019}$ is 1.050155. The results are given in Table 7.

Table 7: Gross production value for wheat([13]) in 2019, in different currencies

Country	Value (in 1000 Int. $$_{2014-2016}$)	Value (in 1000 €$_{2014-2016}$)	Value (in 1000 €$_{2019}$)
Austria	378 190	268 483	281 949
Bosnia and Herzegovina	62 705	44 515	46 748
Belgium	450 542	319 847	335 889
Bulgaria	1 496 683	1 062 519	1 115 810
Switzerland	117 814	83 638	87 833
Cyprus	6 979	4 955	5 203
Czechia	1 139 667	809 068	849 647
Germany	5 461 933	3 877 514	4 071 990
Denmark	1 099 390	780 475	819 619
Estonia	200 496	142 335	149 474
Greece	231 909	164 636	172 893

[10] OECD, https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm; https://stats.oecd.org/index.aspx?DataSetCode=SNA_Table4.
[11] EUROSTAT, https://ec.europa.eu/eurostat/web/hicp/data/database.
[12] For the group EU27.
13 The exact type of wheat covered is not specified in the data source.

Country	Value (in 1000 Int. $2014 - 2016)	Value (in 1000 €2014 - 2016)	Value (in 1000 €2019)
Spain	1 430 735	1 015 702	1 066 644
Finland	216 506	153 701	161 410
France	9 616 503	6 826 909	7 169 313
Croatia	190 239	135 054	141 827
Hungary	1 273 607	904 154	949 502
Ireland	141 000	100 098	105 119
Iceland			
Italy	1 596 114	1 133 107	1 189 938
Lithuania	910 342	646 266	678 680
Luxembourg	19 482	13 831	14 524
Latvia	561 526	398 636	418 630
Montenegro	514	365	383
North Macedonia	56 819	40 337	42 360
Malta			
Netherlands	267 744	190 076	199 609
Norway	108 705	77 171	81 042
Poland	2 559 546	1 817 063	1 908 197
Portugal	14 589	10 357	10 876
Romania	2 438 672	1 731 252	1 818 083
Serbia	600 281	426 149	447 523
Sweden	823 413	584 554	613 872
Slovenia	33 111	23 506	24 685
Slovakia	459 246	326 026	342 378
Turkey	4 499 784	3 194 469	3 354 687
United Kingdom	3 842 579	2 727 908	2 864 726
Kosovo under UN Security Council Resolution 1244/99			

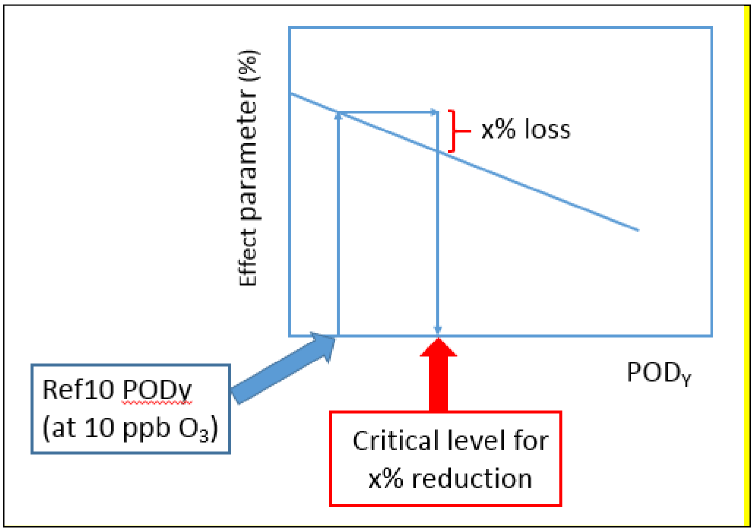
In order to obtain prices at country level, we used wheat production data equally available for 2019 at FAOSTAT, i.e. we divided the gross production value by the wheat production. The result is a unique value, identical for all countries, that amounts to 177 €$_{2019}$/t. It might be that in order to calculate the gross production value, FAO has started from the value of 177 €$_{2019}$/t and then multiplied it for wheat production. The unique value of 177 €$_{2019}$/t is situated within the range of the selling prices obtained from EUROSTAT. This price was used in the present study. We chose this data set because it provided us with prices for more countries, and also because using world commodity prices (as opposed to country specific prices) appears as the right approach for a Europe wide assessment that permits comparison of results across countries.

6 Calculation of yield loss and value of lost production

In order to calculate yield losses, the dose-response function for bread wheat, POD6, of the Mapping Manual is applied to the POD6 values available at grid level and the production data spatialised at grid level. Hereafter, the methodology for the PODy calculation is presented in general, we therefore use the generic term PODy instead of POD6 for wheat.

According to the methodology of the Mapping Manual, the pre-industrial ozone level is to be taken into account in the yield loss calculations. A PODy value corresponding to a constant concentration of 10 ppb of O_3 (pre-industrial average O_3 concentration according to the Mapping Manual) is therefore calculated as a reference situation (Ref10 PODy) for each crop species studied (in our case wheat). The yield loss relative to current ozone levels is calculated simply from a PODy corrected by the Ref10 PODy value for each of the species as shown in Figure 10 (Source: Mills et al., 2017).

Figure 10: Method recommended by the Mapping Manual to take into account the pre-industrial ozone level



Note that Ref10 PODy corresponds to PODy calculated for a constant ozone level of 10 ppb as a reference point. For wheat, the recommended value of REF10 POD6 is zero meaning that the preindustrial level of ozone would have no impact on the wheat yield. The use of this preindustrial ozone level is, of course, an approximation to identify the anthropogenic level of ozone that could in theory be eliminated through emission reduction measures. It is not sure whether, in a situation without any anthropogenic ozone, the use of production technologies that enable current orders of magnitude of production, would still be feasible.

Note also that in the implementation of the PODy tool for the ETC work (Colette et al., 2018, Schucht et al., 2020) the assumption of a preindustrial ozone level (10 ppb) was replaced by a reference calculation with zero anthropogenic emissions, which appears more robust.

For wheat in the year 2019, the yield loss is then calculated for each grid cell as the difference between the actual production data (as found in the statistics, so these data include the ozone impact,) and what is hereafter referred to as the "ideal" production, i.e. understood as the wheat production under the current socio-economic situation, but without any impact of ozone([14]). Following the approach of

([14]) Not necessarily "ideal" from an economic perspective (see the discussion in the concluding section 8).

the Mapping Manual (CLRTAP, 2017), this production is calculated for a zero ozone impact at its pre-industrial level: i.e. 10 ppb according to the assumption of the Mapping Manual.
These two productions are linked by the following equation:

$$Prod_{N,actual} = Prod_{N,ideal} * (1 - POD_N * DRF) \quad (8)$$

With DRF the coefficient of the dose-response function identified for the species under consideration (wheat in the present case), and POD_N the PODy calculated for year N and the species under consideration.

The yield loss for year N calculated as a quantity (index q) on a grid cell is therefore given by the following relationship:

$$Loss_{q,N} = Prod_{N,ideal} - Prod_{N,actual} \quad (9)$$

Which can be replaced by:

$$Loss_{q,N} = Prod_{N,actual} * \frac{POD_N * DRF}{1 - POD_N * DRF} \quad (10)$$

The total quantity of the yield loss is then calculated for each NUTS region by integrating the yield losses over all the grid cells of each NUTS region.

$$Loss_{q,N,NUTS} = \sum_{Grids} Loss_{q,N} \quad (11)$$

The ideal total production (i.e. the production under current socio-economic conditions but without any ozone impact) per NUTS is calculated by summing the total production at grid level using the following equation:

$$Prod_{N,ideal,NUTS} = \sum_{Grids} Prod_{N,ideal} = \sum_{Grids} \frac{Prod_{N,actual}}{(1 - POD_N * DRF)} \quad (12)$$

Then the percentage loss at NUTS level is calculated by dividing the total quantity loss at NUTS level by the total production at NUTS level.

$$Loss_{q,N,NUTS} = \frac{Loss_{q,N,NUTS}}{Prod_{N,ideal,NUTS}} \quad (13)$$

Calculating quantity and percentage losses this way allows using the information available at its highest resolution level without degradation by averaging effects.

This is the approach we use to compute losses for the reference case and the first sensitivity case:

- The reference case “NUTS 2agg” starts from the actual wheat production at NUTS 2 level which is distributed to the appropriate land uses defined in CLC at grid level. Ideal production and losses are calculated at the grid level and are then aggregated at NUTS 2 and then at national level.
- The first sensitivity case “NUTS 0” starts from the actual wheat production at national level (NUTS 0) which is distributed to the appropriate land use areas at grid level. Ideal production and losses are again calculated at the grid level and then aggregated at national level.

For the second sensitivity case, $PODy_{agg}$, we use a unique PODy value at national level, calculated as the average over each country of the PODy values at grid level, and a unique value for the actual wheat production by country. Then we compute the ideal production and the losses using the dose response function directly at country level.

The calculation of the economic value of the production loss in € results from a simple multiplication of total quantity of the yield loss by the respective crop price.

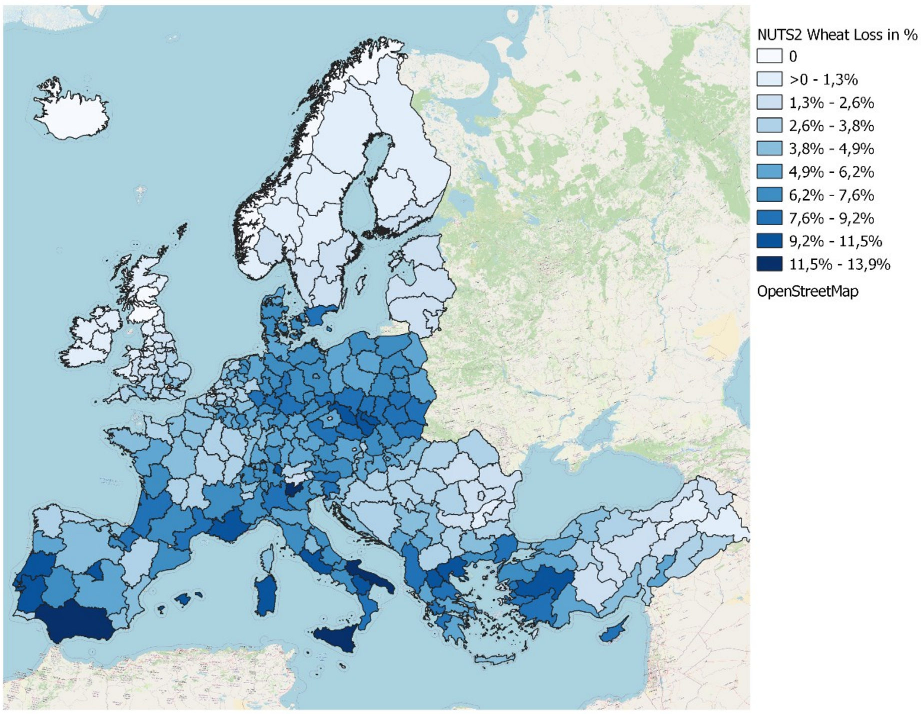
7 Results

In a computational chain such as the one proposed here, the uncertainties cumulate with each stage of calculation: formulation of the PODy calculation, estimation of ozone accumulation periods, use of stomatal conductance values, use of dose-response relationships per species not differentiated by regions, quantification of the ozone fluxes, estimation of lacking data (e.g. production at NUTS 2 level), geolocation of the production data within the NUTS regions only based on CLC([15])... Although it is impossible to quantify this uncertainty, the uncertainties in the economic results are likely to be high. It is therefore suggested to present results in terms of percentage yield loss, quantitative and monetary production loss. This is done here.

7.1 Reference case NUTS 2_{agg}

Figure 11 shows a graphical representation of the losses at NUTS 2 level expressed in % of yield loss. This representation takes account of the ozone fluxes, but not of the quantity in wheat production.
The highest impacts which exceed yield losses of 10% are shown along the south coasts: Southern Spain and Portugal, south of France, south of Italy. We can also note high values in the north of Italy, Central Europe, Greece and Turkey.

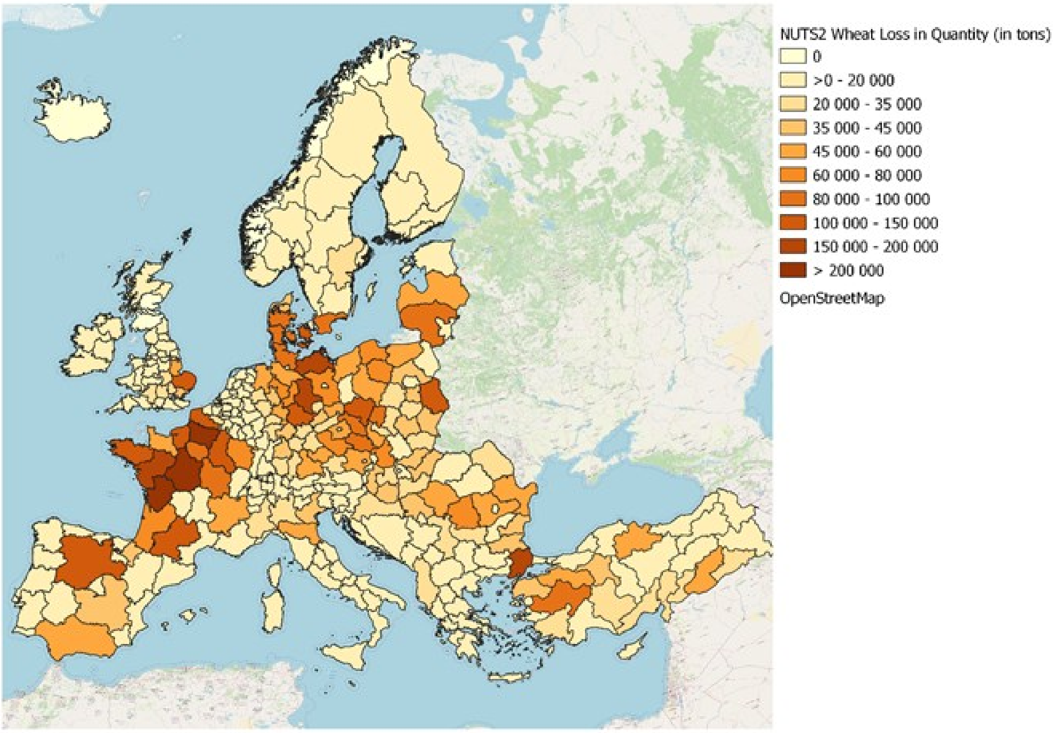
Figure 11: Loss in % at NUTS2 level – reference case



The actual wheat production levels are accounted for in Figure 12, showing this time the losses in quantity. As can be seen, the regions most affected by the loss in quantity are the regions with high wheat production. These are: the northern half of France and Castilla and León in Spain, Northern Germany and Denmark, parts of Poland and Czechia. These regions are not identical to the regions affected by the highest losses in %.

([15]) Production data on a higher level of spatial resolution (NUTS 3) would decrease uncertainty, but to our knowledge is not available.

Figure 12: Loss in quantity at NUTS2 level – reference case



The same type of differences is also visible at the country level aggregation (cf. Figure 13 and Figure 14). Once again, we can see here that the losses in quantity and in % are not distributed the same way either at country level.

Figure 13: Loss in % aggregated from Nuts 2 to NUTS 0 level – reference case

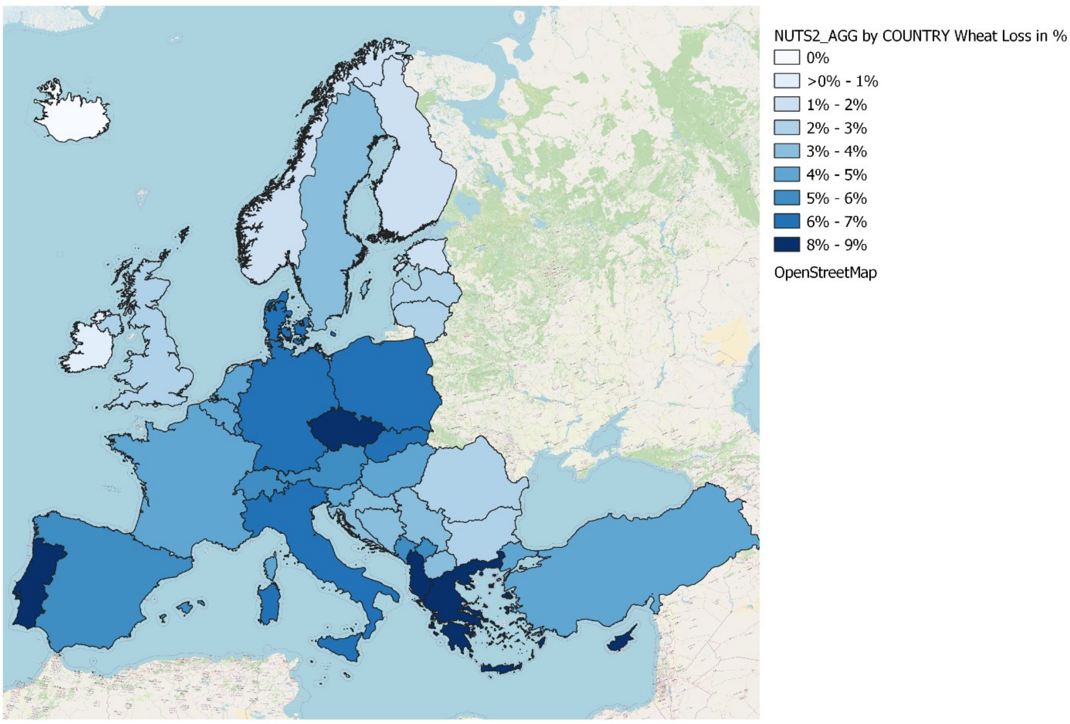


Figure 14: Loss in quantity aggregated from Nuts 2 to NUTS 0 level – reference case

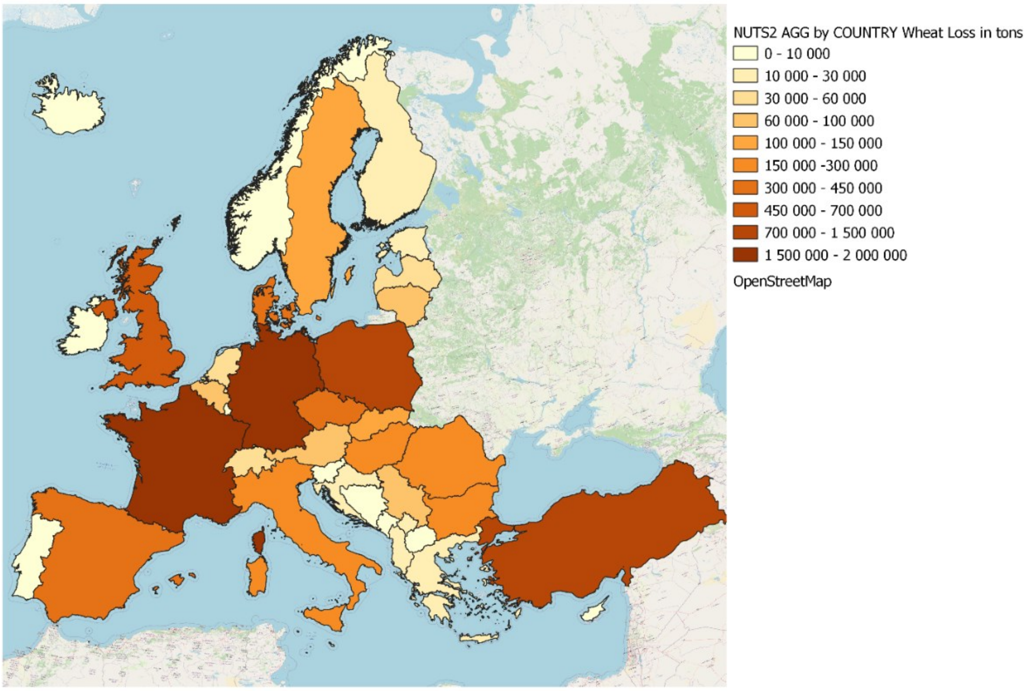
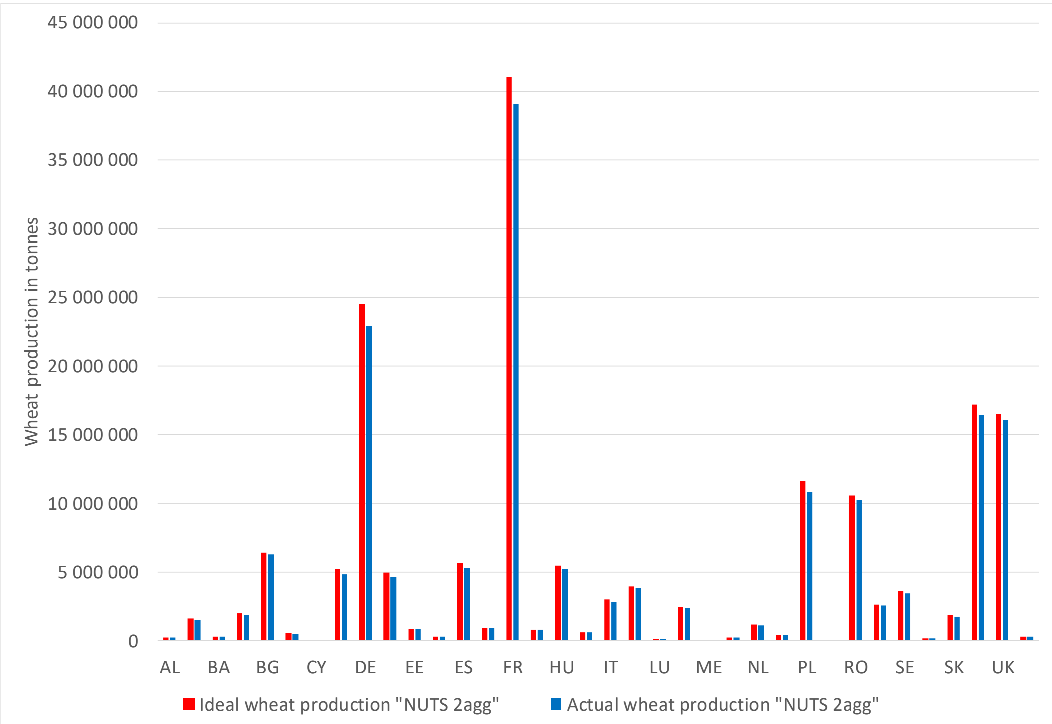


Figure 15 indicates the ideal wheat production (i.e. the hypothetical wheat production as it would have been in the absence of anthropogenic ozone, but still under other current socio-economic conditions), next to the actual wheat production in 2019 as reported in the European statistics.

Figure 15: Ideal wheat production and actual wheat production reduced by ozone by country in 2019, tonnes – reference case



The difference between the two is given in Figure 16, which shows the production loss in 2019 in tonnes. It indicates that the production loss, at least in some countries, is important, exceeding 500 thousand tonnes of wheat in Turkey and Poland, and reaching levels of 1.5 million and almost 2 million tonnes in Germany and France, respectively. Obviously, the absolute amount of loss is also correlated with the absolute production quantity in a country.

Figure 16: Production loss by country in 2019, tonnes – reference case

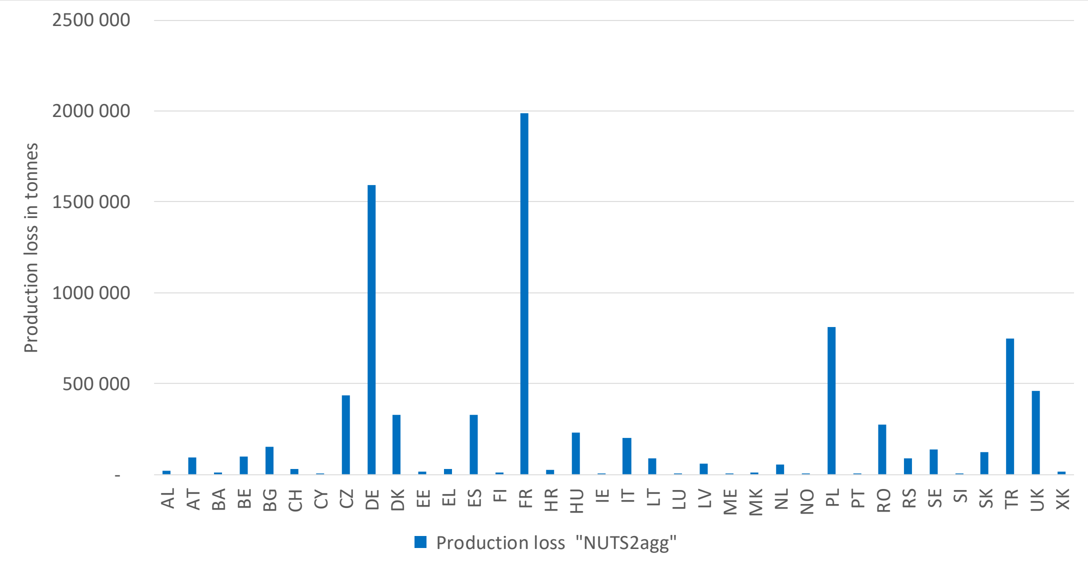
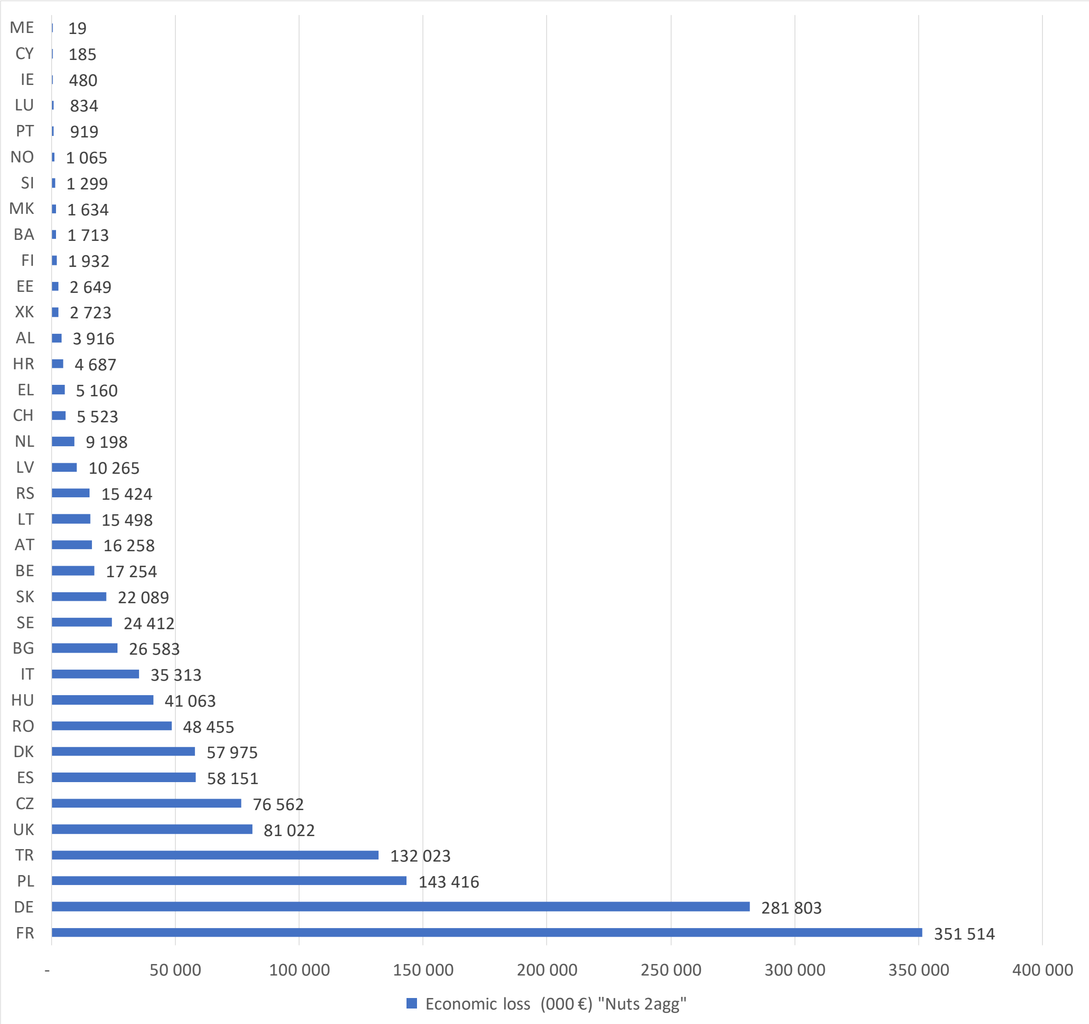


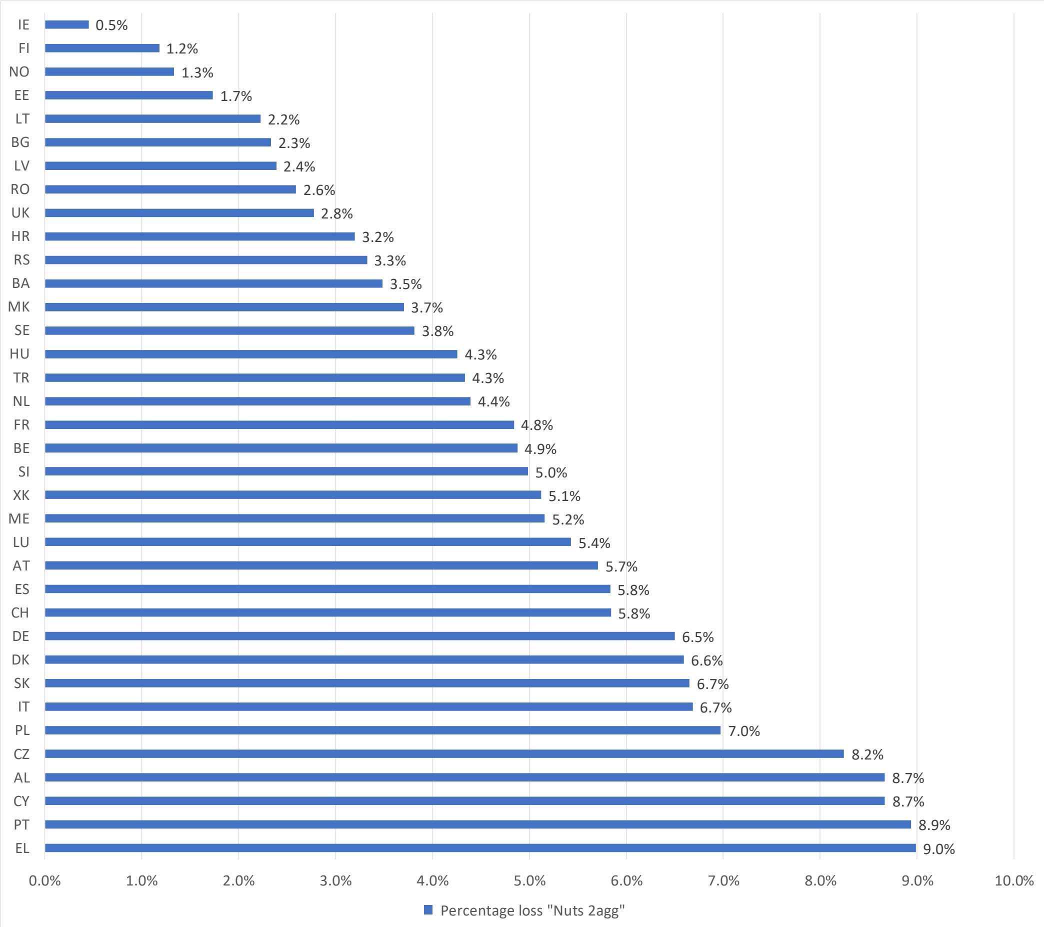
Figure 17 ranks the countries in terms of the economic value in 2019 of lost wheat production compared to pre-industrial ozone levels. This economic loss is calculated by multiplying the wheat production lost in each country with the price of 177 $€_{2019}$/t of wheat from FAOSTAT. The figure indicates losses reaching 350 million € in France, 280 million € in Germany, 140 million € and 130 million €, respectively, in Poland and Turkey, but also several millions of € in the majority of countries. The ranking of countries would be identical for production quantities.

Figure 17: Production loss by country in 2019, thousand € – reference case



When ranking countries in terms of the percentage loss in their wheat production, the order of countries is different, and the differences between countries are lower (Figure 18). This is of course so as production losses expressed in tonnes or € are highest where wheat production is highest in absolute terms. Percentage losses are highest for Greece, Portugal, Cyprus, Albania and Czechia, all situated between 8 % and 9 %. Percentage losses are lowest in Ireland (0.5 %), Finland (1.2 %), Norway (1.3 %) and Estonia (1.7 %). Approximately half of the countries suffer losses below 5%, the other half above 5 %.

Figure 18: Production loss by country in 2019, in % – reference case



7.2 Comparison with the results of the sensitivity cases

Figure 19 shows the production loss by country in 2019, in %, side by side for the reference case NUTS 2_{agg} and the two sensitivity cases NUTS 0 and $PODy_{agg}$. What can be said about this figure is that losses reach levels up to 9% in some countries, and that which of the three cases studied yields the highest loss, varies amongst the countries. No clear pattern can be detected.

Figure 19: Production loss aggregated by country in 2019, in % - reference case (NUTS 2_{agg}) and the two sensitivity cases NUTS 0 and $PODy_{agg}$

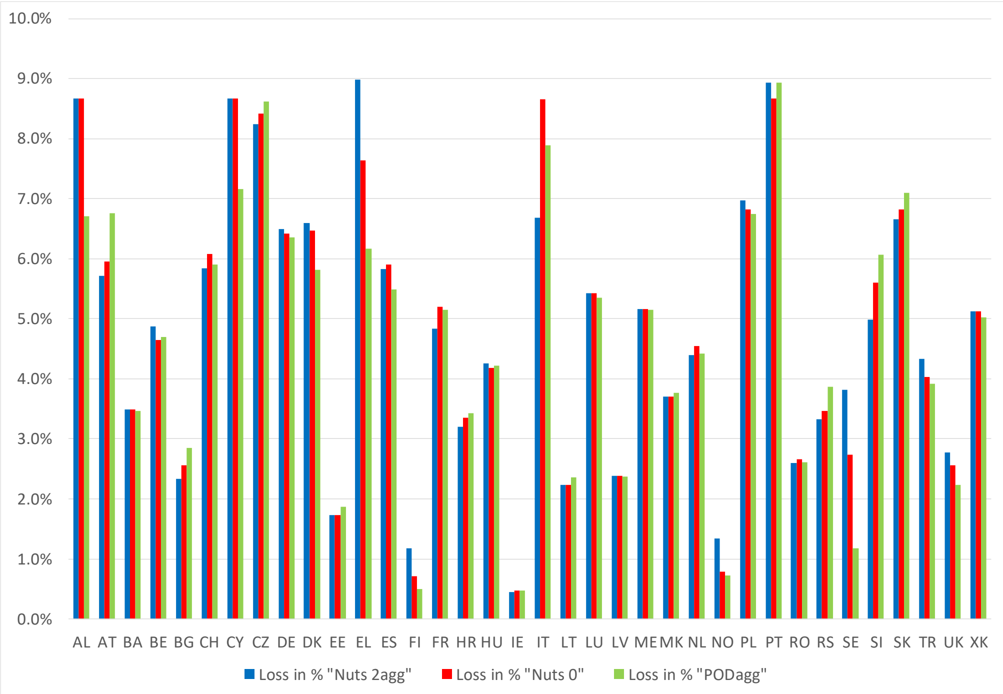
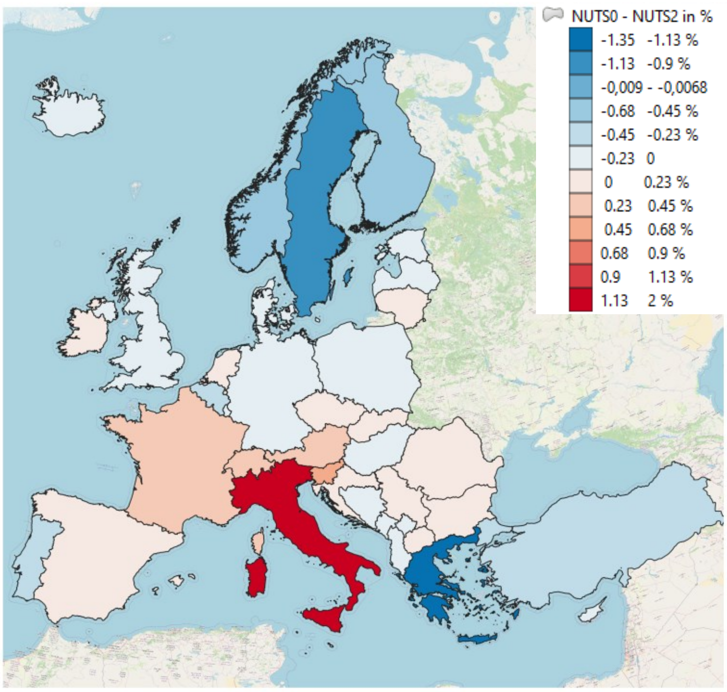


Figure 20 and Figure 21 show the difference in loss at the country level in 2019, in %, when subtracting the reference case NUTS 2_{agg} from the first sensitivity case NUTS 0. In Figure 20 results are presented in a map, in Figure 21 in the form of bars to more easily see the differences in percentage change. There is no clear evidence of pattern in this difference map, even if we can note that positive differences (sensitivity case – reference case) are found slightly more in the central latitudes.

Figure 20: Mapped difference in loss in 2019, in % - NUTS 0 minus NUTS 2_{agg}



The highest “positive difference” is found in Italy, reaching 2% between the two cases, the highest “negative difference” in Greece, followed by Sweden, with 1.4 and 1.1 %, respectively. For the majority of countries the absolute difference does not exceed 0.5%.

Figure 21: Difference in loss in 2019, in % - NUTS 0 minus NUTS 2_{agg}

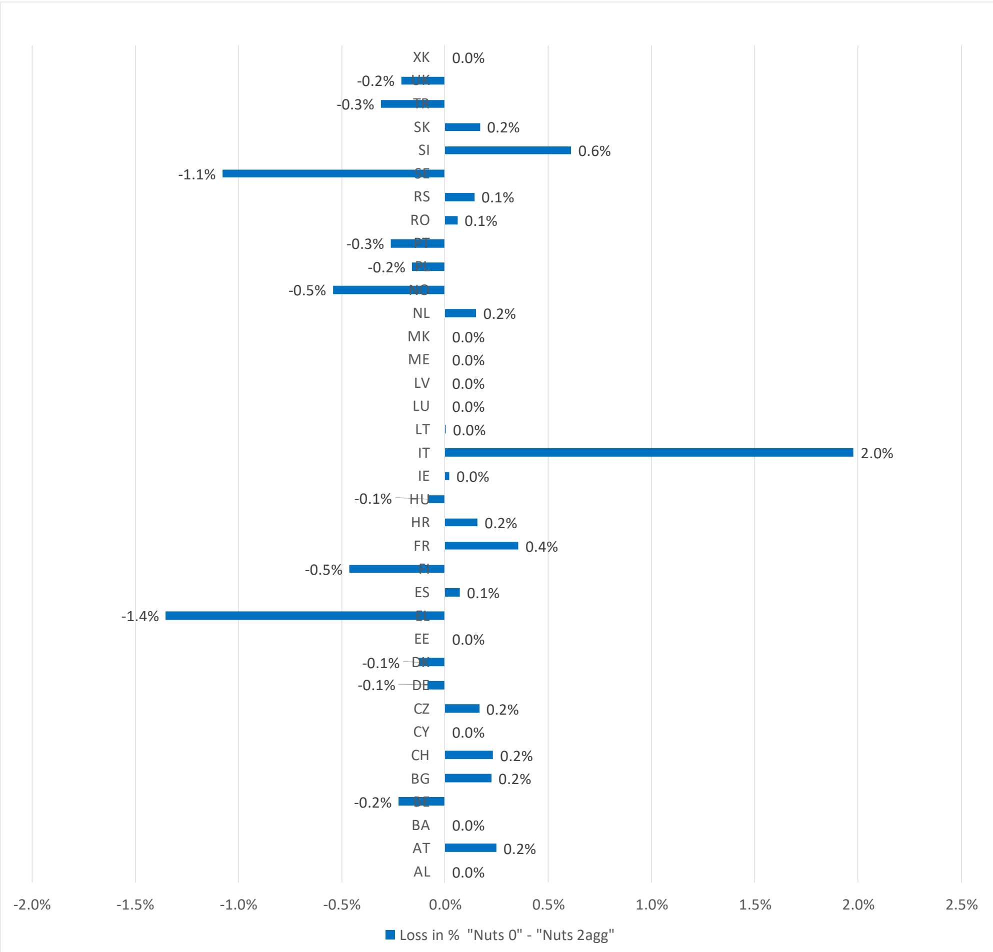
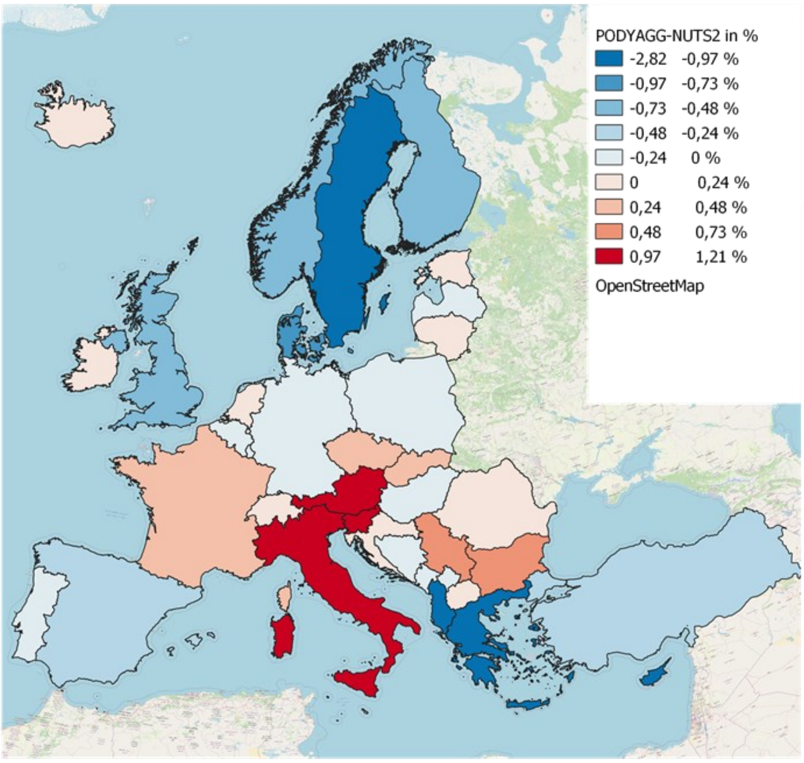


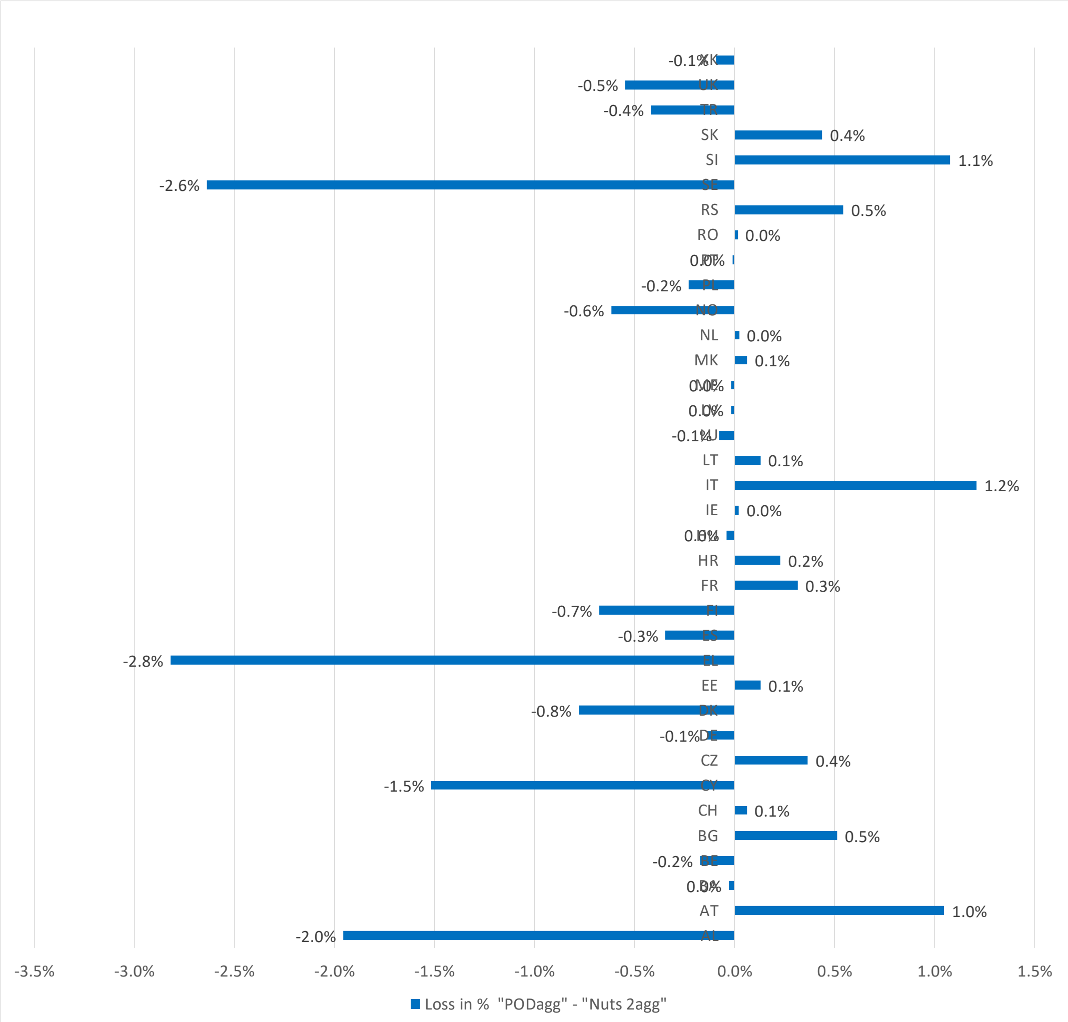
Figure 22 and Figure 23 show the difference in loss in 2019, in % at the country level, when subtracting the reference case NUTS 2_{agg} from the second sensitivity case $PODy_{agg}$. Again, results are first presented in a map in Figure 20, and then in the form of bars in Figure 23. As for Figure 20 and Figure 21, there is no evidence of a clear pattern.

Figure 22: Mapped difference in loss in 2019, in % - PODy$_{agg}$ minus NUTS 2$_{agg}$



Here differences range from -2.8 % in Greece, over -2.6 % in Sweden and -2 % in Albania to +1.2 % in Italy. Italy is closely followed by Slovenia and Austria, with respectively +1.1 % and +1 %.

Figure 23: Difference in loss in 2019, in % - $PODy_{agg}$ minus NUTS 2_{agg}



In the following two tables, the losses have been aggregated over the whole European domain. Table 8 indicates the loss in million €, and Table 9 in per cent.

The maximum difference between the reference case and the sensitivity cases amounts to 24 million € (Table 8). The maximum difference in % amounts to 0.11 (Table 9). In the first case it is the difference between NUTS 2_{agg} and $PODy_{agg}$, and the second one between NUTS0 and $PODy_{ass}$. These differences, overall, are lower than what we would have expected. It is possible that the comparatively low PODy values in 2019 are partly responsible for this.

Table 8: Loss in 2019 aggregated over Europe, in million €

Economic loss in 2019 in million € in Europe (*)		
"NUTS 2_{agg}"	**"NUTS 0"**	**"$PODy_{agg}$"**
1 499	1 511	1 475
(*) Sum over 36 countries		

Table 9: Loss in 2019 aggregated over Europe, in %

Loss in 2019 in % in Europe (*)		
"NUTS 2_{agg}"	**"NUTS 0"**	**"$PODy_{agg}$"**
4.78%	4.81%	4.70%
(*) Sum over 36 countries		

8 Conclusions and perspectives

In this study the ozone maps of indicators based on the PODy tool developed at Ineris, and calculated by CHMI under the ETC/ATNI's task on spatial mapping are used as starting point to quantify and monetize losses of bread wheat production due to tropospheric ozone pollution in 2019 in Europe.
To this end, the POD6SPEC flux-effect function recommended by the Mapping Manuel of the Air Convention (CLRTAP, 2017) was chosen. Soft (bread) wheat production data for 2019 come from EUROSTAT and international wheat prices were calculated by dividing the Gross production value of wheat in 2019 by the production quantities, both from FAOSTAT.

Monetary valuation of crop losses by gross production value or sales prices implicitly assumes that pollutant damage is not sufficient to affect the price of crops. This is the approach followed in many European and non-European studies. However, this is an approximation for two reasons. First, the reduction in output and therefore in the economic offer could affect prices (the sign and magnitude of such an effect is difficult to predict since wheat is traded at a global market). Second, the loss in production is not necessarily equal to the economic damage; for example, if production factors can be saved and/or used for other productive activities, or if adaptative measures can reduce the loss in revenues. Nevertheless, the use of more complex models for the economic evaluation of crop loss may be considered disproportionate given that the associated impacts correspond to only a few percentage points of the health damage due to air pollution([16]).

Also, this approximation needs to be seen in the context of further uncertainties, which accumulate at each step of the calculation chain of ozone impacts on crops (formulation of the PODy calculation, estimation of ozone accumulation periods which are not differentiated between varieties of the same crop species, use of stomatal conductance values and a single dose-response function per species over all biogeographical areas, quantification of ozone fluxes, estimation and geo-location of production data). It is difficult to quantify this uncertainty precisely. Moreover, it cannot be excluded that some biases may be compensated in the calculations. The calculation of a hypothetical production of wheat corresponding to levels of zero ozone has the caveat of abstracting from the fact that wheat production might not be as high as it is currently if all technologies and practices leading to ozone pollution would be abandoned. Altogether, this implies that the uncertainties in the economic results for ozone impacts on crops must be considered as high, with a tendency to overestimation due to the PODy calculation methodology using limiting functions of the ozone flux which favour ozone absorption. In addition, the use of flux-effect relationships and critical levels for crops gives, according to the Mapping Manual, a potential maximum rate of reduction which can be understood as a high end estimate of the impact.

In our reference case (NUTS 2_{agg}), gap filling approaches were applied to obtain wheat production quantities at NUTS 2 level, the highest spatial resolution at which these data are available for the European countries. These were then spatialized at the 2 km x 2 km grid using Corine Land Cover. At the grid level, ozone fluxes and production data were combined to calculate the production loss in % and in tonnes. These were then aggregated at NUTS 2 and at country level, and then also valued in terms of economic losses using the wheat prices for monetization.

A geolocation (spatialization) of crop production data across the domain, permitting to account for local differences in ozone fluxes, will lead to more accurate results than calculating impacts directly at country level, as is the case for $PODy_{agg}$. The geographical level for which wheat production statistics are available will also impact on the accuracy of results. In order to investigate the size of the impact

([16]) Furthermore, since ozone levels cannot be predicted over a full agricultural season, and agricultural activities can hardly take this factor into account in the short term, on a yearly basis these factors might not play an important role. However, when using economic calculations for long-term policy studies, adaptation to, and mitigation actions against, losses should probably be taken into account.

of different levels of spatial resolution (production and PODy) on the results, two sensitivity cases were also studied. In the first sensitivity case, denoted as NUTS 0, wheat production data at country level were spatialized at grid level using CLC. The rest of the calculations was as in the reference case. In the second sensitivity case, $PODy_{agg}$, ozone flux data initially available at grid level was averaged over each country and wheat production losses were calculated directly at this level. This case, hence, does not take account of the actual location of the wheat production nor of the geographical variation of the PODy values, implicitly assuming that exposure to ozone is uniformly distributed over the domain, which of course is not the case.

Ozone levels in 2019 appear low compared to earlier years. One reason for this might be the droughts that affected large areas of Europe in 2019.

Despite this, the results for our reference case, NUTS 2_{agg}, show important losses of wheat production in 2019. Expressed in percentage, they reach levels of up to 9% in Greece, and levels between 8% and 9 % in Portugal, Cyprus, Albania and Czechia. For 17 countries the loss exceeded 5 %.

In terms of quantities and monetary equivalent, losses were highest in France (almost 2 million tonnes or 350 million €), Germany (1.6 million tonnes or 280 million €), Poland (about 800 thousand tonnes or 140 million €) and Turkey (almost 750 thousand tonnes or 130 million €). Economic losses amounted to several millions of € in the majority of countries.

When comparing the percentage loss results of the reference case to the two sensitivity cases no clear pattern can be detected. Depending on the country, each of the three cases can show the highest percentage loss. In a comparison between NUTS 2_{agg} and NUTS 0, highest percentage differences are at 2%. In the comparison between NUTS 2_{agg} and $PODy_{agg}$, differences went up to 2.8 %.

Aggregated at a European level, the maximum differences are indeed found between the reference case and the sensitivity case $PODy_{agg}$. They amount to 24 million € or 0.8 %, which is however less than what we would have expected. Again, it is possible that the comparatively low ozone levels in 2019 are partly responsible for this, which might be due to the heat waves and extreme droughts 2019 was subject to.

For future work, it is, therefore, suggested to not only carry out the same reference and sensibility calculations for the most recent available data year, but also for a year known to have had what can be considered as average ozone levels associated to less severe droughts than in the year 2019, in order to get an idea of the robustness of the impact on the results of different variants of spatialization of data. We suggest to add a further “intermediate” sensitivity case, where ozone flux levels are aggregated at NUTS 2 level and losses calculated at this level. This case would avoid the spatialization at grid using CLC and therefore neglect the distribution of wheat production at the local level, however, it would take account of the regional distribution of wheat production. It is also suggested to further assess the sensitivity of different weights applied to the CLC land use classes when distributing wheat production over the grid, as well as the relative shares of these classes.

For future work, a discussion about a more realistic reference case for the calculation of the hypothetical crop production could be engaged also with the Air Convention Community.
The current version of the PODy tool does not differentiate stomatal conductance parameters between different biogeographical regions. For wheat, the method could be optimised by introducing differentiated maximum conductance values (g_{max}) and mid-anthesis degree days reference values by biogeographical region. We are planning to do this in the next edition of the work.
The inclusion of other crops species, especially potato, is considered for a future update of the work.

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