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# Wheat and potato yield loss in 2022 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 bread wheat ([1]) and potato production in Europe in 2022. 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 ([2]) in connection with the Working Group on Effects (WGE).

The main 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 in 2022 on wheat and potatoes for which methodological uncertainties are lower than for other crops and for forests, using an impact modelling chain.

In the report the PODy maps are compared to those for the AOT40 indicator for protection of vegetation. The statistical data available are 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.

In the main body of the report, a reference case (REF) was calculated for which ozone impacts on wheat and potatoes were quantified at the highest spatial resolution possible. REF uses wheat and potato 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 and potatoes 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 and potato selling prices.

The sensitivity of the results to the degree of spatialization of the input data was also studied. 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/HE work. In response to this two sensitivity cases were calculated for which the spatial resolution within the calculations was reduced. They are presented in annex 2. The first sensitivity case (SENS 1) uses wheat and potato production data provided this time at country level, which again are spatialized at the grid using CLC. Ozone impacts on wheat and potatoes 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 sensitivity case (SENS 2) does not at all spatialize wheat and potato production data. It aggregates average POD levels at the country level and calculates wheat production losses directly at the country level.

The results of the reference scenario indicate losses across Europe that amount to 6 683 kilo tonnes of wheat or 1.3 billion €$_{2022}$ in 2022. The importance of losses varies across regions, being the result of levels of ozone and the absolute production of the respective crop. Absolute losses in wheat production are highest in France (2.5 million t), Germany (1.4 million t) and Poland (465 kt). 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 less pronounced. This is so because production losses expressed in tonnes or € are highest where wheat production is highest in absolute terms. Percentage losses for wheat are highest for Belgium (7.3 %), France (6.9 %), Czechia (6.6 %) and Spain (6.4 %). They exceed 4 % also in Italy, Germany, Albania, the Netherlands, Portugal, Austria, Luxembourg, Greece and Switzerland. 19 out of 34 countries suffer losses above 2 %.

Production losses calculated for potatoes in 2022 amount to 3 223 kilo tonnes or 680 million € (price base 2022). The countries accounting for the highest production losses in absolute terms are Germany (933 kt), France (615 kt), the Netherlands (445 kt) and Poland (360 kt). In 17 countries, losses are higher

([1]) For simplification the term "wheat" is used throughout the text of this study, without specifying at each use that the calculations are carried out for bread wheat.

([2]) Convention on Long-Range Transboundary Air Pollution (CLRTAP).

than 4 %, the mean is about 4 %. The highest percentage losses are found in Czechia (10 %), Slovenia (8.9 %), Germany (8 %) and France (7%).

The impacts of ozone calculated here are important in terms of quantity and economic loss. However, they are lower than estimates from some earlier studies where ozone levels were higher (Schucht et al., 2019 a, b). However, depending on the country, they are higher or lower than in estimates by Schucht et al. (2021a) for 2019.

A geolocation (spatialization) of crop production data across the domain, permitting to account for local differences in ozone fluxes, leads to more accurate results than calculating impacts directly at country level. The results of two sensitivity calculations degrading the geographical spatialisation of input data showed a limited impact on the results, at least as far as the aggregate European level is concerned.

Expressed in million €, the loss aggregated at the European domain amounts to 1.34 billion € for wheat in REF, to 1,30 billion € in SENS1 and to 1.24 billion € in SENS2. The maximum difference is between REF and SENS2 (99 million €), the difference is 40 million € between REF and SENS1 and 59 million € between SENS1 and SENS2. In terms of percentages, the difference between REF and SENS1 is 0.1 percentage points and between REF and SENS2 0.3 percentage points. The difference between the two sensibility calculations amounts to 0.2 percentage points. At country level, differences between the scenarios are partly higher, but they do not exceed 1.68 percentage points for wheat in any country.

The results are comparable for potatoes. The aggregated economic loss is estimated at 680 million € in REF, at 655 million € in SENS1 and at 650 million € in SENS2. The difference between REF and SENS1 amounts to 25 million €, between REF and SENS2 to 30 million € and between SENS1 and SENS2 to 5 million €. Aggregated over Europe, the differences between the losses expressed in percentage and calculated in the sensitivity analyses are limited: 5.6 % in REF, 5.4 % in SENS1 and 5.4 % in SENS2. Hence, the differences between the three scenarios amount to between 0.2 percentage units and 0.01 percentage units. At a country level, the highest difference between scenarios is estimated at 5.5 percentage units.

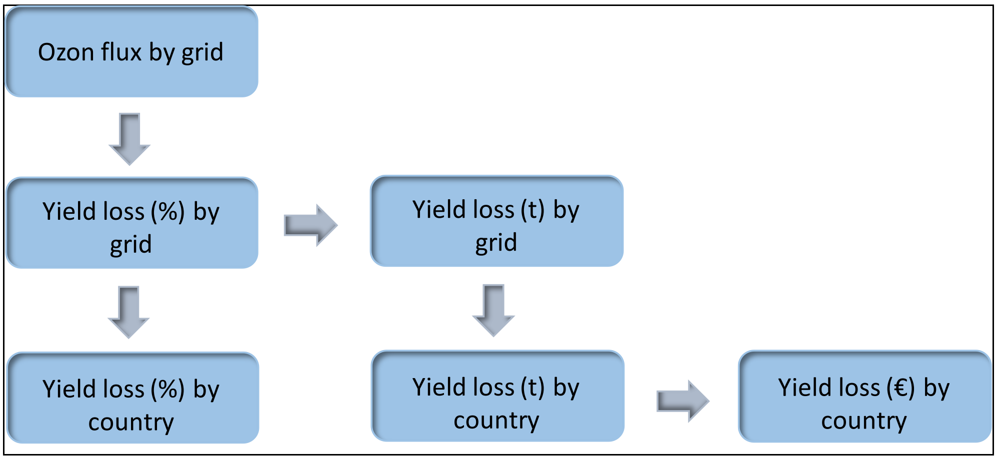
It is difficult to exactly know why the influence of spatial aggregation level of calculations on the results is relatively this limited. A possible reason for the low differences at the aggregate European level is error compensation. At the country level, differences in percentage points are partly more important, especially between REF and SENS2 (Figure 38 and Figure 42). This goes in the expected direction as in SENS2 geolocation is most degraded. Based on this, we would advise against giving up geolocation and using the SENS2 approach. Calculating ozone loss for the simplified approach SENS1 leads to more limited differences relative to the reference calculation, however, the simplification (and time saving) between REF and SENS1 is limited. In the latter 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. Only the statistical input data used for production here is initially available only at country level (instead of at NUTS 2 level as in REF). Concluding, our recommendation is to continue applying the core approach (REF), privileging calculations starting from the highest level of spatialisation possible, also in future assessments. Especially, as long as the ozone impacts on crops are calculated only for a few species. This is because calculations starting from the highest level of spatialisation possible can be expected to be more accurate, and, because the additional work charge is limited.

# 1 Introduction

Tropospheric ozone impacts agricultural crop and timber production (yield, quality) entailing significant economic effects for the sector. The European Regulation (EU, 2008) defines a target value for the protection of vegetation based on an indicator of annual Accumulated Ozone over a Threshold (AOT) ([3]) for May-July. However, this indicator does not consider 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 in connection with the Working Group on Effects (WGE).

The PODy approach was implemented by the European Topic Centre on Air pollution and Climate change Mitigation (ETC/ACM, predecessor of the ETC/ATNI and ETC/HE) 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, 2023). 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 bread wheat ([4]) 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 European Topic Centre on Air pollution, Transport, Noise and Industrial pollution (ETC/ATNI, predecessor of the ETC/HE) 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. The work started with ozone impacts on wheat (EEA Briefing, 2022; Schucht et al., 2021a) for which

([3]) AOT40 is the sum of the differences between hourly ozone concentrations greater than 80 µg/m³ (= 40 ppb) and 80 µg/m³ 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]) For simplification the term "wheat" is used throughout the text of this study, without specifying at each use that the calculations are carried out for "bread wheat".

methodological uncertainties are lowest. Since 2023 (Schucht et al., 2023) it has included ozone impacts on wheat and potatoes. For potatoes there remains uncertainty with respect to the dates defining the accumulation periods, notably with respect to the dates for tuber initiation.

To estimate the economic impact of ozone on crops, ozone flux calculations need to be translated into yield losses in % and into yield losses expressed in terms of quantity and economic value (cf. second and third column in Figure 1).

An impact modelling chain has been implemented to quantify and monetize the loss in wheat and potato production due to tropospheric ozone exposure for 2022 (the latest reporting year for which ozone data are available at the moment of the calculations for this report). To the extent possible, all input data are for this same year: meteorology, ozone concentrations, PODy maps, ozone fluxes, wheat and potato production and wheat and potato prices.

The sensitivity studies carried out in the previous reports (Schucht et al., 2021a and 2023) were also repeated. The aim is to assess 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 need. A second reason is to assess the additional uncertainty of an aggregated approach as it is applied in other tasks within the ETC/HE (and its predecessors') work (notably the work calculating marginal damage costs per tonne of pollutant emitted in the framework of work on environmental externalities).

To this end a reference (REF) has been calculated for which ozone impacts on wheat (potato) were quantified at the highest spatial resolution possible. REF uses wheat (potato) production data provided at NUTS 2 level ([5]), which are then spatialized at the grid with a resolution of 2 km using spatial information on areas occupied by different agricultural activities from Corine Land Cover (CLC ([6])). Ozone impacts on wheat (potatoes) 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 (potato) selling prices. The reference calculation is presented in chapter 4 to chapter 7 of the report.

Results were, furthermore, calculated for two alternative cases where the spatial resolution of the input data was reduced. The first alternative case (SENS1) uses wheat (potato) production data provided at NUTS 0 (i.e., country) level, which again is spatialized at the grid using CLC. Ozone impacts on wheat (potatoes) 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 (SENS2) does not at all spatialize wheat (potato) production data. It aggregates average POD levels at the country level and calculates wheat (potato) production losses directly at the country level. Compared to the reference calculation, these two are less time intensive because they do not require an estimation of production data at NUTS2 level for the countries and regions for which these data are not available in the statistics. The two sensitivity calculations are presented in annex 2.

This report is structured as follows. Chapter 2 presents the necessary calculation steps. Chapter 3 shows the ozone maps provided by the ETC HE/Czech Hydrometeorological Institute (CHMI) on which the subsequent impact calculations are based and compares these maps to the alternative ozone impact indicator AOT40 for protection of vegetation. Chapter 4 presents the available statistical data on wheat and potato 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 and potato prices. In chapter 6 the calculation of yield loss and economic loss is explained. Chapter 7 presents the

([5]) The level of European regions known as NUTS level 2: . https://ec.europa.eu/eurostat/web/nuts/overview/
([6]) [CORINE Land Cover — Copernicus Land Monitoring Service]

results in terms of crops losses in %, quantity, and economic loss for REF. Chapter 8 discusses the results, also with respect to the two sensitivity cases, and presents conclusions. The method for calculating ozone fluxes is briefly summarised in annex 1. Sensitivity calculations are the object of annex 2.

## 2 Calculations steps to quantify and monetise crop losses

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, Schucht et al., 2021a):

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, 2023). The geographic domain aimed at covering 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, Kosovo under UNSCR 1244/99, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Monaco, Montenegro, Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, San Marino, Serbia, ,Slovakia, Slovenia, Spain, Sweden, Switzerland and Türkiye. However, due to some missing data either for production or prices, the set is limited to 34 countries for wheat ([7]) and to 36 countries for potatoes ([8]).

The spatial resolution of the ozone flux calculation is 2 km and the ozone concentration 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) and carried out within the topic centre for the calculation of the European air quality maps (Horálek et al., 2020, 2021, 2022a, b, 2023, 2024).

Concerning the following steps, data on crop production quantities and economic indicators (production volume, prices) are collected for the latest year for which ozone data are available (2022) and applied to ozone fluxes calculated for the same year.

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

In REF ozone impacts on wheat and potatoes are quantified at the highest spatial resolution possible. For this, wheat and potato 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 and potatoes 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 valued in € using wheat and potato selling prices. In this assessment, all steps of the ozone impact

([7]) Excluded are Andorra, Liechtenstein, Malta, Monaco, Norway, Slovenia and San Marino.
([8]) Excluded are Andorra, Liechtenstein, Monaco, Norway and San Marino.

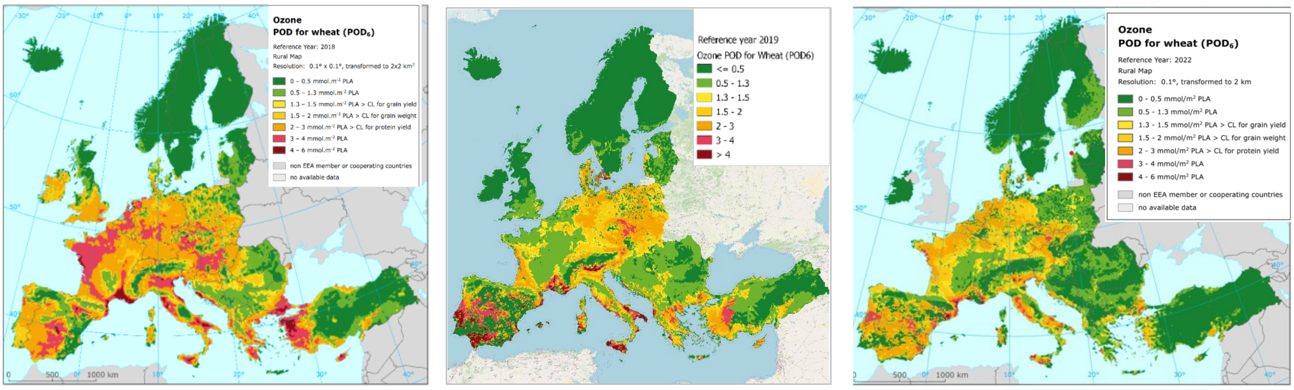
calculation as presented in Figure 1 were followed, as well as all steps indicated in the list above, with an additional intermediate aggregation of results at regional level. This is also the approach applied in an earlier study by Ineris (Schucht et al., 2019a, b). For the shortcuts applied in the sensitivity case 2, cf. the annex as well as Schucht et al. (2021a).

# 3 Ozone maps

The POD6SPEC values (accumulated POD above a threshold dedicated for crops of 6 mmol m-2 PLA) for wheat and potatoes were computed by ETC-HE/CHMI (Horálek et al., 2023) using the PODy tool developed by Ineris for the year 2022. The POD6SPEC was calculated for 41 countries.

Figure 2 shows the POD6SPEC maps for wheat for the years 2018, 2019 and 2022.

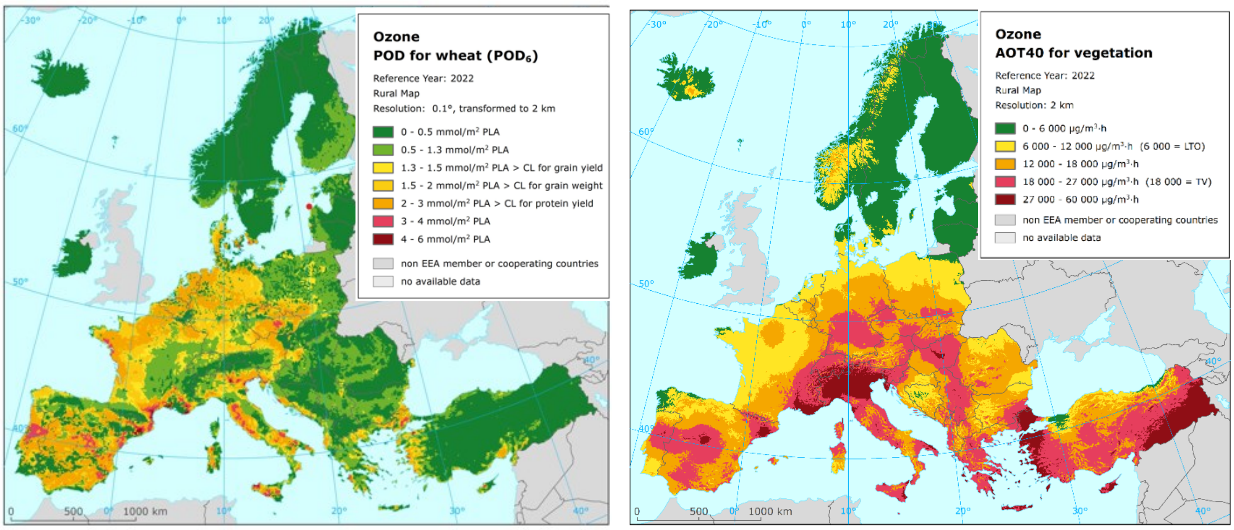
**Figure 2 Wheat POD6SPEC (in mmol.m$^{-2}$ PLA) maps for Europe in 2018 (left), 2019 (centre) and 2022 (right)**




The maps show a significant decline in POD6SPEC values for wheat in 2019 relative to 2018. The values of POD6SPEC for 2022 are higher in some regions, and lower in others.

Figure 3 and Figure 4 present POD6 map for wheat and potatoes for 2022, respectively, in comparison with the AOT40 values for protection of vegetation for the same year. AOT 40 is the alternative and older indicator of ozone accumulation used in the AAQ Directive 2008/50/EC (see description in footnote 5).

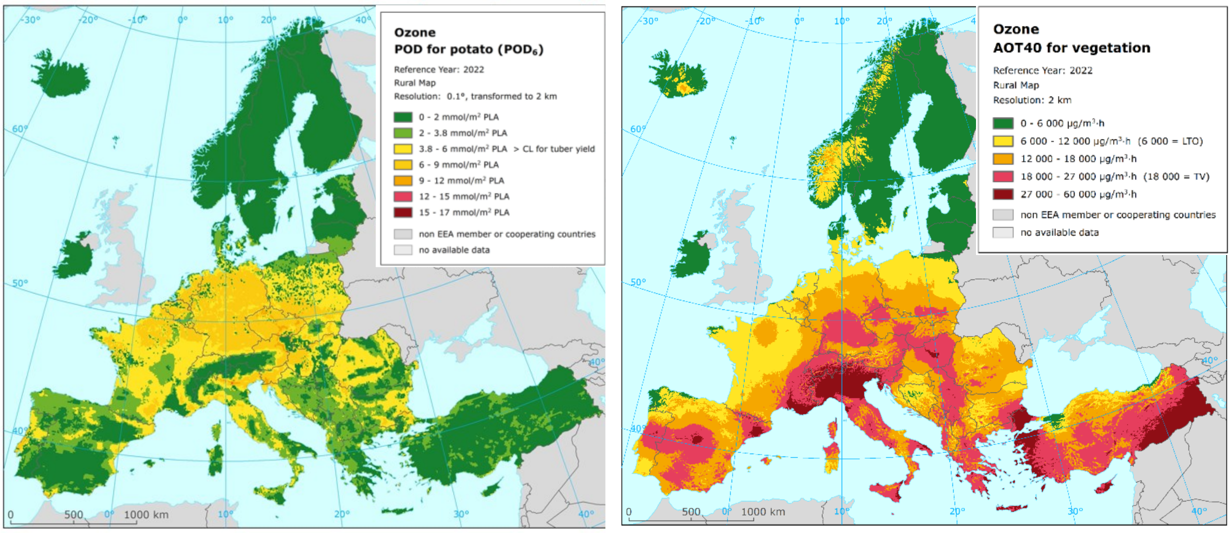
**Figure 3 Ozone indicators wheat POD6SPEC (left, in mmol.m-2 PLA) and AOT40 for vegetation protection (right, in ppb) maps for Europe in 2022**




The maps for POD6SPEC for wheat and for AO40 for vegetation (Figure 3) show some clear differences in the patterns. Indeed, the AOT40 map for vegetation shows high levels of AOT40 in northern Italy, the Alpine region, Germany, Austria and Türkiye that are not found in the POD map. The map

POD6SPEC for wheat shows also some patterns of medium-high levels of POD6SPEC in the west and north of France, the north of Belgium, the Netherlands, Germany and Denmark that are not shown in the AOT 40 map.

**Figure 4 Ozone indicators potato POD6SPEC (left) and AOT40 for vegetation protection (right) maps for Europe in 2022**




As for wheat, the POD6SPEC map for potatoes and the AO40 map for vegetation (Figure 4) also show some differences in the patterns. The POD6SPEC map for potatoes shows the highest levels of POD in the north of central Europe (north of France, Belgium, the Netherlands, Austria, Germany, Hungary, Czechia, Slovakia and Poland) and lower levels elsewhere. The AOT40 map shows high levels of AOT40 in some other parts in Europe (Spain, Portugal, parts of Italy, Greece, Türkiye) and in Austria, Germany, Hungary, Czechia, Slovakia and Poland.

# 4 Spatialization of crop production data

Production data are available at different regional scales (NUTS2, NUTS 1, national). PODy fluxes are calculated at high spatial resolution (about 2 km). This chapter explains the process to refine the agricultural production data available to make it match with the PODy data. This process involves, in a first step, the filling of gaps in production data at NUTS2 level and, in a second step, the use of Corine Land Cover to geographically refine the production data.

## 4.1 Available Production data

### *4.1.1 Wheat*

Wheat production data at a national level for Europe are available both from the European statistical office EUROSTAT ([9]) and from the statistics of the international Food and Agricultural Organisation FAOSTAT ([10]). 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 1 and gives the quantity (in kT) of wheat produced (cf. Table 2 ([11])).

**Table 1 Data sources used for wheat production in Europe**

| Crops | Crop sub-category | Production data |
|---|---|---|
| **Wheat** | Common wheat and spelt | Harvested production in EU standard humidity (1000 t) [apro_cpsh1] |

Source: EUROSTAT.

Data for 2022 are available from EUROSTAT for 34 countries (Table 2): Albania, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Kosovo, Latvia, Lithuania, Luxembourg, Montenegro, Netherlands, North Macedonia, Poland, Portugal, Romania, Serbia, Slovakia, Spain, Sweden, Switzerland and Türkiye. We, therefore, have not calculated losses in wheat production for Andorra, Liechtenstein, Malta, Monaco, Norway, Slovenia and San Marino.

Table 2 indicates the wheat production data from EUROSTAT compared to the data available at FAOSAT in order to get an idea of the uncertainty in the data, in particular as FAO data are used for the economic assessment (see section 5). The last column indicates the difference between the two data sources. Data from the two sources diverge.

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([9]) https://ec.europa.eu/eurostat/databrowser/view/apro_cpsh1/default/table?lang=en&category=agr.apro.apro_crop.apro_cp.apro_cpsh

([10]) https://www.fao.org/faostat/fr/#data/QCL

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

**Table 2 Common wheat and spelt production data, in 1000 t in 2022**

| ISO code | Country | EUROSTAT | FAOSTAT | Difference |
|---|---|---|---|---|
| AL | Albania | 233 | 233 | |
| AT | Austria | 1 593 | 1 713 | -7% |
| BA | Bosnia and Herzegovina | 227 | 281 | -19% |
| BE | Belgium | 1 852 | 1 852 | |
| BG | Bulgaria | 6 390 | 6 448 | -0,9% |
| CH | Switzerland | 490 | 487 | 0,6% |
| CY | Cyprus | 13 | 33 | -61% |
| CZ | Czechia | 5 189 | 5 189 | |
| DE | Germany | 22 369 | 22 587 | -1% |
| DK | Denmark | 4 165 | 4 165 | |
| EE | Estonia | 854 | 854 | |
| EL | Greece | 263 | 1 203 | -78% |
| ES | Spain | 5 813 | 6 509 | -11% |
| FI | Finland | 844 | 864 | -2% |
| FR | France | 33 302 | 34 632 | -4% |
| HR | Croatia | 967 | 971 | -0,4% |
| HU | Hungary | 4 218 | 4 355 | -3% |
| IE | Ireland | 701 | 701 | |
| IS | Iceland | 0 | 0 | |
| IT | Italy | 2 819 | 6 610 | -57% |
| LT | Lithuania | 4 483 | 4 483 | |
| LU | Luxembourg | 85 | 86 | -2% |
| LV | Latvia | 2 539 | 2 539 | |
| ME | Montenegro | 2,1 | 2,2 | -8% |
| MK | North Macedonia | 227 | 225 | 1% |
| MT | Malta | 0 | 0 | |
| NL | Netherlands | 1 163 | 1 163 | |
| PL | Poland | 13 195 | 13 195 | |
| PT | Portugal | 49 | 62 | -21% |
| RO | Romania | 8 661 | 8 684 | |
| RS | Serbia | 3 110 | 3 110 | |
| SE | Sweden | 3 229 | 3 229 | |
| SI | Slovenia | | 151 | -100% |
| SK | Slovakia | 1 735 | 2 048 | -15% |
| TR | Türkiye | 16 617 | 19 750 | -16% |
| XK | Kosovo (under United Nations Security Council Resolution 1244/99) | 331 | | |

Source: EUROSTAT, FAOSTAT.

In the reference scenario (REF), 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).

These data for common wheat are available also from the EUROSTAT statistics. The source is the same as for the country level data (apro_cpshr), only with the addition of “by NUTS 2 regions” in the title . These data use the NUTS 2021 classification ([12]).

However, data are not available at a NUTS 2 level for all countries. For some countries, production is available only at NUTS 1 (larger regions than NUTS 2) (Germany) or at national level (NUTS 0) (Bosnia & Herzegovina, Kosovo and Switzerland).

### *4.1.2 Potatoes*

As for wheat, EUROSTAT is the data source used for production data for potatoes. The exact data set is indicated in Table 3 and gives the quantity (in kT) of potatoes produced by country (Table 4). Data are published at country level [apro_cpsh1] and at NUTS2 level (apro_cpshr), amongst others.

**Table 3 Data sources used for potato production in Europe**

| Crops | Crop sub-category | Production data |
|---|---|---|
| **Potatoes** | Potatoes (including seed potatoes) | Harvested production in EU standard humidity (1000 t) [apro_cpsh1] |

Source: EUROSTAT

Data at country level from Eurostat are available for 36 countries (Table 4)([13]): Albania, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Kosovo, Latvia, Lithuania, Luxembourg, Malta, Montenegro, Netherlands, North Macedonia, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland and Turkey. We, therefore, have not calculated losses in potato production for Andorra, Liechtenstein, Monaco, Norway and San Marino.

Table 4 also shows the comparison of the potato production data from EUROSTAT to that available from FAOSTAT. Unlike for wheat, differences between the two data sets for potatoes are rare and amount to a few percent only.

(12) https://ec.europa.eu/eurostat/documents/345175/629341/NUTS2021.xlsx
([13]) https://ec.europa.eu/eurostat/web/main/data/database.

**Table 4 Potato production data, in 1000 t in 2022**

| ISO code | Country | EUROSTAT | FAOSTAT | Difference |
|---|---|---|---|---|
| AL | Albania | 263 | 263 | |
| AT | Austria | 686 | 686 | |
| BA | Bosnia and Herzegovina | 286 | 313 | -8% |
| BE | Belgium | 3 578 | 3 578 | |
| BG | Bulgaria | 172 | 172 | |
| CH | Switzerland | 381 | 390 | -2% |
| CY | Cyprus | 90 | 90 | |
| CZ | Czechia | 655 | 655 | |
| DE | Germany | 10 683 | 10 683 | |
| DK | Denmark | 2 618 | 2 618 | |
| EE | Estonia | 73 | 73 | |
| EL | Greece | 392 | 392 | |
| ES | Spain | 1 882 | 1 882 | |
| FI | Finland | 533 | 562 | -5% |
| FR | France | 8 067 | 8 067 | |
| HR | Croatia | 103 | 103 | |
| HU | Hungary | 199 | 199 | |
| IE | Ireland | 368 | 368 | |
| IS | Iceland | 7 | 7 | |
| IT | Italy | 1 333 | 1 333 | |
| LT | Lithuania | 226 | 226 | |
| LU | Luxembourg | 15 | 15 | |
| LV | Latvia | 130 | 130 | |
| ME | Montenegro | 23 | 25 | -6% |
| MK | North Macedonia | 197 | 197 | |
| MT | Malta | 7 | 7 | |
| NL | Netherlands | 6 916 | 6 916 | |
| PL | Poland | 6 031 | 6 031 | |
| PT | Portugal | 320 | 320 | |
| RO | Romania | 1 346 | 1 346 | |
| RS | Serbia | 524 | 524 | |
| SE | Sweden | 852 | 852 | |
| SI | Slovenia | 58 | 58 | |
| SK | Slovakia | 131 | 131 | |
| TR | Türkiye | 5 200 | 5 200 | |
| XK | Kosovo (under United Nations Security Council Resolution 1244/99) | 76 | | |

Source: EUROSTAT, FAOSTAT.

In REF, the quantification of the impact of ozone on potatoes is again based on production quantities reported at NUTS2 level.

Also, for potatoes, for some countries, production is available only at NUTS 1 (Germany) or at national level (Bosnia & Herzegovina, Czechia, Denmark, Kosovo, Lithuania, Romania and Switzerland).

## 4.2 Gap filling for wheat

### *4.2.1 Gap filling for NUTS 2 using the number and size of wheat holdings*

With the aim to start spatialization in REF 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 5). These statistics are detailed by type of crops. The type 'Common wheat and spelt' was selected. The dataset on detailed holdings available for the year 2016 was used here.

**Table 5 Data sources used for number of wheat producing holdings in Europe**

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

Source: EUROSTAT

Table 6 shows the different area categories of the wheat and spelt holdings distinguished in the data set (left column).

**Table 6 Area categories of wheat producing 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 |

It is 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 5. The mean area of a holding category was estimated as mean of minimum and maximum area of this category (right column in Table 6).

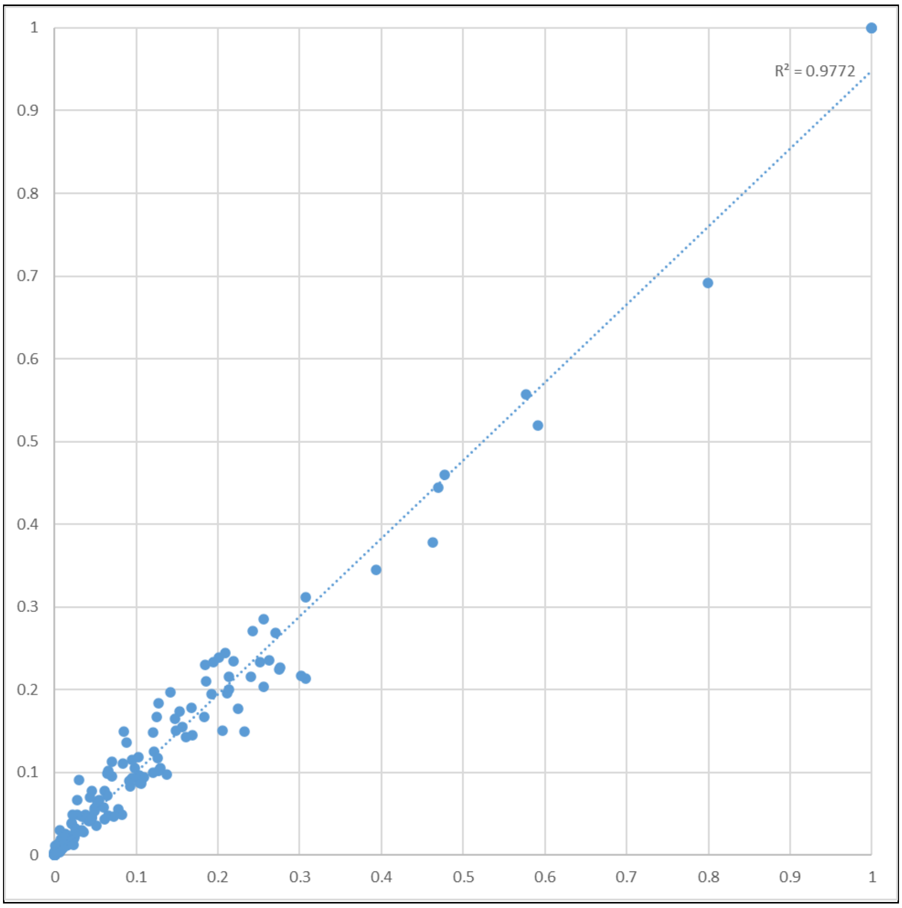
The wheat areas by NUTS2 were evaluated by summing number of holdings multiplied by their mean area.

$$Wheat\ area_{\ NUTS\ 2} = \sum_m (Number\ of\ holding_{category,NUTS2} * Mean\ area_{category}) \qquad (1)$$

The areas assessed 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 Germany.

Figure 5 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. 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 5.

**Figure 5 Comparison of the production share of NUTS 2 between production data and estimated wheat areas**




### 4.2.2 Gap filling for NUTS 2 using earlier data

For Switzerland, 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 2021 and then applied to the wheat production at country level available in 2022 to estimate the corresponding NUTS 2 production levels.

### 4.2.3 Countries for which no NUTS 2 data were estimated

For Bosnia & Herzegovina and Kosovo, NUTS 0 is equal to NUTS 2. Therefore, no gap filling was necessary.

## 4.3 Gap filling for potatoes

### *4.3.1 Gap filling for NUTS 2 using the number and size of potato holdings*

The statistics for potatoes are indicated in Table 7.

**Table 7 Data sources used for number of potato producing holdings in Europe**

| Crops | Holdings data |
|---|---|
| Potatoes (including seed potatoes) | Root crops by NUTS 2 regions [ef_lac_rootcrop]: number of holdings by area category |

Source: EUROSTAT.

Table 8 shows the different area categories of the potato holdings distinguished in the data set (left column).

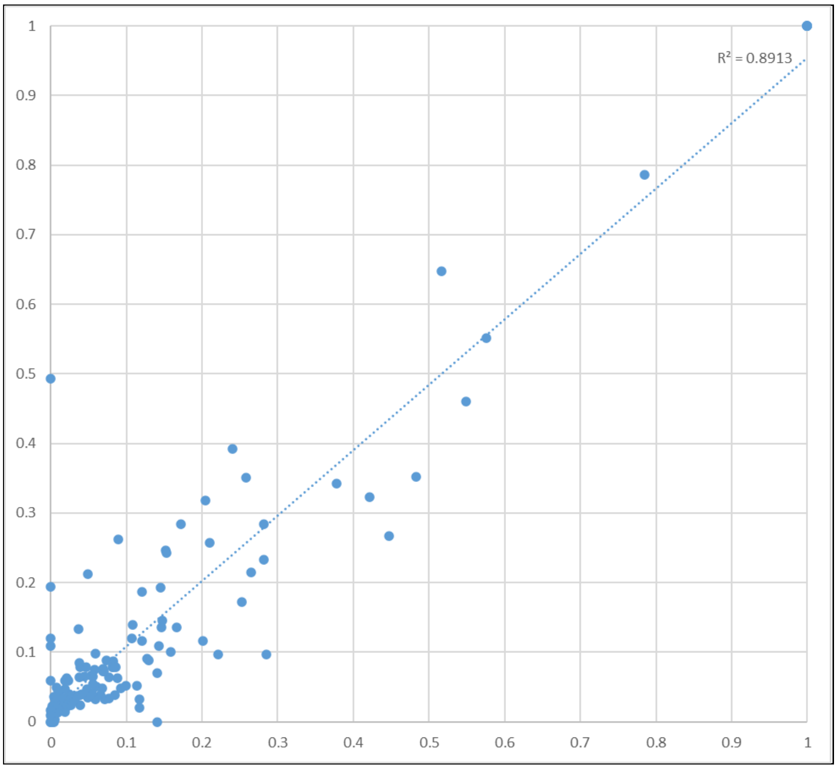
**Table 8 Area categories of potato producing holdings**

| Area category | Mean calculated area (ha) |
|---|---|
| Less than 0.25 ha | 0.25 |
| From 0.25 to 0.49 ha | 0.37 |
| From 0.50 to 0.99 ha | 0.745 |
| 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 49.9 ha | 34.95 |
| 50 ha or over | 60 |

As was done for wheat, for potatoes the number of holdings in a given NUTS 2 area was also re-evaluated by summing all classes weighted by their mean area. This was done for all NUTS 2 areas. Again, the existence of a linear relationship between potato areas and the produced quantity of potatoes was assumed. These areas were calculated in each NUTS 2 using the data shown in Table 7. The mean area of a holding category was estimated as mean of minimum and maximum area of this category (right column in Table 8).

The areas assessed by NUTS 2 were then again 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 potato production over the NUTS 2 regions. This method was applied for gap filling in Czechia, Denmark, Lithuania and Romania (year 2016) and for Germany (year 2013).

**Figure 6** **Comparison of the production share of NUTS 2 between production data and estimated potato areas**




### *4.3.2 Gap filling for NUTS 2 using earlier data*

For Germany, potato production data for earlier years was not available at NUTS 2 level, nor 2016 holdings data. Only 2013 holdings data were available.
2013 holdings data were used for spreading production at NUTS 2 level for Germany, otherwise using the same methodology as with the 2016 holdings data.
For Switzerland, potato production data for earlier years was available at NUTS 2 level. The ratios of potato production at each NUTS 2 level to production at country level were calculated for the year 2021 and then applied to the potato production at country level available in 2022 to estimate the corresponding NUTS 2 production levels.

### *4.3.3 Countries for which no NUTS 2 data were estimated*

For Bosnia and Herzegovina and Kosovo, NUTS0 is equal to NUTS2. Therefore, no gap filling was necessary, as it was the case for wheat.

## 4.4 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 4.2.3 and 4.3.3) 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.

In this work, it was assumed that the spatial distribution over land use classes is identical for wheat and potatoes. Four land-use classes were selected for distributing the crop (wheat and potato) production data to the grid. These are indicated in Table 9. 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 and potato production over the grid the assumption was made 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. It was also assumed that category 243 should have a higher weight than the other two because it deals with land "principally occupied by agriculture". This class was assigned a weight of 0.8, the other classes were assigned weights of 0.2 each. A sensitivity analysis on the impact of modifying these hypotheses was presented in last year's assessment. It showed that the impact remained very limited and is therefore not repeated.

**Table 9 CLC codes used to spatialize crop data**

| Crops | CLC codes | Weight for spatialization |
|---|---|---|
| Wheat / potatoes | ***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* | 0.8 |

To give an example, assume a NUTS 2 administrative region producing wheat (potatoes) 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:

$$Share\ of\ production_{Sn} = \frac{Weight_n * Surface_n}{\sum_m (Weight_m * Surface_m)} \quad (2)$$

With $Weight_n$ representing the spatialization weight of the CLC type of entity n as given in Table 9.

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 REF is illustrated in Figure 8 (for wheat) and Figure 10 (for potato) while Figure 7 and Figure 9 show the production at NUTS 2 level, before the spatialisation.

The highest absolute levels of wheat production per NUTS2 region are located in the northern half of France and in Lithuania (Figure 7). The highest levels of potato production per NUTS2 region are located in north of France (Picardie and Nord Pas de Calais) and north of Germany (Lüneburg) (Figure 9). Unlike wheat production, potato production tends to be concentrated around the latitude in central Europe.

**Figure 7 Wheat production at Nuts 2 level in Kt in 2022 (REF)**

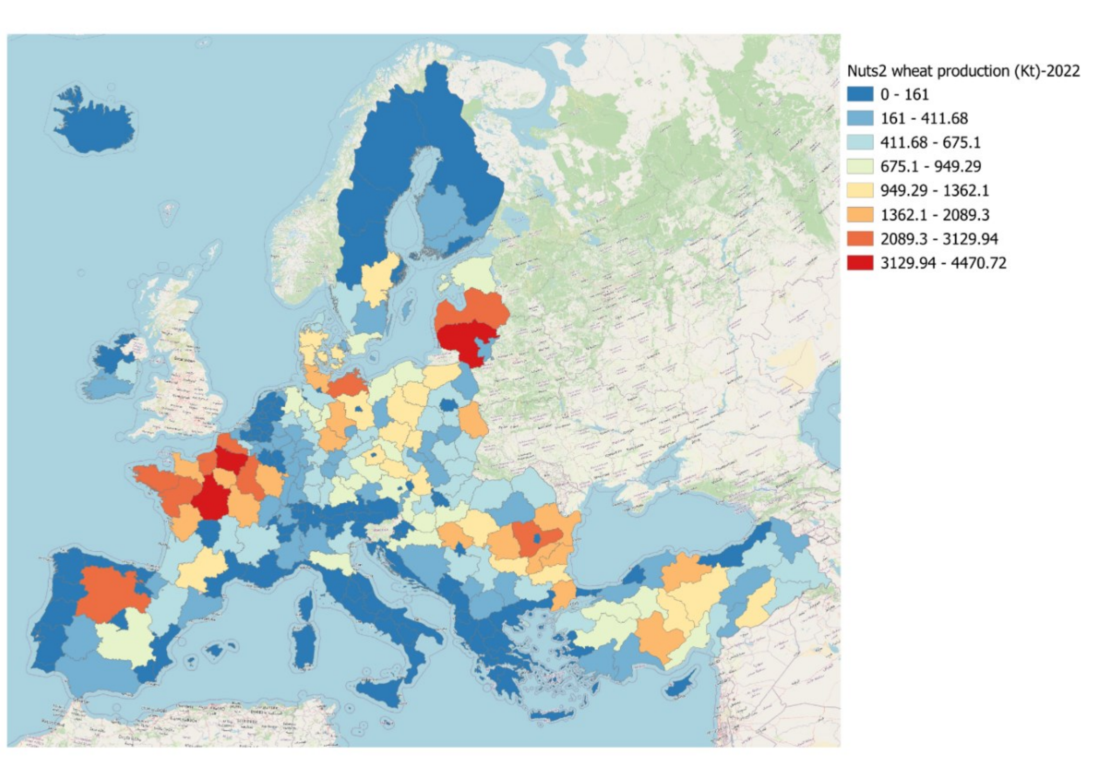
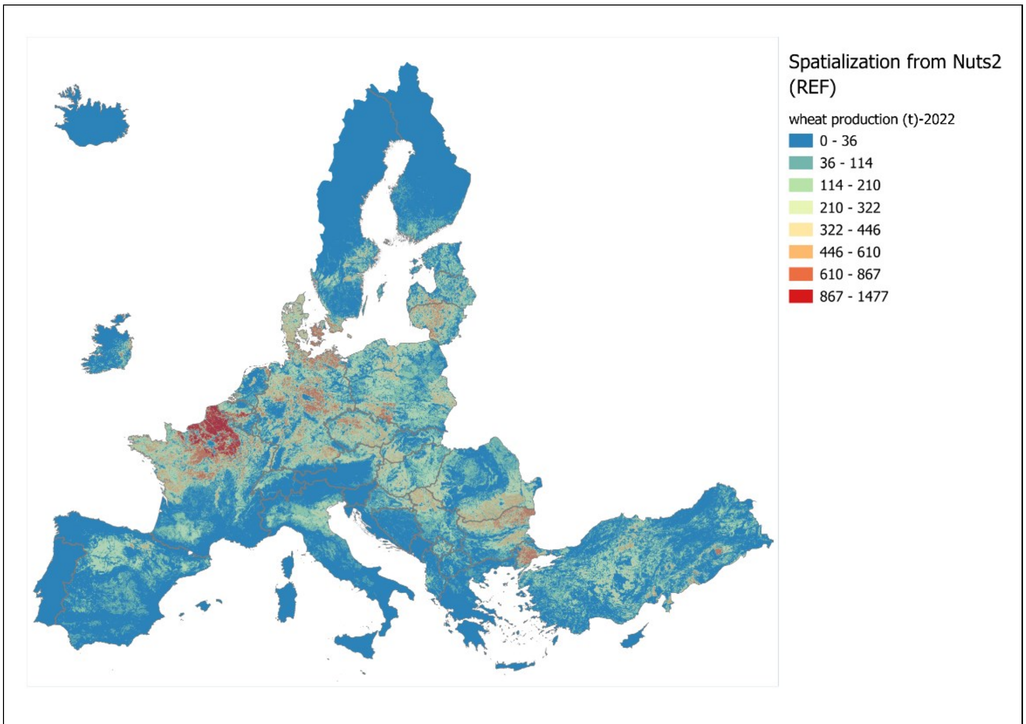
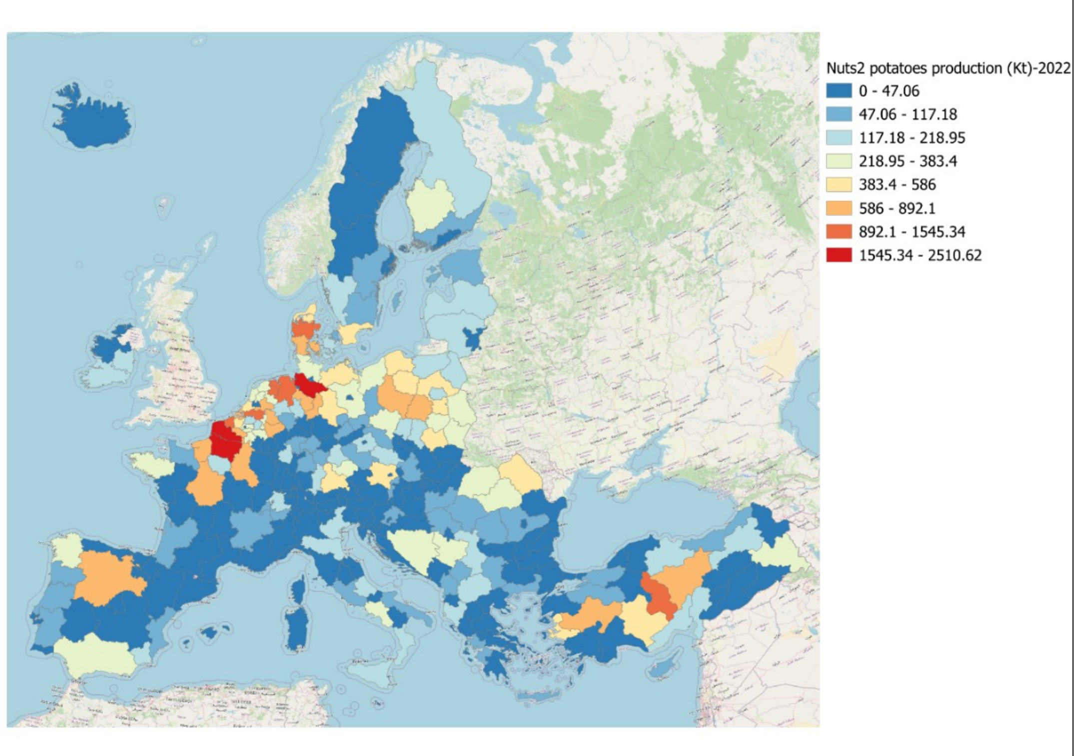


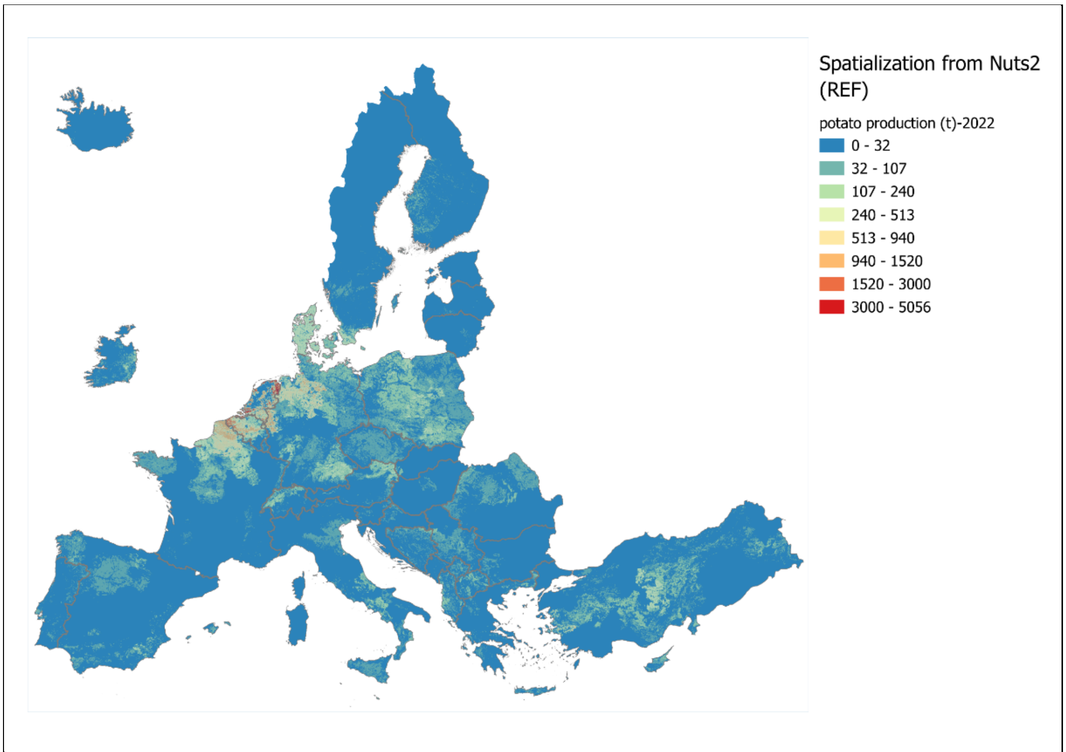

**Figure 8 Spatialization of the wheat production at the grid in 2022 (REF)**



## Figure 9 Potato production at Nuts 2 level in Kt in 2022 (REF)




## Figure 10 Spatialization of the potato production at the grid in 2022 (REF)



# 5 Price data

## 5.1 Wheat

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 because 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, 2021b); 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).

Economic data for crops is available from EUROSTAT and from the UN Food and Agriculture Organization (FAO([14])).

Data available from **EUROSTAT** are Selling prices ([15]) of soft (bread) wheat (prices given per 100 kg) in the data set apri_ap_crpouta. These statistics cover 37 countries, with 2022 values available only for 23 amongst these. **FAOSTAT** also provides data on producer prices, initially expressed in USD/tonne. These were converted to €$_{2022}$ using the OECD's PPP exchange rate data ([16]) from US$ to € of 0,620679 for 2022. The FAO dataset provides prices for 31 countries. Differences between the two data sets are situated around 50%. The data are provided in cf. Table 10.

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

([15]) These are defined as the prices "received" by farmers for their products (output prices). The "output" price is the average price received by farmers on the market for an agricultural commodity, produced within a specified 12-month period. This price is measured at the farm gate, i.e., at the point where the commodity leaves the farm and, therefore, does not cover the costs for transport or processing.

([16]) OECD, https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm.

**Table 10 Selling prices of wheat in 2022, in €$_{2022}$/tonne**

| Iso code | Country | EUROSTAT | FAOSTAT | Difference |
|---|---|---|---|---|
| AL | Albania | 0 | 272 | -100% |
| AT | Austria | 281 | 182 | 54% |
| BA | Bosnia and Herzegovina | NA | 211 | -100% |
| BE | Belgium | 321 | 210 | 53% |
| BG | Bulgaria | 311 | 203 | 53% |
| CH | Switzerland | 0 | 361 | -100% |
| CY | Cyprus | 384 | 200 | 92% |
| CZ | Czechia | 310 | 202 | 53% |
| DE | Germany | 321 | 203 | 58% |
| DK | Denmark | 269 | 176 | 53% |
| EE | Estonia | 320 | 186 | 72% |
| EL | Greece | 383 | 273 | 40% |
| ES | Spain | 342 | 237 | 44% |
| FI | Finland | 336 | 220 | 53% |
| FR | France | 0 | 0 | |
| HR | Croatia | 298 | 194 | 53% |
| HU | Hungary | 324 | 215 | 51% |
| IE | Ireland | 0 | 0 | |
| IS | Iceland | NA | NA | |
| IT | Italy | 360 | 295 | 22% |
| LT | Lithuania | 317 | 207 | 53% |
| LU | Luxembourg | 0 | 0 | |
| LV | Latvia | 290 | 185 | 57% |
| ME | Montenegro | 0 | NA | |
| MK | North Macedonia | 0 | 134 | -100% |
| MT | Malta | 0 | NA | |
| NL | Netherlands | 310 | 203 | 53% |
| NO | Norway | NA | 295 | -100% |
| PL | Poland | 324 | 212 | 53% |
| PT | Portugal | 388 | 264 | 47% |
| RO | Romania | 302 | 197 | 53% |
| RS | Serbia | 0 | 184 | -100% |
| SE | Sweden | 301 | 198 | 52% |
| SI | Slovenia | 315 | 206 | 53% |
| SK | Slovakia | 299 | 201 | 48% |
| TR | Türkiye | 0 | 202 | -100% |
| XK | Kosovo | NA | NA | |

Source: Eurostat, FAOSTAT. A "0" indicates that no data was reported for a country, NA indicates that the country was not part of the statistics.

The values from EUROSTAT range from a minimum of 269 €$_{2022}$/t in Denmark, to a maximum of 388 €$_{2022}$/t in Portugal and imply a mean of 322 €$_{2022}$/t. The lowest value from FAOSTAT amounts to 134 €$_{2022}$/t (North Macedonia), the highest to 361 €$_{2022}$/t (Switzerland), two of the countries not included in the EUROSTAT data set. The mean amounts to 217 €$_{2022}$/t. Amongst the countries missing 2022 prices in both data sets is the biggest European wheat producer France, for which last reported prices (2016) were the highest in Europe.

In the past, FAOSTAT provided gross production value for wheat (expressed in 2014-2016 constant 100 international $) and representing output prices at farm gate, a category that appears comparable to EUROSTAT's selling prices, at country level. For 2022, these data are no longer available for EU countries, instead they are provided for the EU27 aggregate. The international $ were converted into € using PPP (Purchasing Power Parity) exchange rates ([17]) from OECD, and corrected for inflation using HICP ([18]) (Harmonised Index of Consumer Prices) data from EUROSTAT to convert them to € in 2022. The average PPP exchange rate for the years 2014 to 2016 to convert international $$_{2014-2016}$ into €$_{2014-2016}$ ([19]) is 0.71. The HICP coefficient converting €$_{2014-2016}$ to €2022 is 1.188. The results are given in Table 11.

**Table 11 Gross production value for wheat ([20]) in 2022, in EU27**

| Area | Value 1000 Int. $ 2014-2016 | 1000 € 2014-2016 | 1000 € 2022 |
|---|---|---|---|
| EU27 | 31 812 535 | 22 587 388 | 26 832 073 |

Source: FAOSTAT

In order to obtain prices at country level, wheat production data equally available for 2022 from FAOSTAT for EU27 were used, i.e., the gross production value was divided by the wheat production (134.3 million tonnes). The resulting value amounts to 199.8 €$_{2022}$/t. (The same value is found when dividing the gross production value for non-EU countries by these countries' production data.) The value is situated below the lowest value of the selling prices obtained from EUROSTAT, but at the same order of magnitude as the mean value from FAOSTAT's producer prices. The price of 199.8 €$_{2022}$/t is used because using international 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.

## 5.2 Potatoes

Data available from EUROSTAT are Selling prices of Main crop potatoes (prices given per 100 kg) in the data set apri_ap_crpouta. The statistics for potatoes are limited to 29 countries, with 2022 values available only for 24 amongst these. Producer prices from FAOSTAT are available for 34 countries. As was the case for wheat, the prices for potatoes were converted from US$ to € using the PPP exchange rate ([21]) of € of 0,620679 in 2022. Table 12 shows the two data sets side by side with an indication of the difference between the two in the last column.

([17]) OECD, https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm.
([18]) EUROSTAT, https://ec.europa.eu/eurostat/web/hicp/database.
([19]) For the group EU27.
([20]) The exact type of wheat covered is not specified in the data source.
([21]) OECD, https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm.

**Table 12 Selling prices of main crop potatoes in 2022, in €$_{2022}$/tonne**

| Iso code | Country | EUROSTAT | FAOSTAT | Difference |
|---|---|---|---|---|
| AL | Albania | NA | 286 | -100% |
| AT | Austria | 258 | 169 | 53% |
| BA | Bosnia and Herzegovina | NA | 268 | -100% |
| BE | Belgium | 231 | 158 | 46% |
| BG | Bulgaria | 277 | 181 | 53% |
| CH | Switzerland | NA | 354 | -100% |
| CY | Cyprus | 412 | 285 | 44% |
| CZ | Czechia | 235 | 175 | 35% |
| DE | Germany | 233 | 152 | 53% |
| DK | Denmark | 287 | 187 | 53% |
| EE | Estonia | 0 | 216 | -100% |
| EL | Greece | 631 | 410 | 54% |
| ES | Spain | 368 | 252 | 46% |
| FI | Finland | 205 | 134 | 53% |
| FR | France | 0 | 0 | |
| HR | Croatia | 319 | 190 | 68% |
| HU | Hungary | 326 | 224 | 45% |
| IE | Ireland | 0 | NA | |
| IS | Iceland | NA | 685 | -100% |
| IT | Italy | 567 | 371 | 53% |
| LT | Lithuania | 302 | 209 | 44% |
| LU | Luxembourg | 434 | 282 | 54% |
| LV | Latvia | 246 | 144 | 71% |
| ME | Montenegro | NA | NA | |
| MK | North Macedonia | NA | 339 | -100% |
| MT | Malta | 494 | 323 | 53% |
| NL | Netherlands | 212 | 138 | 53% |
| NO | Norway | NA | 258 | -100% |
| PL | Poland | 193 | 97 | 98% |
| PT | Portugal | 387 | 254 | 52% |
| RO | Romania | 487 | 319 | 53% |
| RS | Serbia | NA | 311 | -100% |
| SE | Sweden | 386 | 261 | 48% |
| SI | Slovenia | 342 | 384 | -11% |
| SK | Slovakia | 371 | 242 | 53% |
| TR | Türkiye | NA | 179 | -100% |
| XK | Kosovo | 0 | NA | |

Source: Eurostat, FAOSTAT. A “0” indicates that no data was reported for a country, NA indicates that the country was not part of the statistics.

The values from EUROSTAT range from a minimum of 193 €$_{2022}$/t in Poland, to a maximum of 631 €$_{2022}$/t in Greece, and imply a mean of 342 €$_{2022}$/t. In the FAO data set the lowest value is also found for Poland (97 €$_{2022}$/t), the highest for Iceland (685 €$_{2022}$/t), a country for which EUROSTAT does not provide price data. The mean value reaches 253 €$_{2022}$/t in FAOSTAT. Overall, the size of the differences between the prices varies strongly amongst the countries.

As for wheat, also for potatoes the gross production value from FAOSTAT (expressed in 2014-2016 constant 100 international $ representing output prices at farm gate) is now only available for EU27 as a whole. Data provided in international $ are again converted to € for the same period and finally to €2022 (cf. details of the conversion rate in the previous section). The results are provided in Table 13.

**Table 13 Gross production value for potatoes ([22]) in 2022, in EU27**

| Area | Value 1000 Int. $ 2014-2016 | 1000 € 2014-2016 | 1000 € 2022 |
|---|---|---|---|
| EU27 | 11 886 172 | 8 439 364 | 10 025 314 |

As done for wheat, for potatoes prices per tonne have also been calculated by dividing the gross production value by the potato production available from FAOSTAT (47.5 million tonnes). The result amounts to 211 $€_{2022}$/t. This value is situated within the range of the selling prices obtained from EUROSTAT but remains below the calculated mean value of that data source. It is closer to FAOSTAT's mean producer price. Again, the price of 211 $€_{2022}$/t is used in the present study.

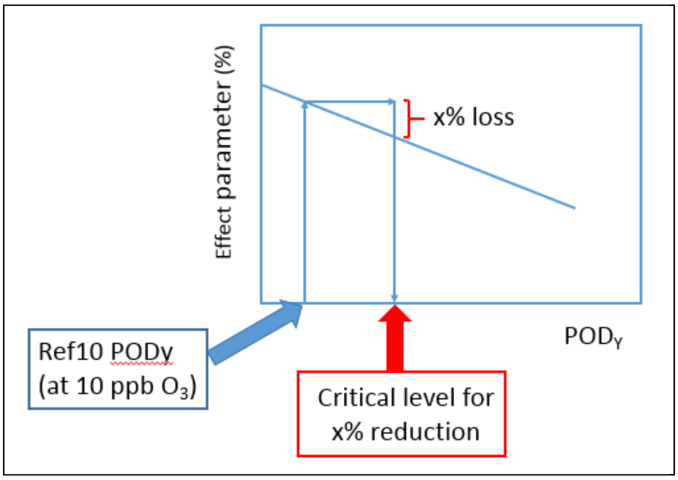
(22) The exact type of potatoes covered is not specified in the data source.

# 6 Calculation of yield loss and value of lost production

In order to calculate yield losses, the dose-response function of the Mapping Manual for the respective crop (wheat and potatoes) is applied to the POD6SPEC values available at grid level and the production data spatialised at grid level. Hereafter, the methodology for the PODy calculation is presented in general, therefore, the generic term PODy is used instead of POD6SPEC for wheat or potatoes.

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 and potatoes). 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 11 (Source: Mills et al., 2017).

**Figure 11 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 and potatoes, the recommended value of REF10 POD6SPEC 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. However, it is unlikely that, in a situation without any anthropogenic ozone, the use of production technologies that enable current orders of magnitude of production and current productivity rates, would still be feasible.

For wheat and potatoes, in the year 2022, 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 “no-production-impact” (npi) ozone level, i.e. understood as the wheat production under the current socio-economic situation, but without any impact of ozone on the production of wheat and potatoes. Following the approach of the Mapping Manual, this production is calculated for a zero-ozone impact at its pre-industrial level, i.e., 10 ppb (CLRTAP, 2023).

These two productions are linked by the following equation:

$$Prod_{N,actual} = Prod_{N,npi} * (1 - POD_N * DRF) \tag{3}$$

With the coefficient of the dose-response function (DRF) identified for the species under consideration (wheat and potatoes 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:

$$Loss_{q,N} = Prod_{N,npi} - Prod_{N,actual} \tag{4}$$

Which can be replaced by:

$$Loss_{q,N} = Prod_{N,actual} * \frac{POD_N * DRF}{1 - POD_N * DRF} \tag{5}$$

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.

$$Loss_{q,N,NUTS} = \sum_{Grids} Loss_{q,N} \tag{6}$$

The "npi" 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:

$$Prod_{N,npi,NUTS} = \sum_{Grids} Prod_{N,npi} = \sum_{Grids} \frac{Prod_{N,actual}}{(1 - POD_N * DRF)} \tag{7}$$

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

$$Loss\%_{q,N,NUTS} = \frac{Loss_{q,N,NUTS}}{Prod_{N,npi,NUTS}} \tag{8}$$

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 used to compute losses for REF (and also for the first sensitivity case, cf. annex 2): REF starts from the actual wheat production at NUTS 2 level which is distributed to the appropriate land uses defined in CLC at grid level. "Npi" production and losses are calculated at the grid level and are then aggregated at NUTS 2 and then at national 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.

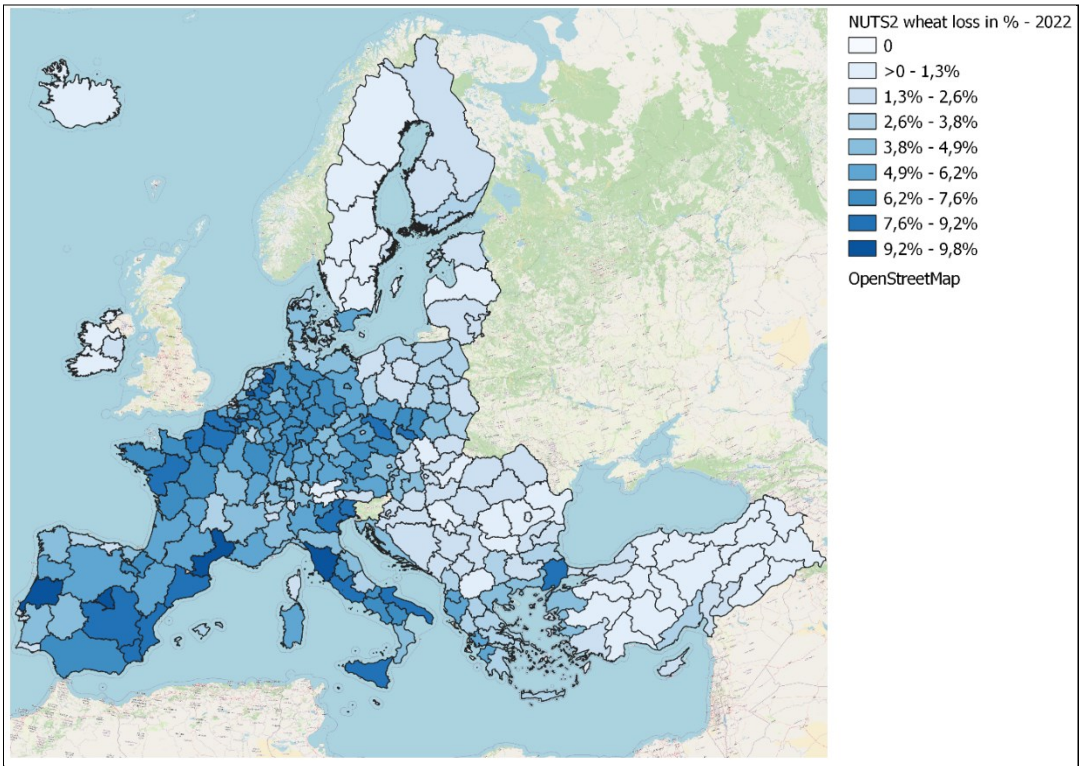
# 7 Results

## 7.1 Wheat

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([23]), data for production and prices... 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 not only expressed as monetary production loss, but also in terms of percentage yield loss and quantitative production loss. This is done here for REF.

Figure 12 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. High impacts are shown in Spain (Madrid region and south-east regions), the Centro region of Portugal, western and northern parts of France with a small zone in the south of France, Sicilia and north-east and central Italy, parts of Belgium, the Netherlands, central and western Germany, parts of Austria and the Marmara region in Türkiye.

**Figure 12 Loss in 2022 in % at NUTS2 level for wheat (REF)**

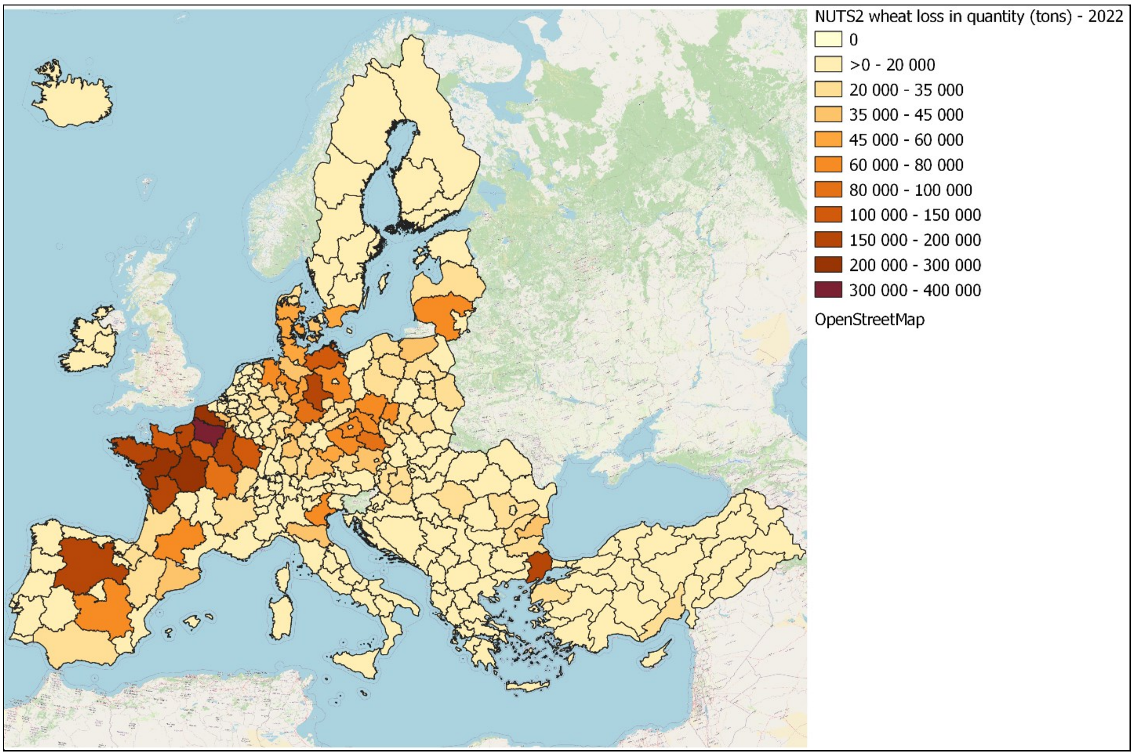



The actual wheat production levels are accounted for in Figure 13, showing this time the losses in quantity. As can be seen, the regions most affected by the loss in quantity are the regions with high wheat production. These are: the northern half of France, Castille and León in Spain, northern Germany

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

and the Marmara region in Türkiye. These regions are not identical to the regions affected by the highest losses in %.

**Figure 13 Loss in 2022 in quantity at NUTS2 level for wheat (REF)**




Differences in results are also visible at the country level aggregation (cf. Figure 14 and Figure 15: losses in quantity and in % are not exactly distributed the same way (see Portugal or Belgium for example).

**Figure 14 Loss in 2022 in % aggregated from Nuts 2 to NUTS 0 level for wheat (REF)**

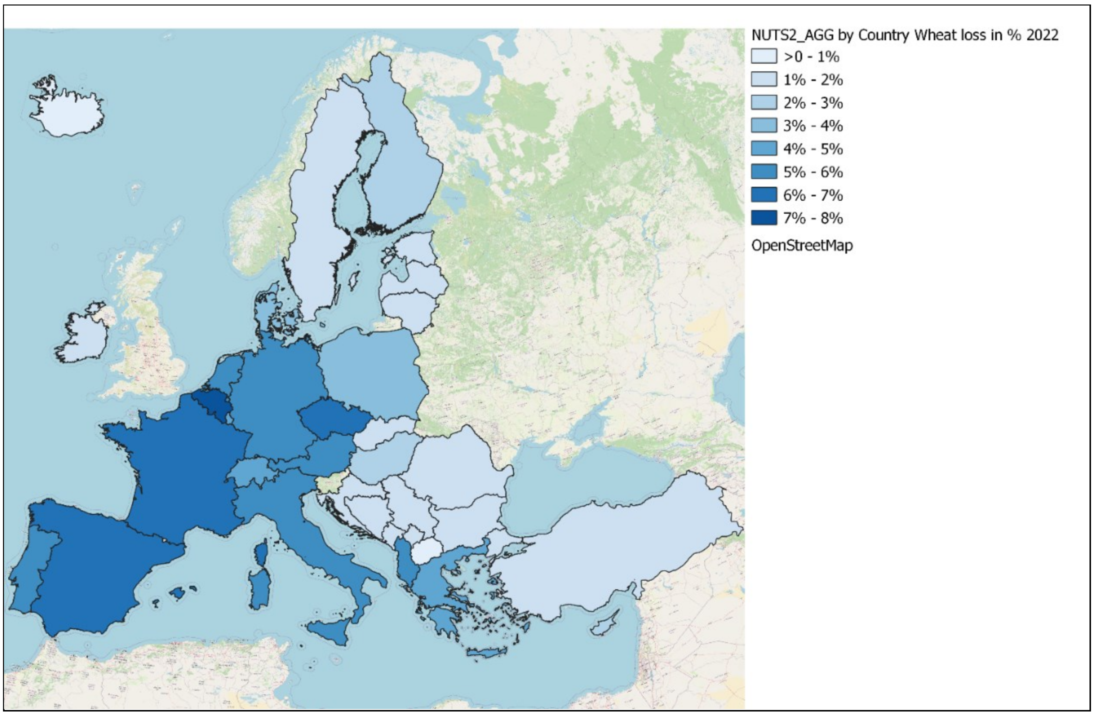



**Figure 15 Loss in 2022 in quantity aggregated from Nuts 2 to NUTS 0 level for wheat (REF)**

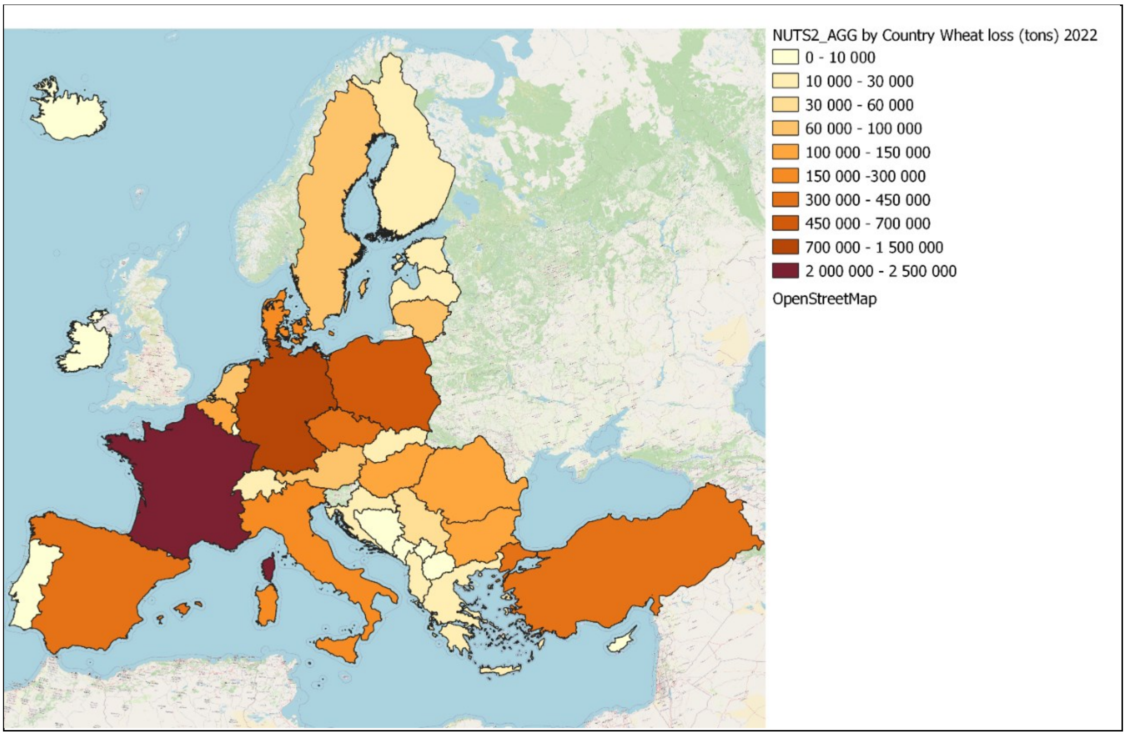
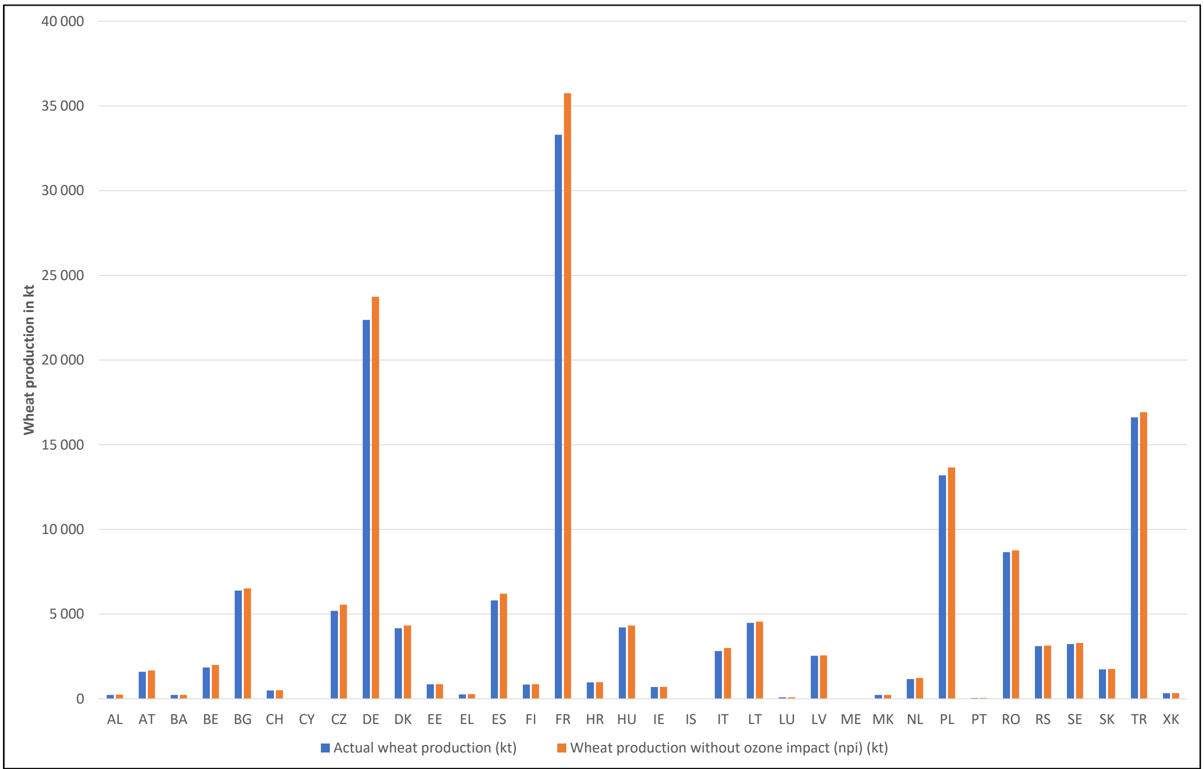


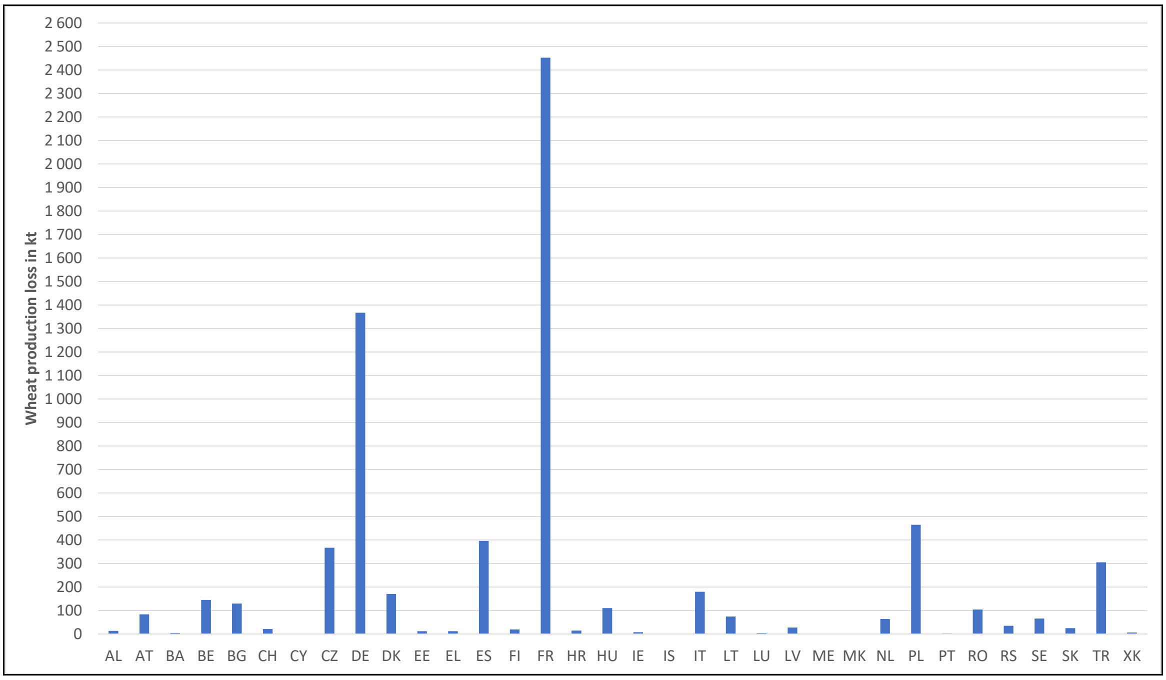

Figure 16 indicates the "npi" wheat production next to the actual wheat production in 2022 as reported in the European statistics. As a reminder, "npi" is the hypothetical wheat production as it would have been in the absence of anthropogenic ozone, taken as the 10 ppb ozone background, but still under current socio-economic conditions.

**Figure 16 “Npi” wheat production and actual wheat production reduced by ozone by country in 2022 in kilo tonnes (REF)**




The difference between the two is given in Figure 17 (please, be aware of the different scales in Y-axes), which shows the production loss in 2022 in thousand tonnes. It indicates that the production loss is important, exceeding 100 thousand tonnes of wheat in 12 countries and reaching losses of 2.5 million tonnes in France, 1.4 million t in Germany and almost 465 kt in Poland. Obviously, the absolute amount of loss is also correlated with the absolute production quantity in a country. Aggregated losses across Europe amount to 6 683 kilo tonnes of wheat.

## Figure 17 Production loss by country in 2022 for wheat in kilo tonnes (REF)




## Figure 18 Production loss by country in 2022 for wheat in million €2022 (REF)

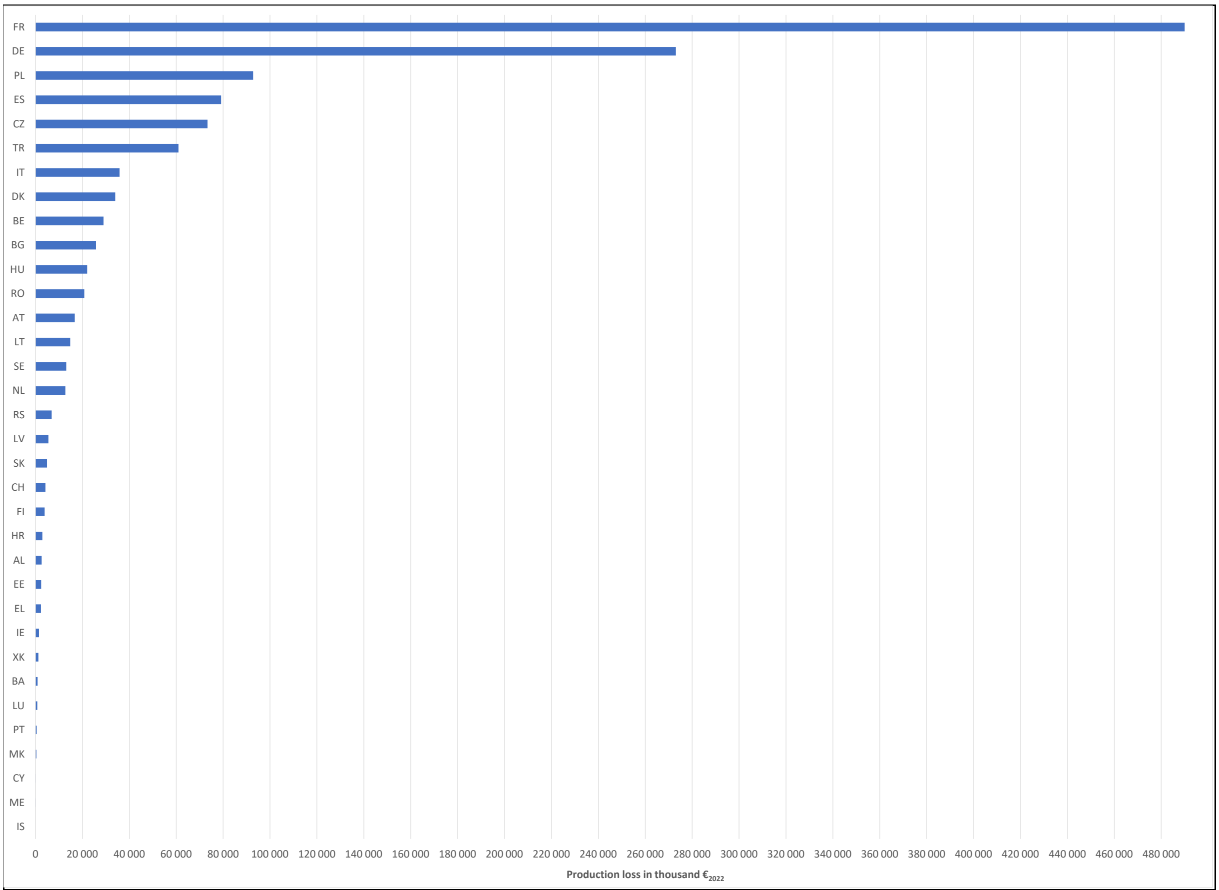
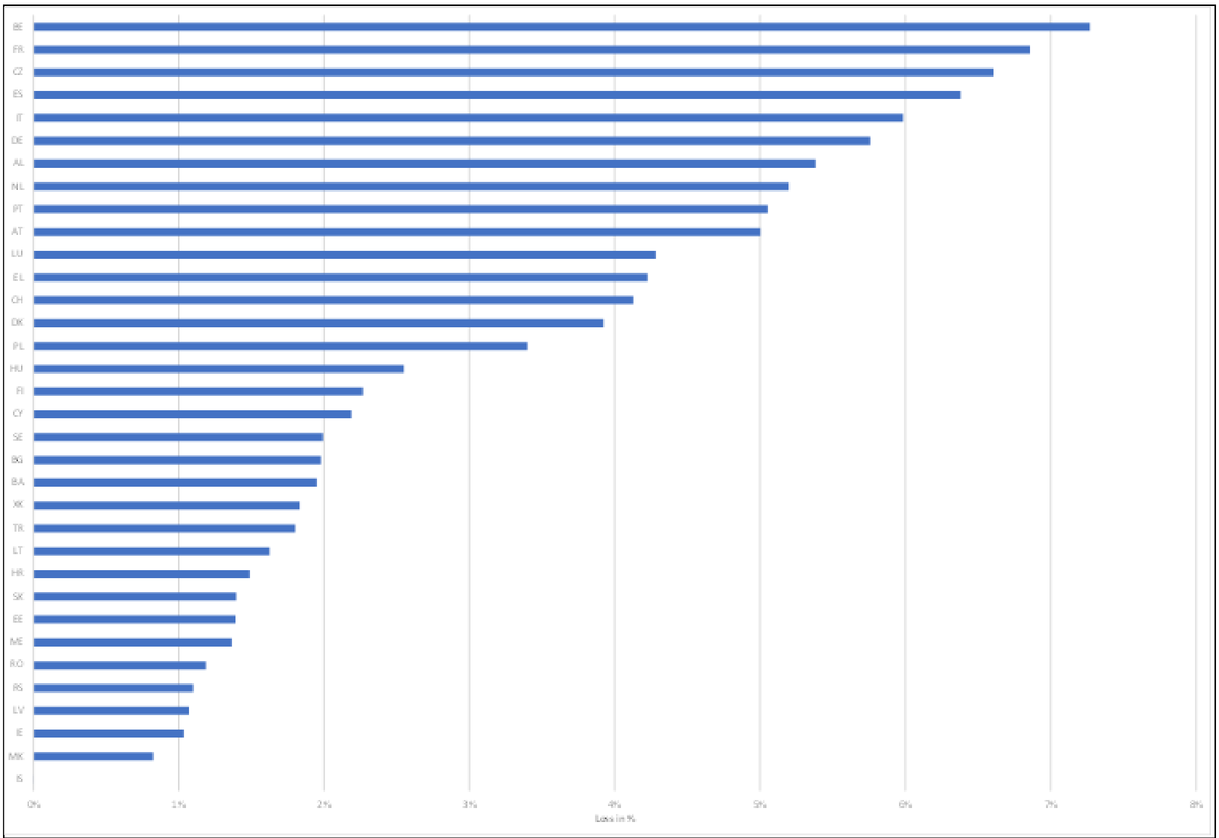



Figure 18 ranks the countries in terms of the economic value in 2022 of lost wheat production compared to pre-industrial ozone levels. This economic loss is calculated by multiplying the wheat production lost in each country with the price of 199.8 $€_{2022}$/t of wheat from FAOSTAT. The figure indicates losses reaching 490 million € in France, 273 million € in Germany and around 93 million € in Poland. Losses are around 80 million € in Spain, 73 million € in Czechia and 60 million € in Türkiye. There are only 7 countries for which the losses remain below one million €. The ranking of countries would be identical for production quantities. Aggregate losses for wheat across Europe amount to 1.3 billion €2022 in 2022.

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 less pronounced (Figure 19). 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 Belgium (7.3 %), France (6.9 %), Czechia (6.6 %) and Spain (6.4 %). They exceed 4 % also in Italy, Germany, Albania, the Netherlands, Portugal, Austria, Luxembourg, Greece and Switzerland. 19 out of 34 countries suffer losses above 2 %.

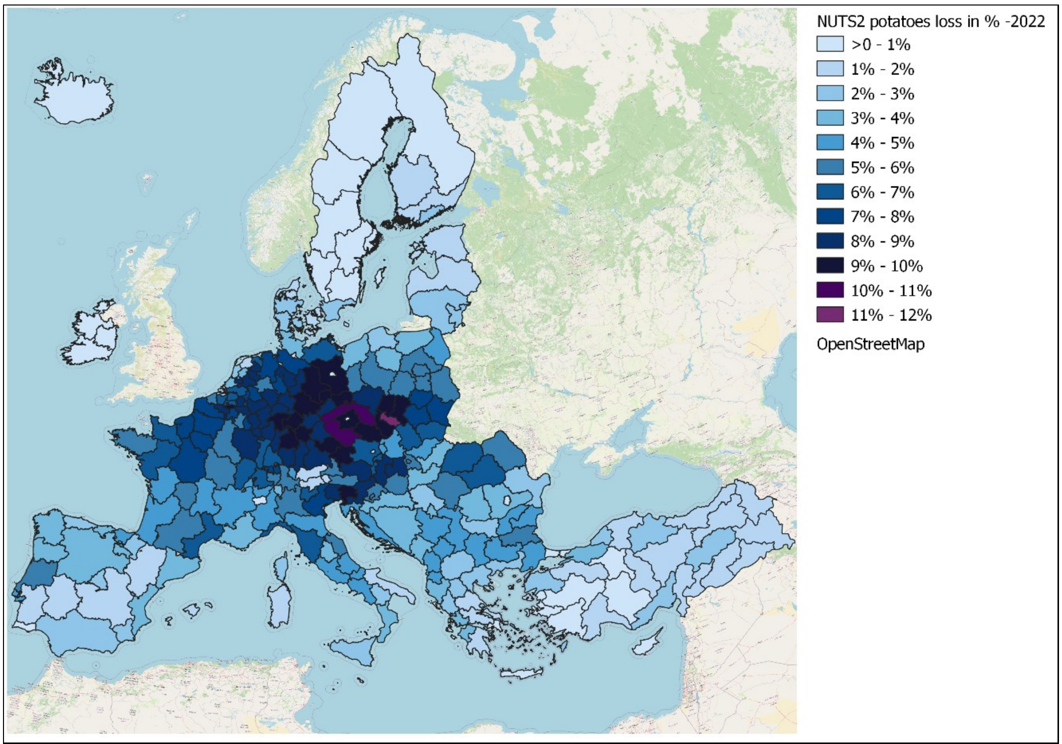
**Figure 19 Production loss by country in 2022 for wheat in % (REF)**




## 7.2 Potatoes

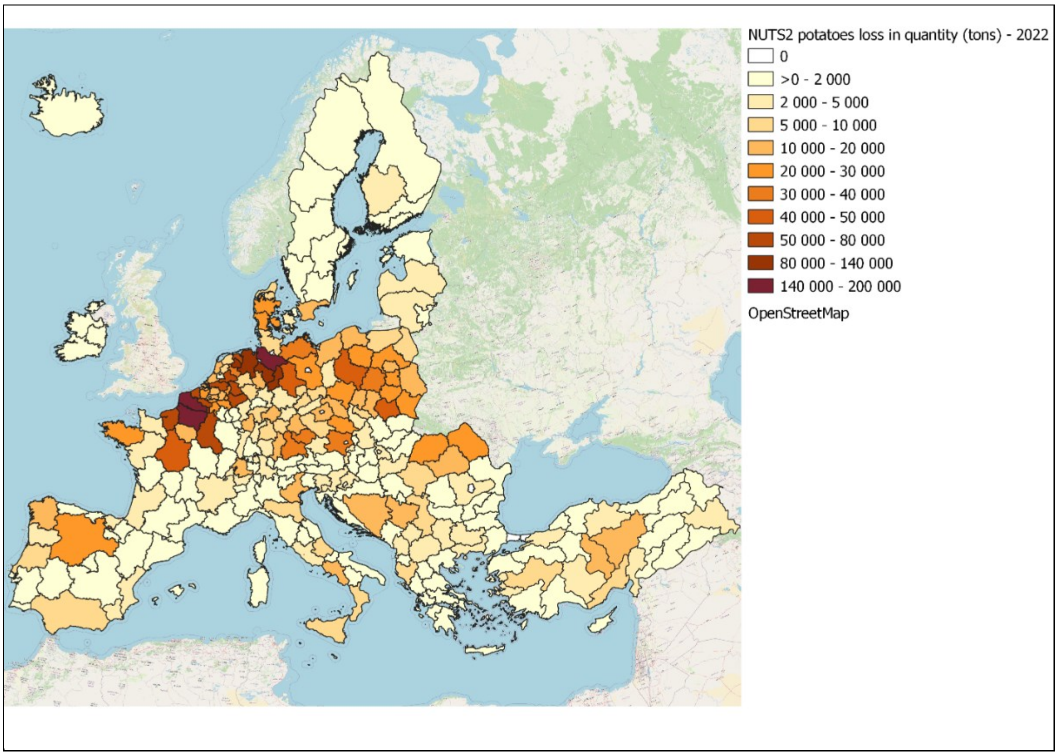
The same type of results is presented for potatoes.
Figure 20 shows a graphical representation of the losses at NUTS 2 level expressed in % of yield loss. This representation takes account of the ozone fluxes, but not of the quantity in potato production. The highest impacts are in the central part of Europe: northern half of France, Belgium, the Netherlands, Germany, Austria, south of Poland, Czechia, Hungary and in Slovakia, the northern half of Italy and the north-west of Romania.

**Figure 20 Loss in 2022 in % at NUTS2 level for potatoes (REF)**




The actual potato production levels are accounted for in Figure 21, showing this time the losses in quantity. The regions most affected by the loss in quantity are the northern parts of France and the north and west of Germany. Central parts and the south of Poland, west Belgium and the Netherlands are also impacted. In 2022, the regions most affected by the loss in quantity are not always the same as those mainly affected in terms of loss in percentage.

Figure 21 Loss in 2022 in quantity at NUTS2 level for potatoes (REF)




Although results are comparable, some differences in the distribution of the losses in quantity and in % are also visible at the country level aggregation (cf. Figure 22 and Figure 23).

Figure 22 Loss in 2022 in % aggregated from Nuts 2 to NUTS 0 level for potatoes (REF)

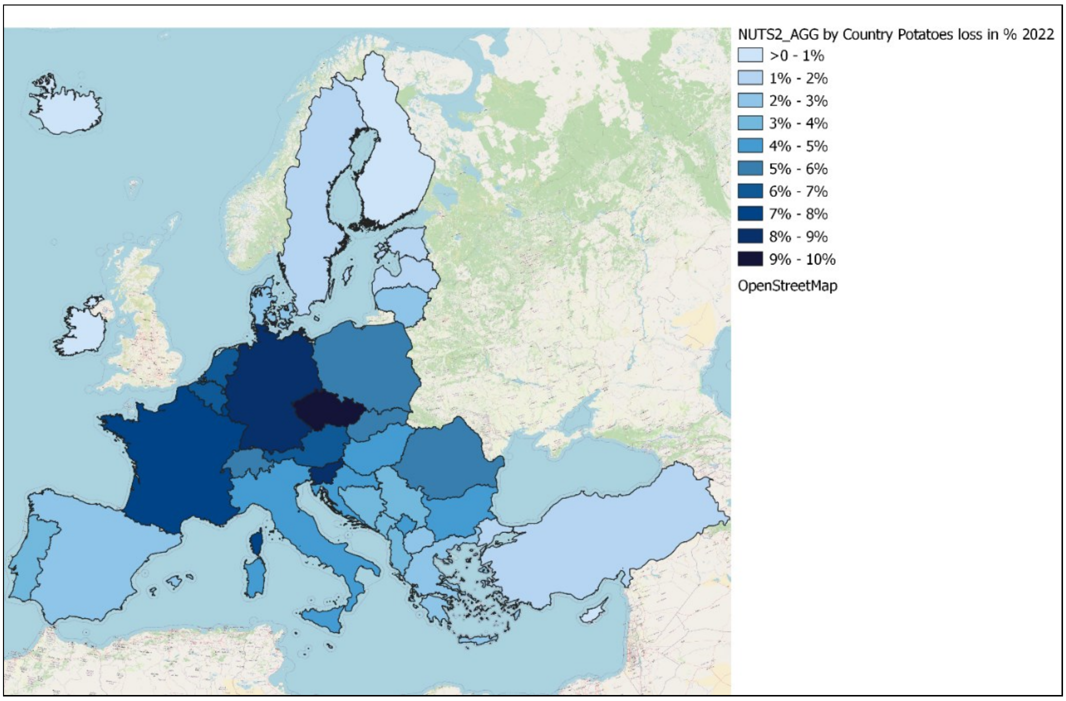


**Figure 23 Loss in 2022 in quantity aggregated from Nuts 2 to NUTS 0 level for potatoes (REF)**

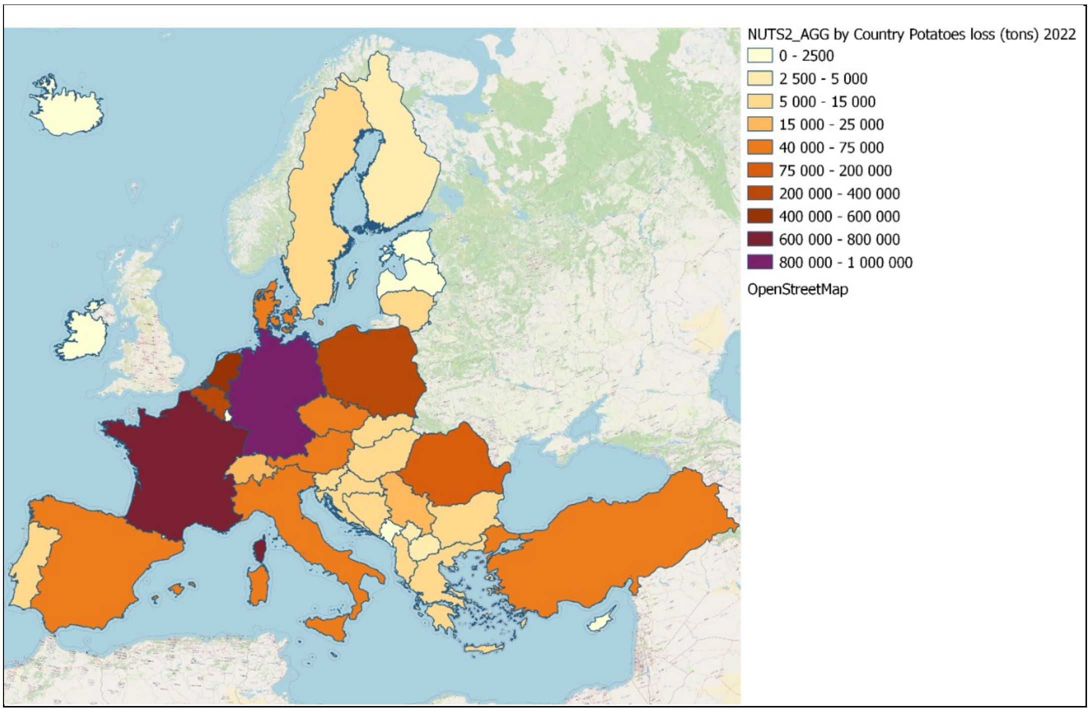
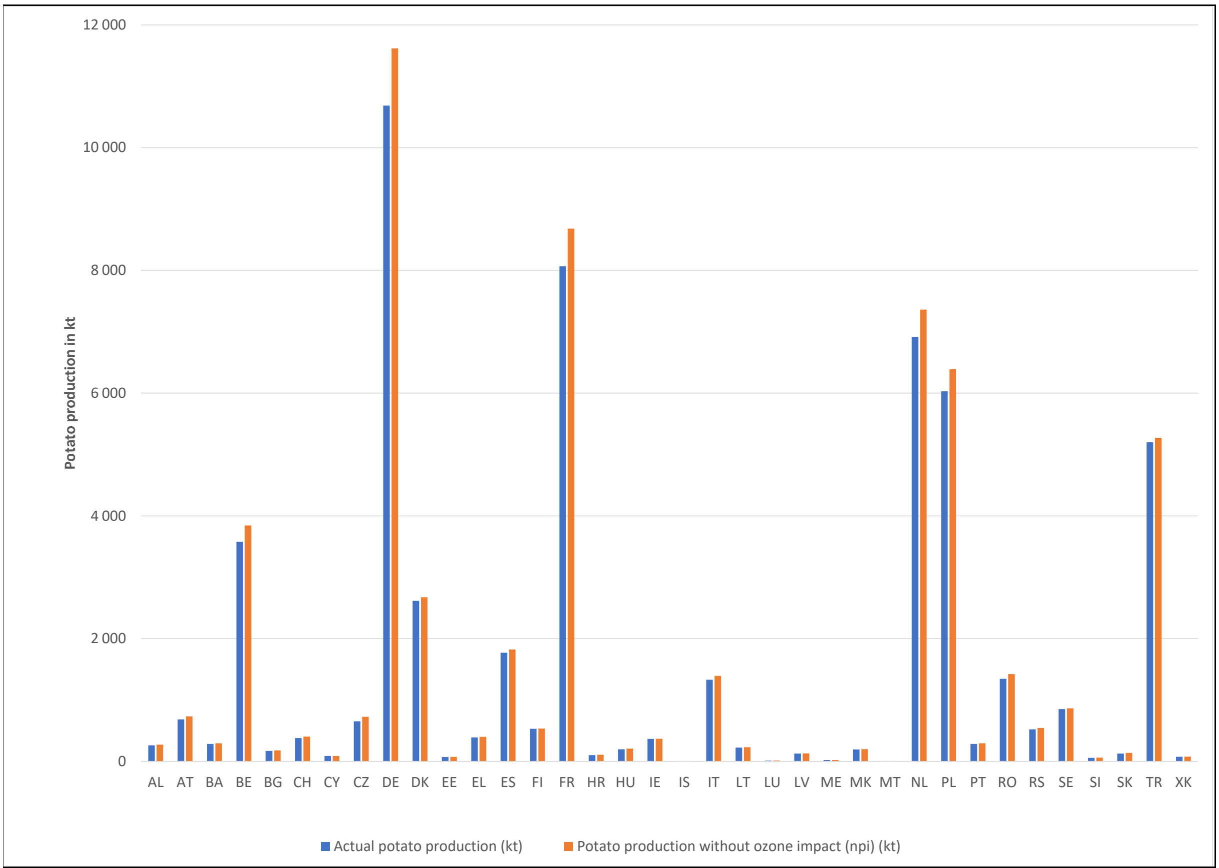



Figure 24 indicates the “npi” potato production next to the actual potato production in 2022 as reported in the European statistics. As a reminder, “npi” is the hypothetical production as it would have been in the absence of anthropogenic ozone, taken as the 10 ppb ozone background, but still under current socio-economic conditions.

**Figure 24 "Npi" potato production and actual potato production reduced by ozone by country in 2022 in kilo tonnes (REF)**




The difference between the two is given in Figure 25 which shows the production loss in 2022 in tonnes. The production loss in 2022 is highest in Germany (933 kt), reaches 615 kt in France, 445 kt in the Netherlands, and 360 kt in Poland. Aggregated over Europe the production losses for potatoes amount to 3 223 kilo tonnes.

**Figure 25 Production loss by country in 2022 in kilo tonnes for potatoes (REF)**

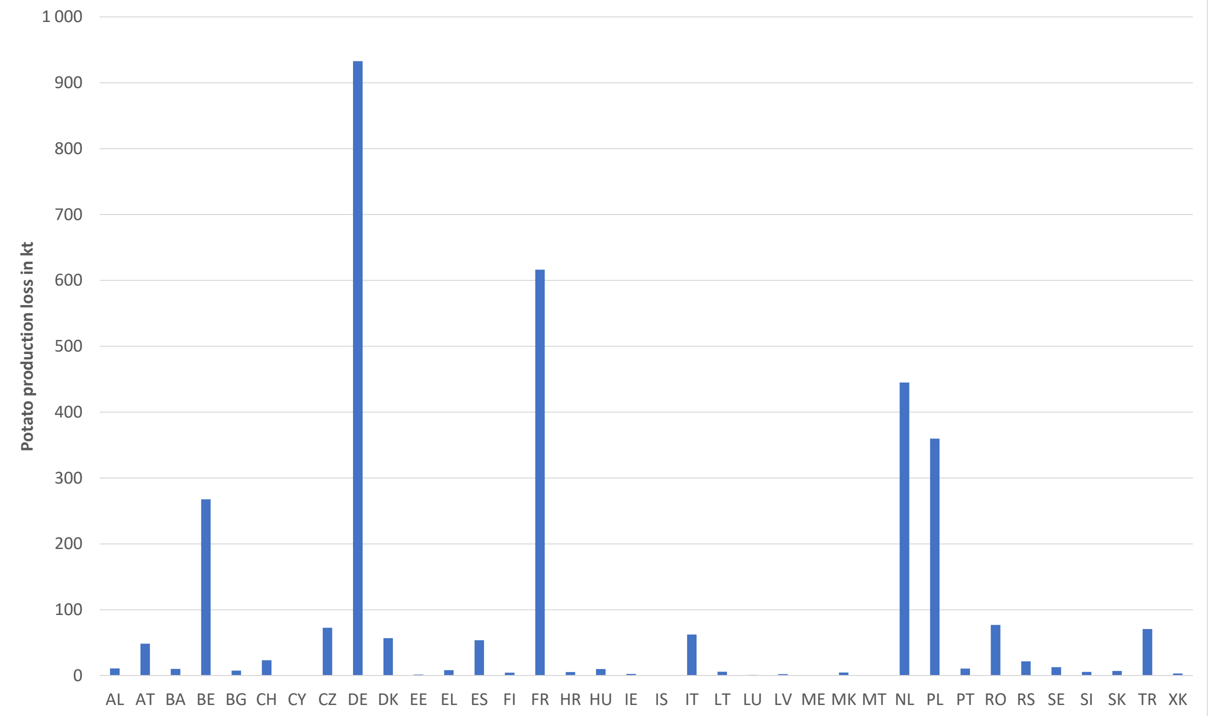
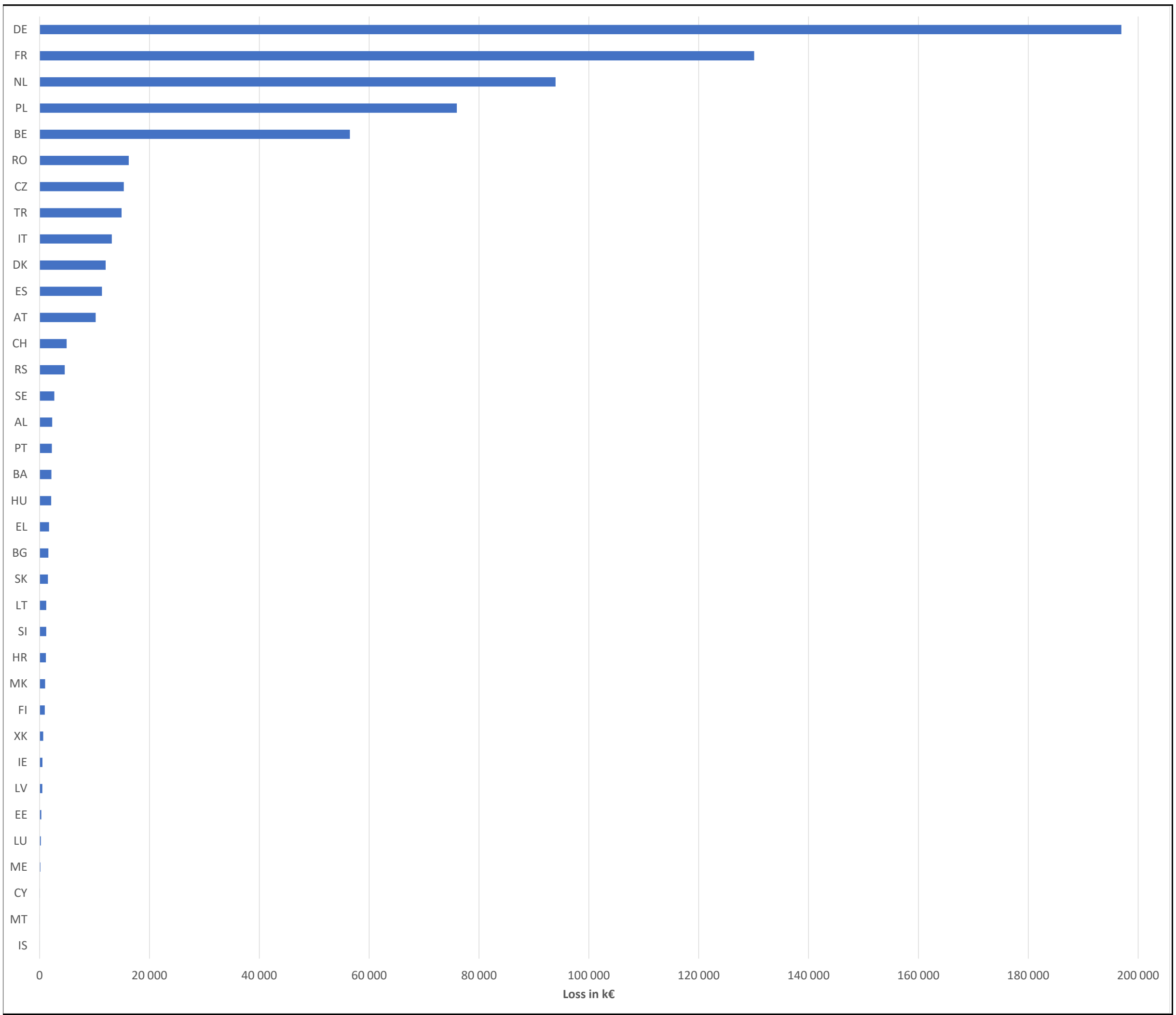


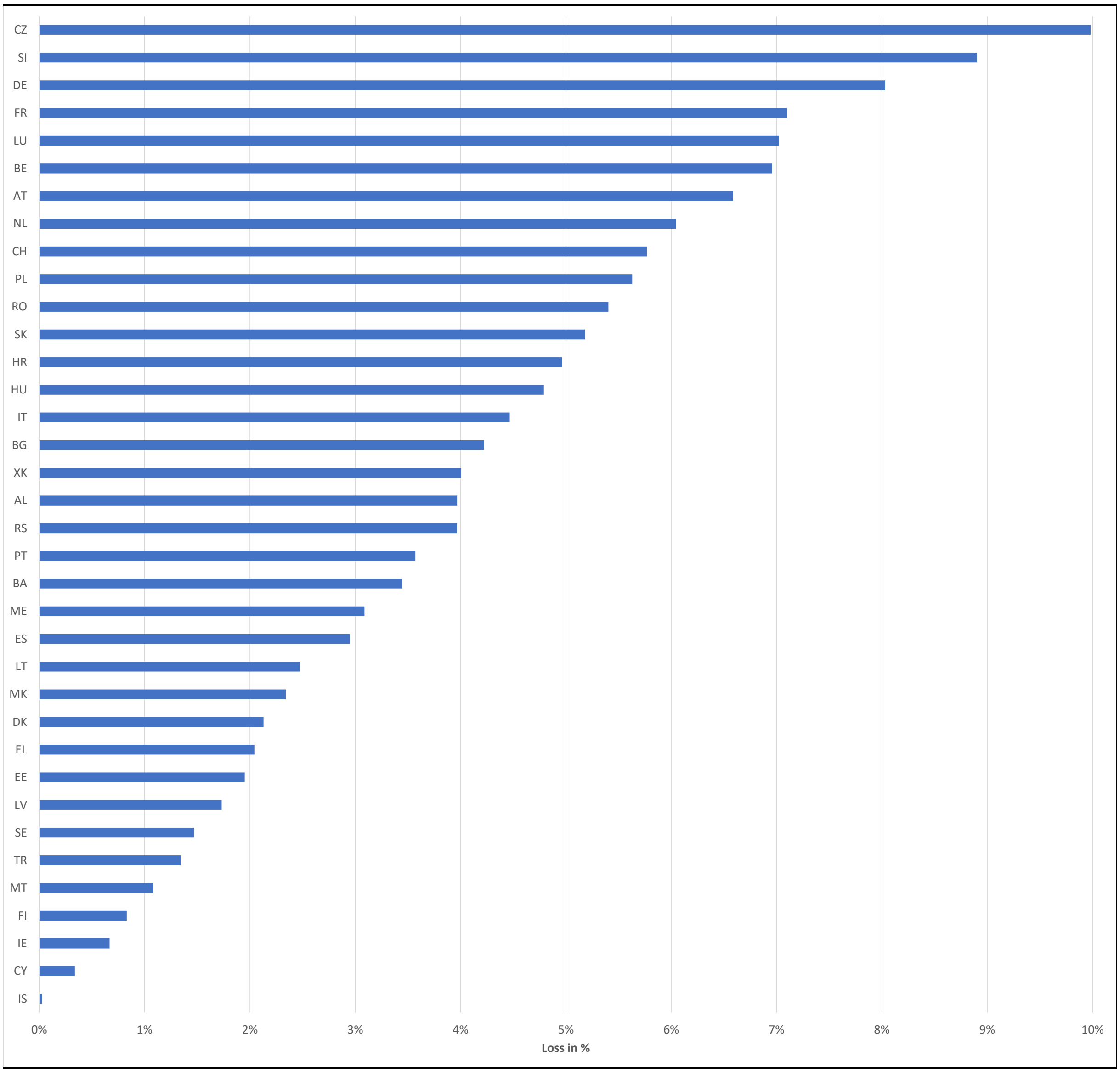

Figure 26 ranks the countries in terms of the economic value in 2022 of lost potato production compared to pre-industrial ozone levels. This economic loss is calculated by multiplying the potato production lost in each country with the price of 211 €$_{2022}$/t of potatoes from FAOSTAT. The figure indicates losses exceeding 10 million € for 12 countries, reaching 197 million € in Germany, 130 million € in France, 94 million in the Netherlands and 75 million € in Poland. Again, the ranking of countries would be identical for production quantities. Aggregated over Europe the production losses for potatoes amount to 680 million € (price base 2022).

**Figure 26 Production loss by country in 2022 in million €$_{2022}$ for potatoes (REF)**




When ranking countries in terms of the percentage loss in their potato production (Figure 27), the differences between countries are again relatively less pronounced than when presenting losses in terms of € (or tonnes). In 17 countries, losses are higher than, 4 %, the mean is about 4 %. The highest percentage losses are found in Czechia (10 %), Slovenia (8.9 %), Germany (8 %) and France (7.1%).

## Figure 27 Production loss by country in 2022 in % for potatoes (REF)



# 8 Discussion and conclusions

## 8.1 Results

In this study the ozone maps of indicators based on the PODy tool developed at Ineris and calculated by CHMI under the ETC/HE task on spatial mapping are used as starting point to quantify and monetize losses of wheat and potato production due to tropospheric ozone pollution in 2022 in Europe.

To this end, the POD6SPEC flux-effect function recommended by the Mapping Manual of the Air Convention (CLRTAP, 2023) was chosen. Wheat and potato production data for 2022 come from EUROSTAT and international wheat and potato prices were calculated by dividing the Gross production value of wheat and potatoes in 2022 by the production quantities, both from FAOSTAT.

Production losses have been calculated, expressed in percentage, quantity, and monetary terms, due to ozone for a reference scenario where quantification takes place at the highest spatial resolution possible. Two sensitivity scenarios, where the spatial resolution of the calculations was degraded, serve to assess the impact of a lower, and, a priori, less correct spatialisation, on results.

In the reference case, production quantities at NUTS 2 level were used as starting point, 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 and potato prices for monetization.

The results of the reference scenario indicate losses across Europe that amount to 6 683 kilo tonnes of *wheat* or 1.3 billion $€_{2022}$ in 2022. The importance of losses varies across regions and countries, being the result of levels of ozone and the absolute production of the respective crop.

Absolute losses in wheat production are highest in France with 2.5 million tonnes of lost production, followed by Germany (1.4 million tonnes), and Poland (465 thousand tonnes).

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 less pronounced. This is so because production losses expressed in tonnes or € are highest where wheat production is highest in absolute terms. Percentage losses for wheat are highest for Belgium (7.3 %), France (6.9 %), Czechia (6.6 %) and Spain (6.4 %). They exceed 4 % also in Italy, Germany, Albania, the Netherlands, Portugal, Austria, Luxembourg, Greece and Switzerland. 19 out of 34 countries suffer losses above 2 %.

Production losses calculated for *potatoes* in 2022 amount to 3 223 kilo tonnes or 680 million € (price base 2022). The countries accounting for the highest production losses in absolute terms are Germany (933 kt), France (615 kt), the Netherlands (445 kt) and Poland (360 kt). In 17 countries, losses are higher than 4 %, the mean is about 4 %. The highest percentage losses are found in Czechia (10 %), Slovenia (8.9 %), Germany (8 %) and France (7%).

While the impacts of ozone calculated here are important in terms of quantity and economic loss, they are partly lower than estimates from earlier studies. In a study published in 2019 (Schucht et al., 2019 a, b), percentage losses for wheat and potatoes in France were estimated at 15 % and 11 %, respectively, in 2010, and forecast to attain 14 % and 11 % respectively, in 2020. In the present study, losses in France in 2022 are estimated at 7 % for both wheat and potatoes. This is directly related to the levels of ozone in 2022. Depending on the country, they are higher or lower than in 2019 (Schucht et al., 2021a). For France, on a national level, percentage loss for wheat is higher in 2022 than in 2019.

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. The geographical level for which wheat and potato production statistics are available will also impact on the accuracy of results. To investigate the size of the impact 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 SENS1, wheat production data at country level were spatialized at grid level using CLC. The rest of the calculations was done as in the reference case. In the second sensitivity case, SENS2, ozone flux data initially available at grid level were 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 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.

The results of these calculations showed a limited impact of the degraded geographical spatialisation on the results at an aggregate European level. Expressed in million €, the loss aggregated at the European domain amounts to 1.34 billion € for wheat in REF, to 1,3 billion € in SENS1 and to 1.24 billion € in SENS2. The maximum difference is between REF and SENS2 (99 million €), the difference is 40 million € between REF and SENS1 and 59 million € between SENS1 and SENS2. In terms of percentages, the difference between REF and SENS1 is 0.1 percentage points and between REF and SENS2 0.3 percentage points. The difference between the two sensibility calculations amounts to 0.2 percentage points. At country level, differences between the scenarios are partly higher, but they do not exceed 1.68 percentage points for wheat in any country.

The results are similar for potatoes. The aggregated economic loss is estimated at 680 million € in REF, at 655 million € in SENS1 and at 650 million € in SENS2. The difference between REF and SENS1 amounts to 25 million €, between REF and SENS2 to 30 million € and between SENS1 and SENS2 to 5 million €. Aggregated over Europe, the differences between the losses expressed in percentage and calculated in the sensitivity analyses are limited: 5.6 % in REF, 5.4 % in SENS1 and 5.4 % in SENS2. Hence, the differences between the three scenarios amount to between 0.2 percentage units and 0.01 percentage units. At a country level, the highest difference between scenarios is estimated at 5.5 percentage units.

It is difficult to exactly know why the influence of spatial aggregation level of calculations on the results is relatively this limited. A possible reason for the low differences at the aggregate European level is error compensation. At the country level, differences in percentage points are partly more important, especially between REF and SENS2 (Figure 38 and

Figure 42). This goes in the expected direction as it is in SENS2 that geolocation is most degraded. Crop production data here are not spatialised at all and all results are directly calculated at country level. Based on this, we would advise against giving up geolocation (SENS2). Calculating ozone loss for the simplified approach SENS1 appears less problematic, however, the simplification (and time saving) between REF and SENS1 is limited. In the latter 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. Only the statistical input data used for production here is initially available only at country level (instead of at NUTS 2 level as in REF). Concluding, our recommendation is to continue applying the core approach (REF), privileging calculations starting from the highest level of spatialisation possible, also in future assessments. Especially, as long as the ozone impacts on crops are calculated only for a few species. This is because calculations starting from the highest level of spatialisation possible can be expected to be more accurate, and, because the additional work charge is limited.

## 8.2 Discussion

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 ([24]).

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, uncertainties on prices). 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 and potatoes 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.

([24]) 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.

## List of abbreviations

| Abbreviation | Name | Reference |
|---|---|---|
| AOT40 | Accumulated Ozone over Threshold of 40 ppb | |
| CLC | Corine Land Cover database | https://www.eea.europa.eu/en/datahub/datahubitem-view/a5144888-ee2a-4e5d-a7b0-2bbf21656348 |
| CLRTAP | Convention on Long-Range Transboundary Air pollution (also: Air Convention) | https://unece.org/environmental-policy-1/air |
| EEA | European Environment Agency | www.eea.europa.eu |
| EMEP | European Monitoring and Evaluation Programme | https://www.emep.int/ |
| EMEP model | Chemistry-transport model developed by the Meteorological Synthesizing Centre - West (MSC-W) | https://emep.int/mscw/ |
| ETC/ACM | European Topic Centre on Air pollution and Climate change Mitigation | https://www.eea.europa.eu/data-and-maps/data-providers-and-partners/air-pollution-and-climate-change |
| ETC/ATNI | European Topic Centre on Air pollution, Transport, Noise and Industrial pollution | https://www.eea.europa.eu/data-and-maps/data-providers-and-partners/european-topic-centre-on-air |
| ETC/HE | European Topic Centre on Human health and the Environment | https://www.eea.europa.eu/data-and-maps/data-providers-and-partners/european-topic-centre-human-health |
| EUROSTAT | European Statistical Office | https://ec.europa.eu/eurostat/web/main/home / |
| FAO | United Nations' Food and Agriculture Organization | https://www.fao.org/home/en |
| FAOSTAT | Statistics and data base service by FAO | https://www.fao.org/faostat/en/#home |
| HICP | Harmonised Index of Consumer Prices | |
| ICP Vegetation | International Cooperative Programme on Vegetation | https://icpvegetation.ceh.ac.uk/ |
| NPI | "no-production-impact" ozone level: the wheat/potato production under the current socio-economic situation, but without any impact of ozone | |
| 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 | https://www.oecd.org/ |

| Abbreviation | Name | Reference |
|---|---|---|
| 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 | https://unece.org/ |
| WGE | Working Group on Effects | https://unece.org/environmental-policy/air/working-group-effects |

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## Annex 1 Method for calculating ozone fluxes

Ineris developed the calculation tool for phytotoxic ozone doses (Colette et al., 2018, Schucht et al., 2019a, b) using the methodology described in the Mapping Manual (CLRTAP, 2023, 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 calculation of ozone fluxes, for the ETC/HE currently carried out in the framework of the production of European Air Quality Maps (Horálek et al., 2024), 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.

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:

$$g_{sto} = g_{max} * [\min(f_{phen}, f_{O3})] * f_{light} * \max\{f_{min}, (f_{temp} * f_{VPD} * f_{SW})\} \tag{9}$$

$g_{sto}$ 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 ($f_{light}$), 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, 2023). 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).

$$F_{sto} = C(z_1) * \frac{1}{r_b + r_c} * \frac{g_{sto}}{g_{sto} + g_{ext}} \tag{10}$$

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 $r_c = 1 / (g_{sto} + g_{ext})$, the equation can also be written:

$$F_{sto} = C(z_1) * g_{sto} * \frac{r_c}{r_b + r_c} \quad (11)$$

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

$$r_b = \frac{2\nu}{k*DH2Ow*Pr} * DH2Og^{2/3} \quad (12)$$

With ν 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:

$$PODy=\Sigma[(F_{sto}-Y)\cdot(3600/10^6)] \ (mmol\ m^{-2}\ PLA) \quad (13)$$

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 and 2023), Colette et al. (2018) and Schucht et al. (2019a, b).

For this study, the wheat and the potato species were selected in relation to the availability of flux-effect functions, their sensitivity to ozone and their importance and representativeness in terms of agriculture.
Table 14 presents information on the estimation of the accumulation period, the PODy threshold value, and the nature of the damage caused by ozone for wheat. Use of these values and associated uncertainty are discussed in the Mapping Manual and in Emberson (2000a & b).

**Table 14 Y threshold 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<br>Weight of 1000 kernels<br>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<br>(POD6SPEC) |

Source: Schucht et al. (2019b), following CLRTAP (2023).

Table 15 presents same information for potatoes. Again, use and uncertainty of these values are discussed in the Mapping Manual and in Emberson (2000a & b).

### Table 15 Y threshold used for potato to calculate the phytotoxic ozone dose, accumulation period and nature of damage

| | Damage indicators | Determining the accumulation period | Y threshold (nmol m-2 PLA $s^{-1}$) |
|---|---|---|---|
| Potato | Tuber yield | Accumulation period defined by the degree-day method (Mapping Manual) in each mesh between 330 degree days before the tuber initialization date and 800 degree days after this date. The tuber initiation date is considered homogeneous throughout Europe due to a lack of local data availability. After discussion with the French national Chamber of agriculture, the tuber initialization starts 15 days after the transplantation in the field which occurs in May. Therefore, the fixed date for the tuber initialization has been set to June 1st. | Y = 6<br>(POD6SPEC) |

Source: Schucht et al. (2019b), following CLRTAP (2023).

Note that a use as consistent as possible of statistical data has been sought. However, in the remainder of the text, the denominations of wheat and potato type as used in the respective statistics are applied. The PODy function used for wheat 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. FAOSTAT also provides data on producer prices. FAO data are just labelled “wheat” without any further specification of the wheat type. Both data sets cover different countries, are incomplete in terms of countries included and the values available for both countries are not identical. It was decided to use, as in the past, the gross production value for wheat from FAOSTAT divided by the FAOSTAT production data, thus resulting in the value of gross production per tonne of wheat produced. The value is situated below the mean value of the selling prices obtained from EUROSTAT, but close to the mean value from FAOSTAT’s producer prices.

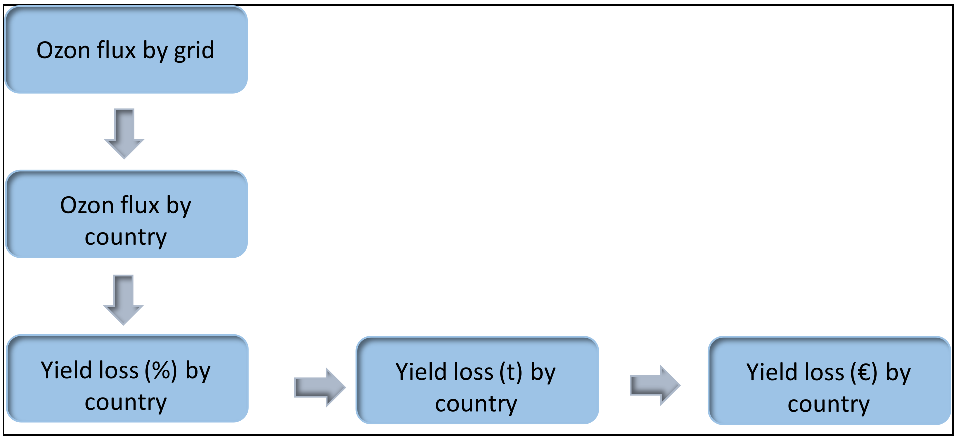
For potatoes the PODy function refers just to potatoes. The EUROSTAT production data is available for potatoes (including seed potatoes). The EUROSTAT price data is available for different potato types, and in discussions with the French national Chamber of agriculture it was decided that the category to be used should be “main crop potatoes”. However, as for wheat, the data on value of gross production per tonne of potato produced from FAOSTAT are used which are just labelled “potato”.

# Annex 2 Sensitivity calculations

Following the EEA's request to identify possibilities of simplification and automation, two further levels of spatial resolution of data and the effect on the results in terms of crop losses were tested. In both the resolution is degraded relative to the REF case.

As in REF, all steps of the ozone impact calculation as presented in Figure 1 were followed also for the first sensitivity case, hereafter referred to as SENS1. 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 (instead of at NUTS 2 level as in REF).
The second sensitivity case applies a shortcut by not spatializing crop production at all, thus avoiding steps 6 and 7 in the list provided in chapter 2 (cf. also Figure 28). 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 SENS2. 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 is also applied in the ETC work assessing marginal damage costs for airborne pollutants and calculating externalities of European industrial facilities (Schucht et al., 2021a, b; EEA Briefing, 2024a, b; Schucht et al., 2024).

**Figure 28 Shortcut ozone impact calculation**




In SENS1, CLC is again used to spatialize production data over the grid. However, in this case the starting point is wheat (potato) production data at the country level (and not at NUTS 2 level as in REF). This is illustrated in Figure 29 and Figure 31 for wheat and in Figure 30 and Figure 32 for potatoes.

## Spatialisation in SENS1 and SENS2

**Figure 29 Spatialization of the wheat production at the grid in 2022 (SENS1)**

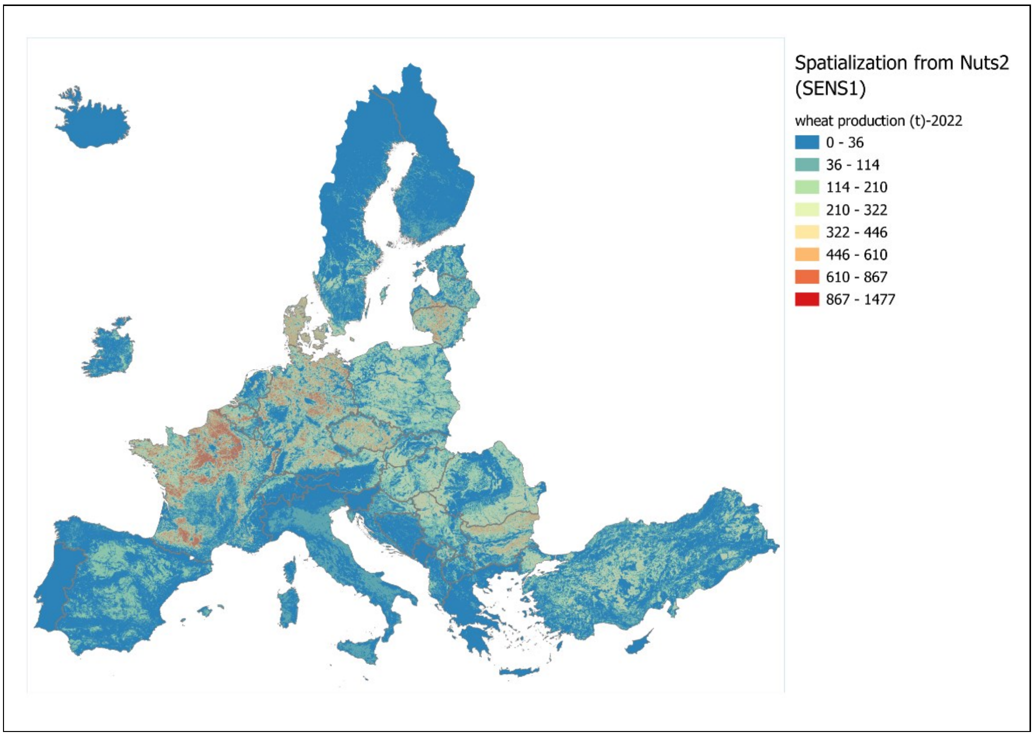



**Figure 30 Spatialization of the potato production at the grid in 2022 (SENS1)**

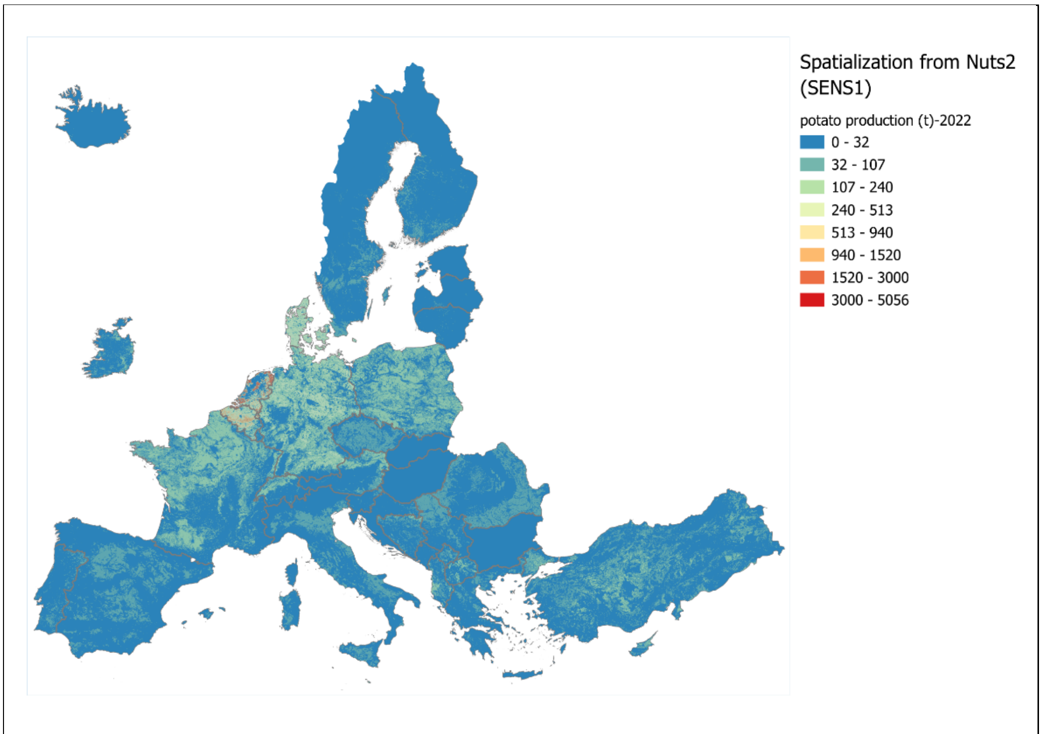



Figure 31 (wheat) and Figure 32 (potato) show the results of the spatialization in a direct comparison between REF starting from wheat and potato production, respectively, at NUTS 2 level (left), and SENS1, starting from wheat (potato) production at national level (right).

As was to be expected, in the sensitivity case SENS1 the production is distributed more evenly over the country: detailed production by NUTS is not used in this case. The impact of this scenario is more visible in the spatialization of potato production. The production is clearly spread out more evenly over each country.

**Figure 31 Results of the spatialization of wheat production over the grid starting from NUTS 2 (REF, left) and from country level (SENS1, right)**

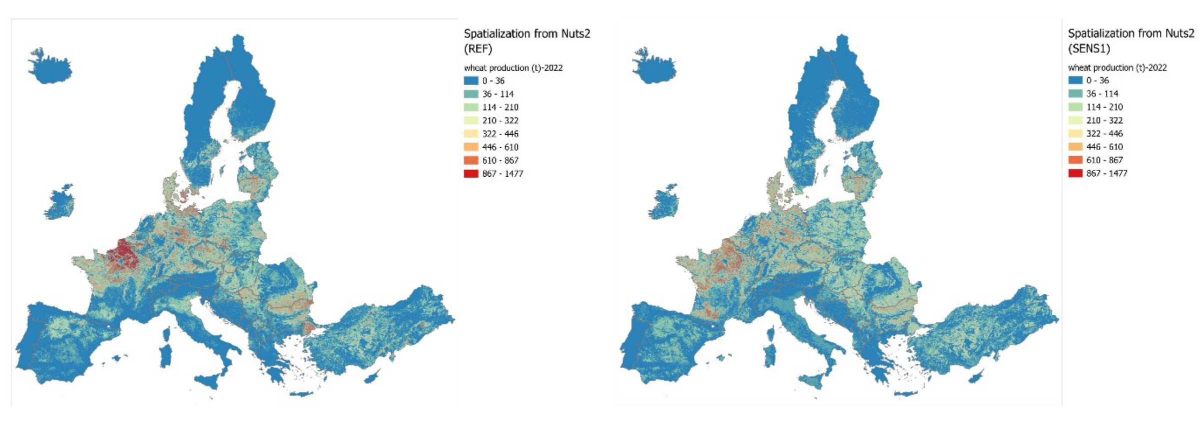
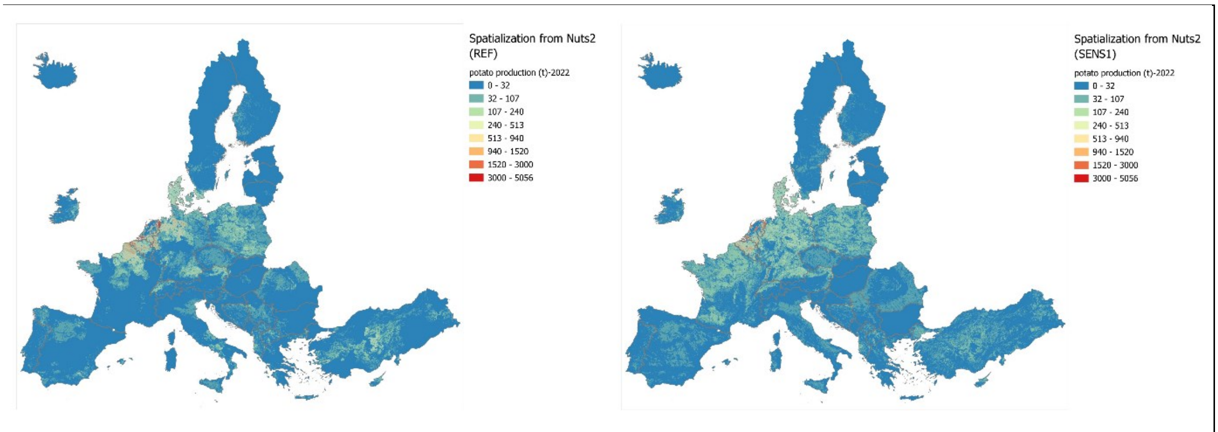



**Figure 32 Results of the spatialization of potato production over the grid starting from NUTS 2 (REF, left) and from country level (SENS1, right)**




In SENS2 the wheat and potato productions are not spatialized. Data provided at country level as shown in Table 2 and Table 4 are directly used.

For the calculation of yield loss and value of lost production, the approach applied to SENS1 is identical to that applied to REF. SENS1 starts from the actual wheat (potato) production at national level (NUTS 0) which is distributed to the appropriate land use areas at grid level. “Npi” production and losses are calculated at the grid level and then aggregated at national level.

For SENS2, a unique PODy value at national level is used, calculated as the average over each country of the PODy values at grid level, as well as a unique value for the actual wheat (potato) production by country. The “npi” production and the losses are then computed using the dose response functions directly at country level.

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

### Production loss for wheat under REF, SENS1 and SENS2

Figure 33 shows the production loss for wheat by country in 2022, in %, side by side for REF, SENS1 and SEN2. The highest loss occurs in Belgium (between 5.9 % and 7.3 %), France (between 5.9 % and 6.9 %), Czechia (between 6.6 % and 6.8 %), the Netherlands (between 5.2 % and 6.7 %), Portugal (between 5.1 % and 6.7 %), Spain (between 6.1 % and 6.5 %) and Italy (between 5.7 % and 6.5 %). The mean percentage loss is between 3.1 % and 3.2 % in the three cases studied. Which of the cases yields the highest loss, varies amongst the countries. No clear pattern can be detected.

**Figure 33 Wheat production loss aggregated by country in 2022 in % (REF, SENS1 and SENS2)**

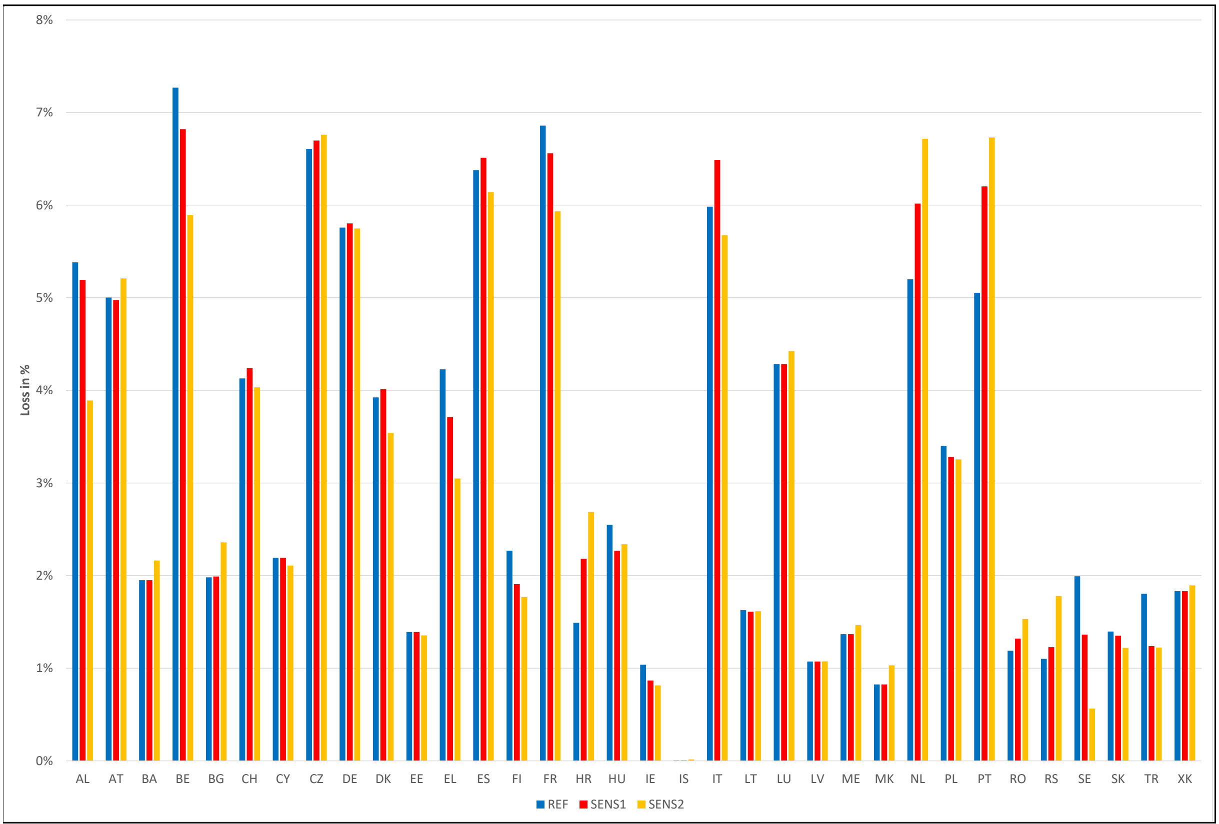
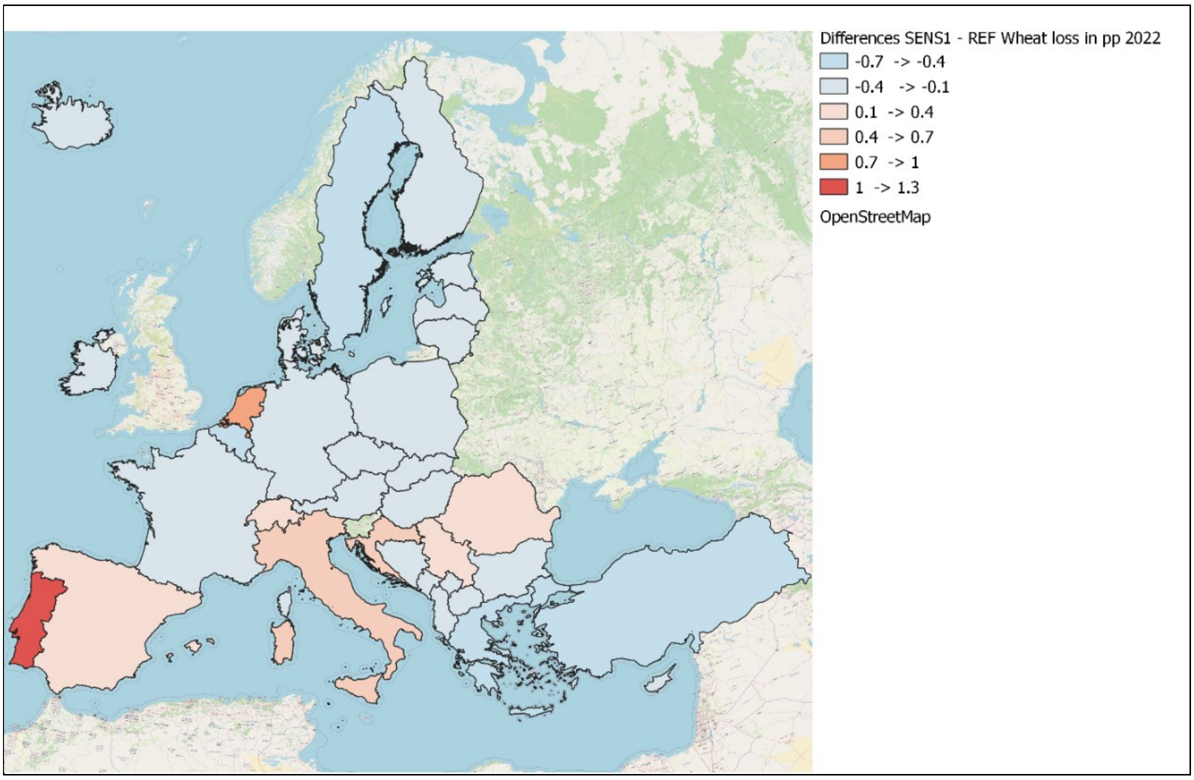



Figure 34 and Figure 35 show the difference in loss at the country level in 2022, in percentage points (pp) when subtracting REF from SENS1. In Figure 34 results are presented in a map, in Figure 35 in the form of bars to more easily see the differences in percentage change.

**Figure 34 Mapped difference in wheat production loss in 2022 in percentage points (pp) (SENS1 minus REF)**




For the year 2022, the differences between SENS1 and REF, in percentage points for wheat, show no clear pattern between the two scenarios except that more positive differences are found in some southern countries. The highest differences in absolute value are found in Portugal (1.15 percentage points), the Netherlands (+0.82 percentage points), Croatia (+0.69 pp) and Sweden (-0.63 percentage points).

**Figure 35 Difference in wheat production loss in 2022 in percentage points (pp) (SENS1 minus REF)**

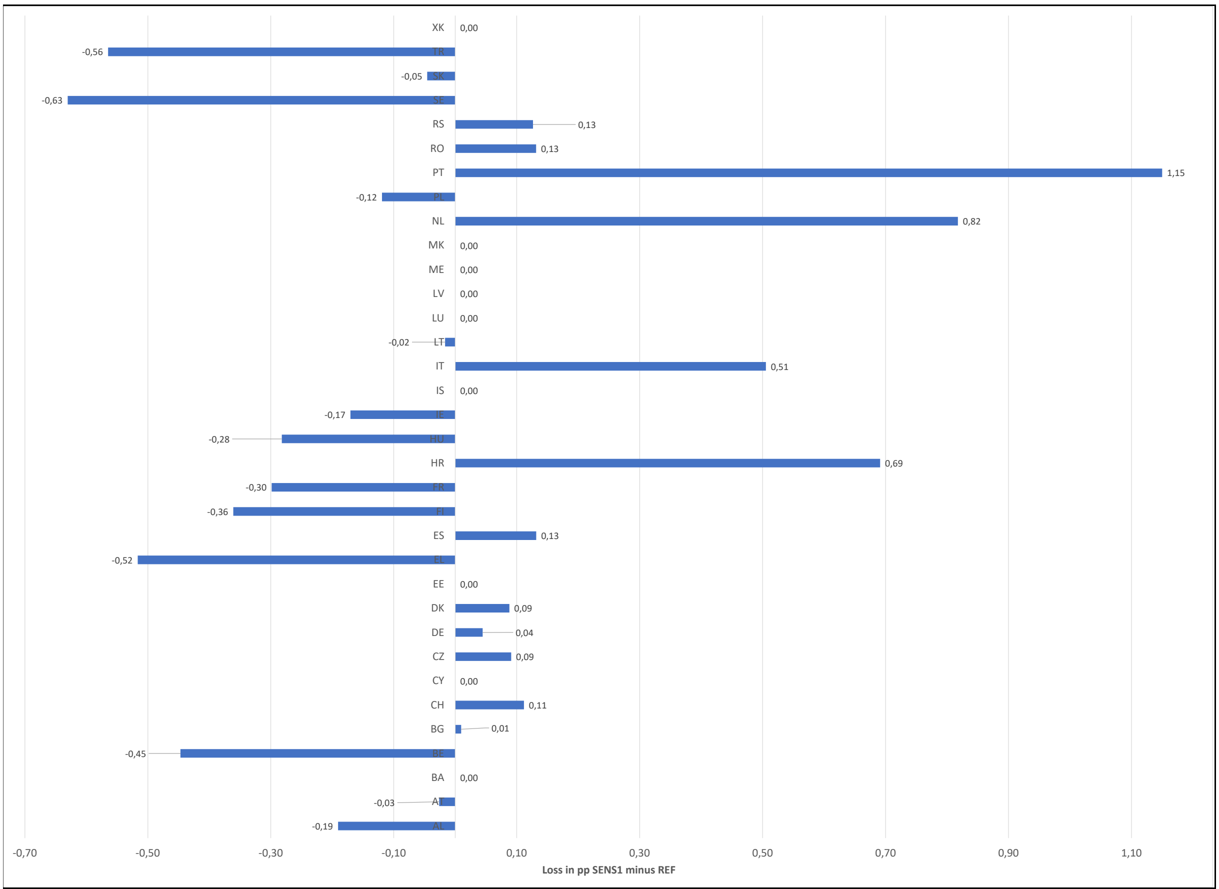
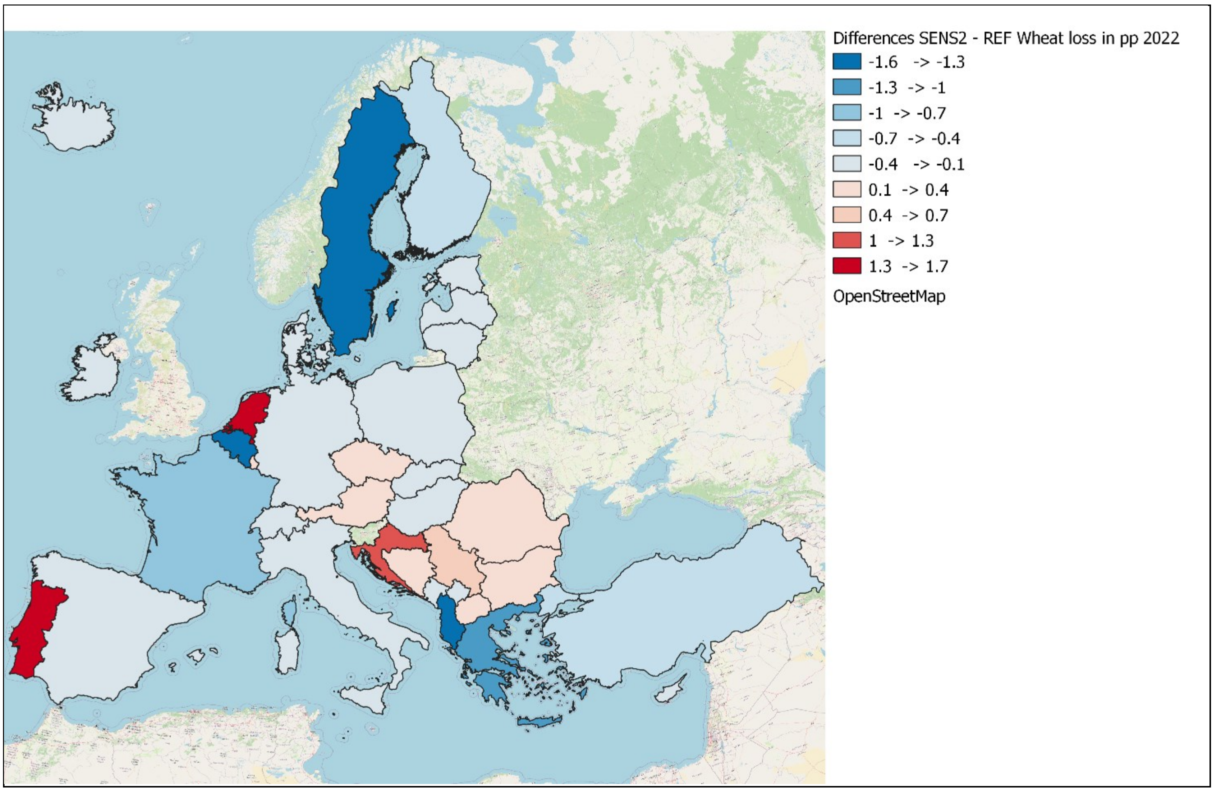


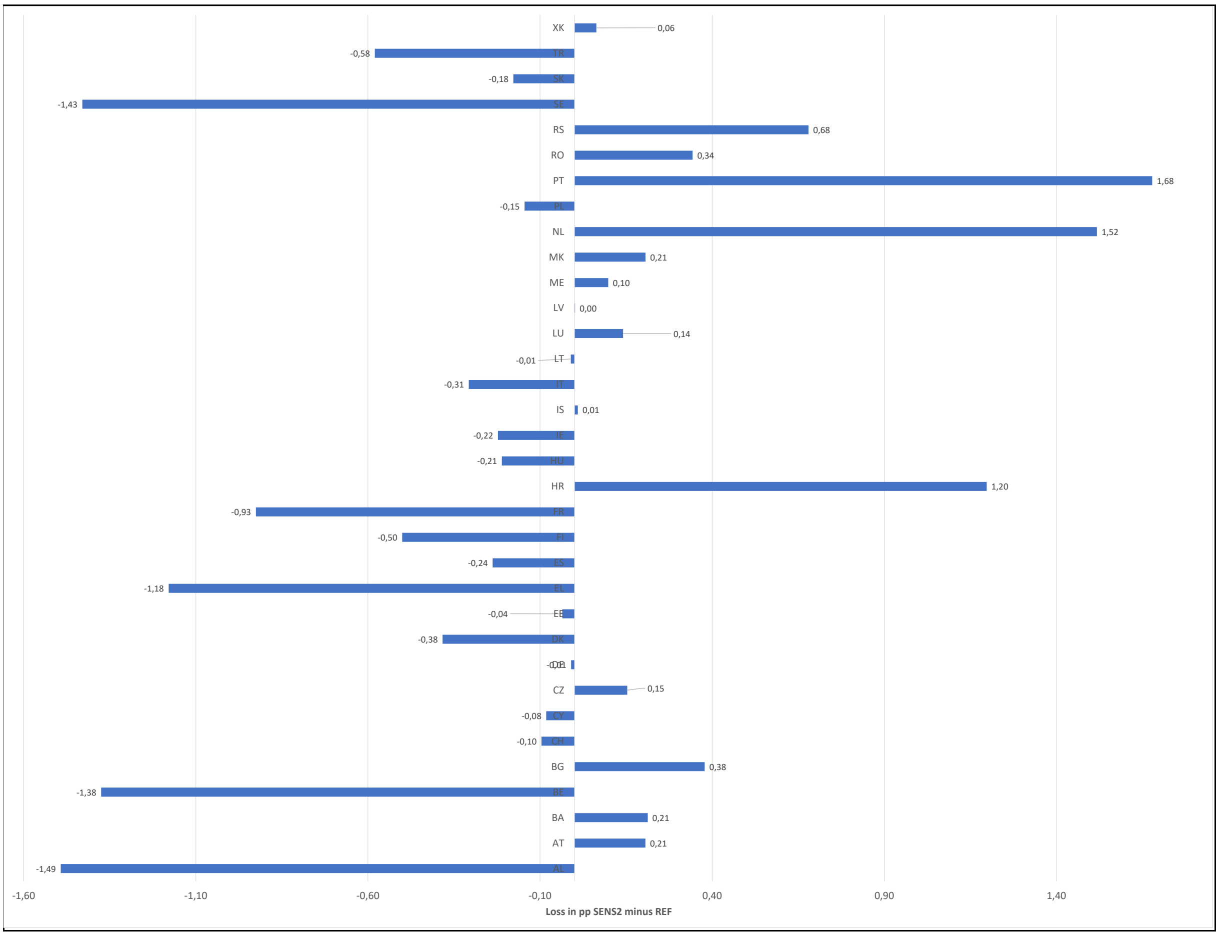

Figure 36 and Figure 37 show the differences in wheat production loss in 2022, in percentage points at the country level, when subtracting REF from SENS2. Again, results are first presented in a map in Figure 36, and then in the form of bars in Figure 37.

**Figure 36 Mapped difference in wheat production loss in 2022 in percentage points (pp) (SENS2 minus REF)**




When comparing SENS2 and REF, the range of differences in percentage points goes from -1.49 percentage points in Albania to +1.68 percentage points in Portugal.

## Figure 37 Difference in wheat production loss in 2022 in percentage points (pp) (SENS2 minus REF)




In the following two tables, the losses for wheat have been aggregated over the whole European domain. Table 16 indicates the loss in million €, and Table 17 in percentage.
The difference between REF and SENS1 amounts to 39.7 million € (Table 16), and the one between REF and SENS2 to 99 million €. The difference between SENS1 and SENS2 consequently is 59.4 million €.

## Table 16 Wheat production loss in 2022 aggregated over Europe in million $€_{2022}$ (REF, SENS1 and SENS2)

| Economic loss in 2022 in million €2022 in Europe (*) | | |
|---|---|---|
| **REF** | **SENS1** | **SENS2** |
| 1 335 | 1 296 | 1 236 |
| (*) Sum over 34 countries | | |

In terms of percentage points (pp), the difference between REF and SENS1 is 0.12 pp and between REF and SENS2 0.31 pp. The difference between the two sensibility calculations amounts to 0.19 pp (Table 17). The similarity of the aggregate results for Europe for the 3 scenarios was already noted in the study for the year 2019 (Schucht et al., 2021a), although it is less pronounced in 2022. As noted in this earlier report, error compensation may explain limited differences at the aggregate level.

**Table 17 Wheat production loss in 2022 aggregated over Europe in % (REF, SENS1 and SENS2)**

| Loss in 2022 in % in Europe (*) | | |
|---|---|---|
| REF | SENS1 | SENS2 |
| 4,33% | 4,21% | 4,02% |
| (*) Sum over 34 countries | | |

## Production loss for potatoes under REF, SENS1 and SENS2

Figure 38 shows the production loss for potatoes by country in 2022, in %, side by side for REF, SENS1 and SEN2. Again, the relative importance between the results of the three scenarios depends on the country. No clear pattern can be identified other than that changes between scenarios are limited for many countries.

**Figure 38 Potato production loss aggregated by country in 2022 in % (REF, SENS1 and SENS2)**

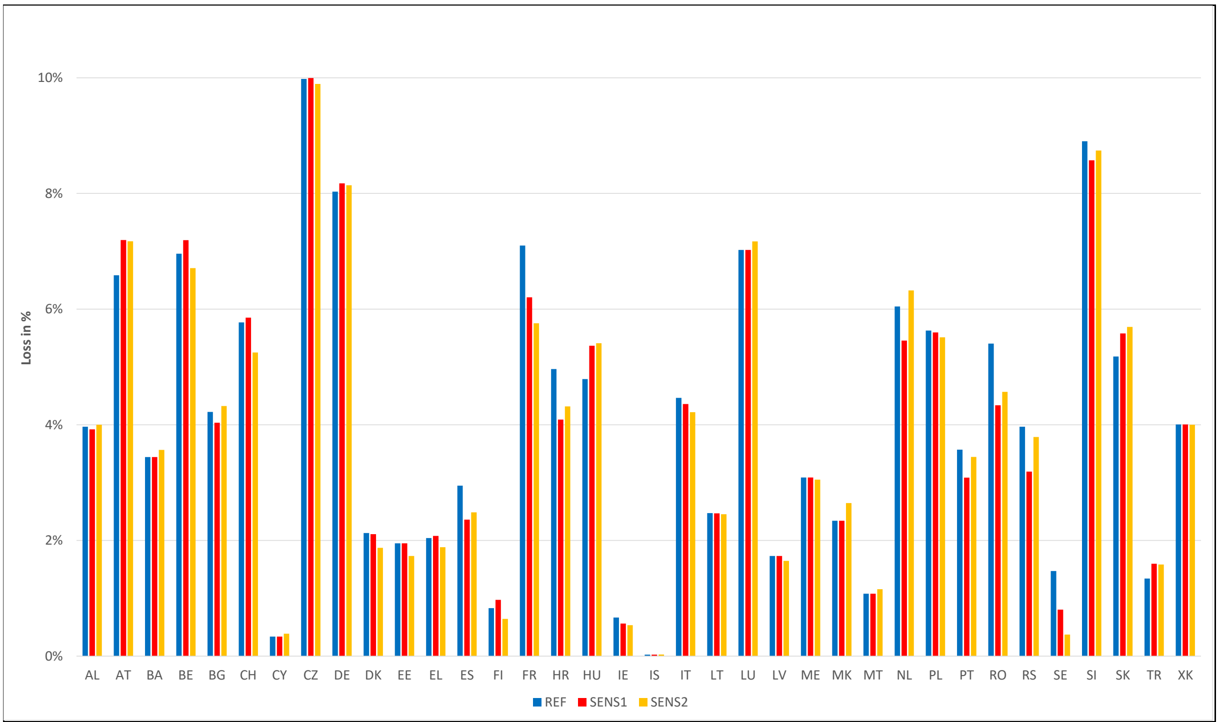
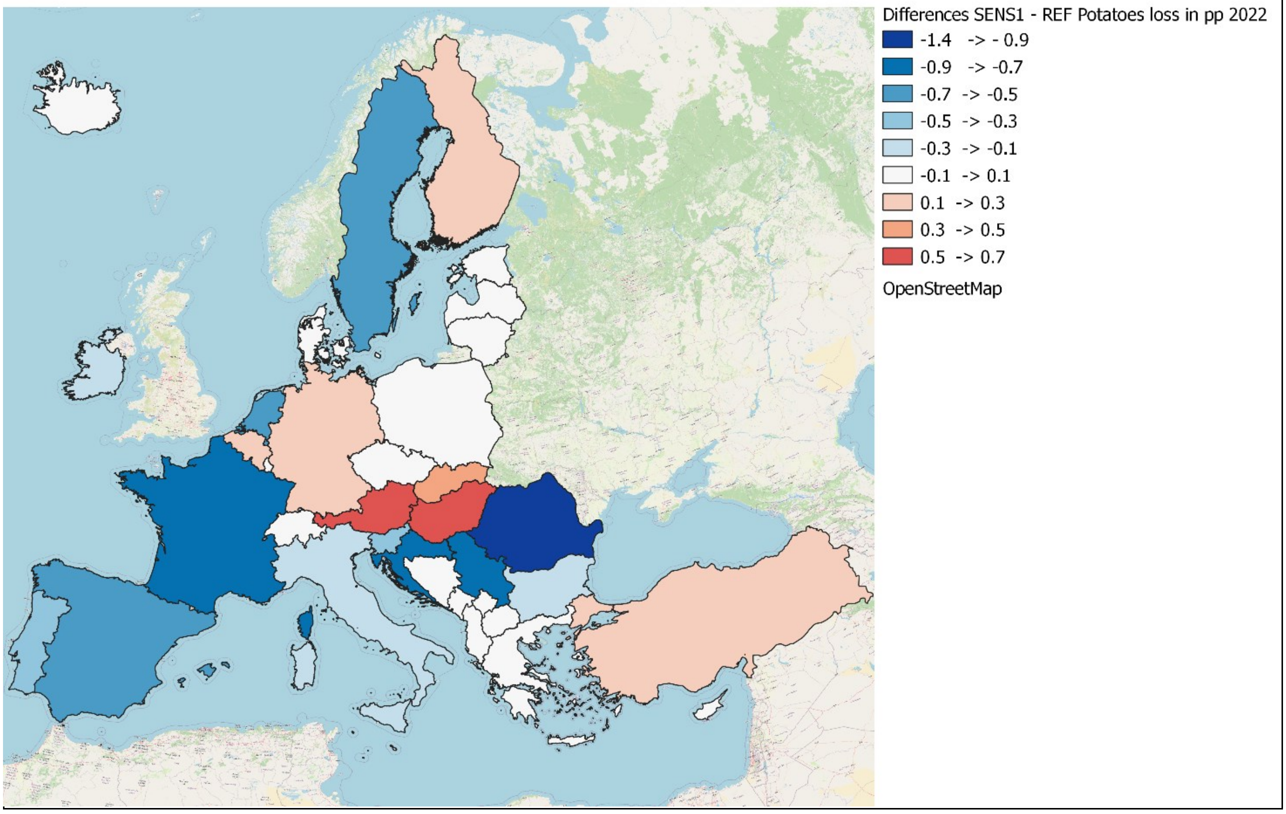



Figure 39 and Figure 40 show the differences in loss at the country level in 2022, in percentage points (pp), when subtracting REF from SENS1, alternatively presented in a map and in the form of bars.

**Figure 39 Mapped difference in potato production loss in 2022 in percentage points (pp) (SENS1 minus REF)**




The lack of a clear pattern for the difference between SENS1 and REF, in pp for potatoes, is confirmed in Figure 40. The differences range from -1.07 pp in Romania to +0.61 pp in Austria. For all other countries, changes remain in absolute terms below 1 pp.

**Figure 40 Difference in potato production loss in 2022 in percentage points (pp) (SENS1 minus REF)**

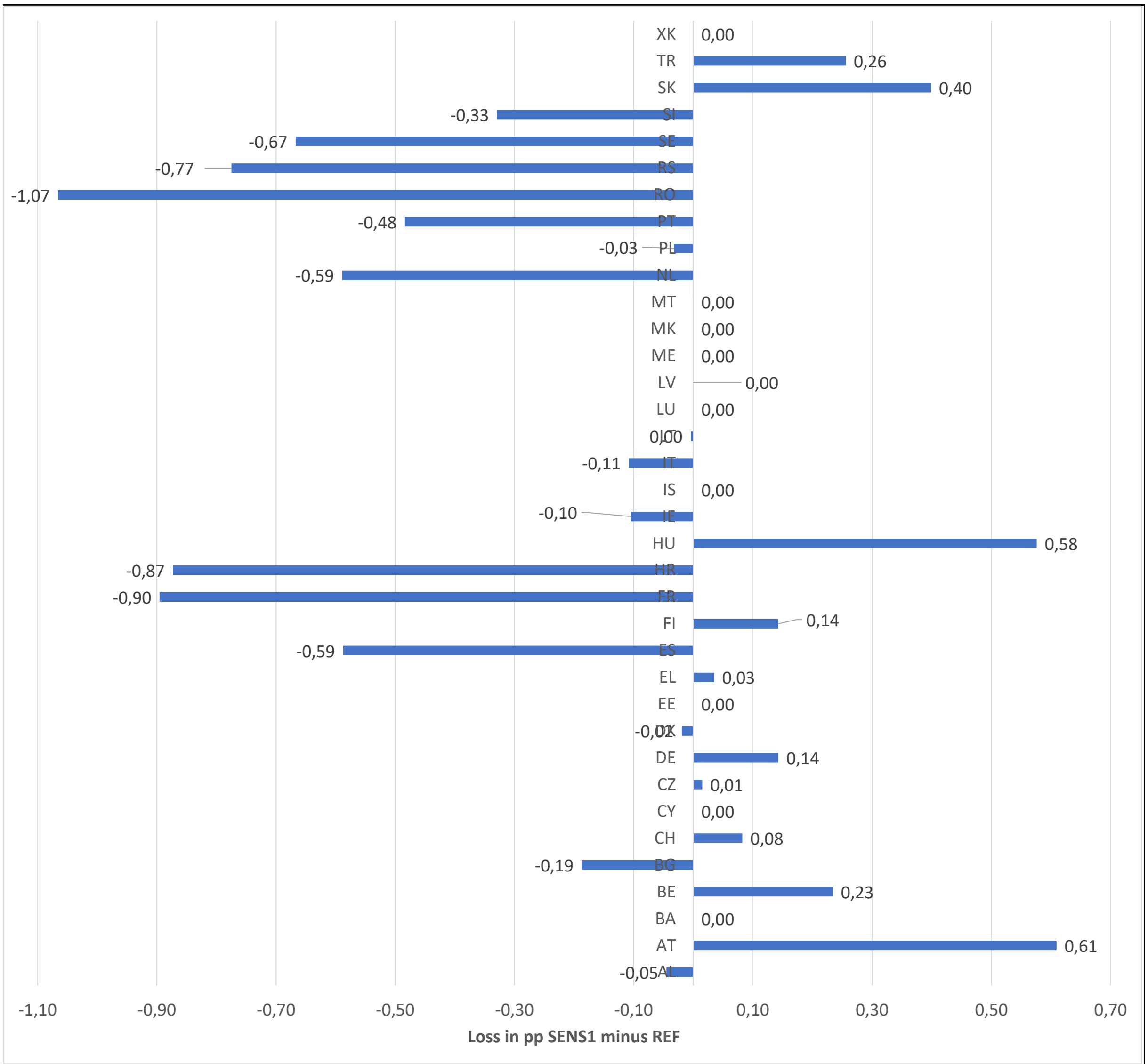
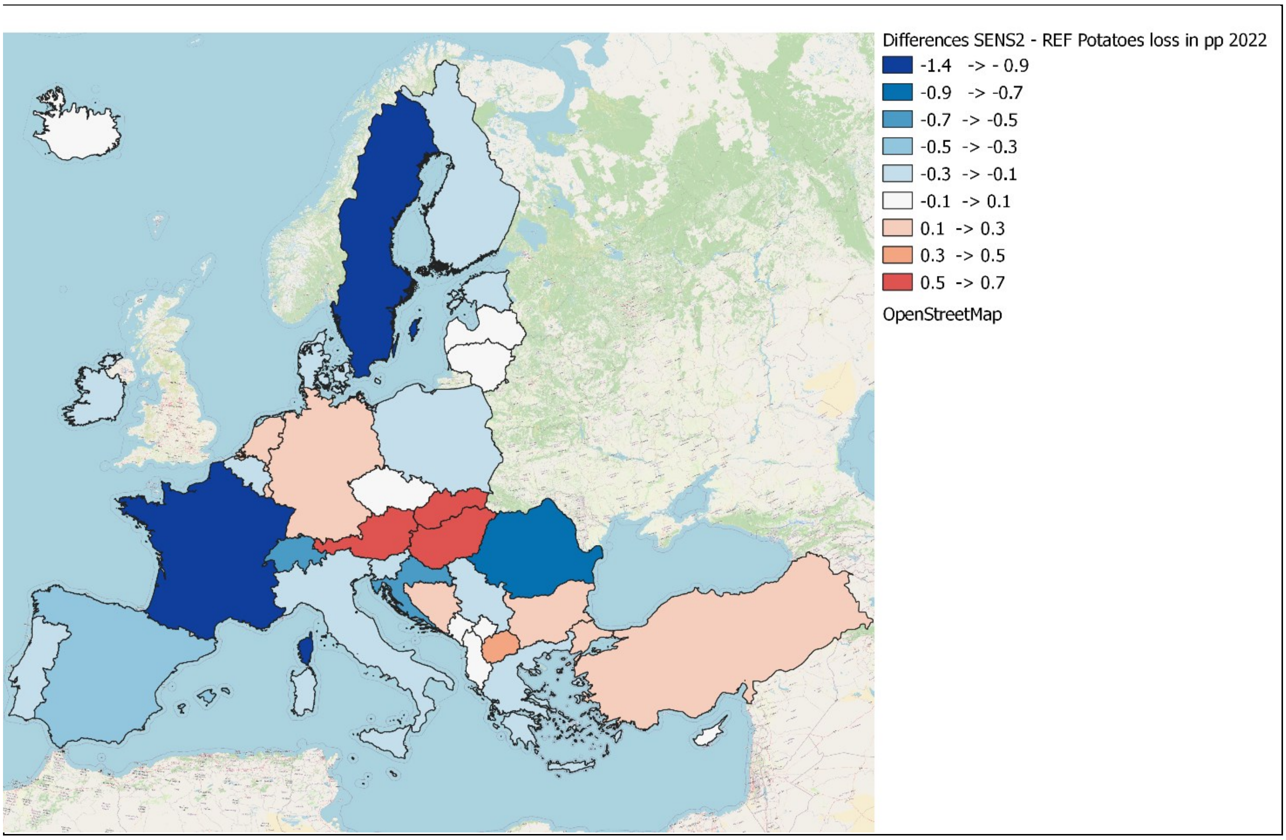


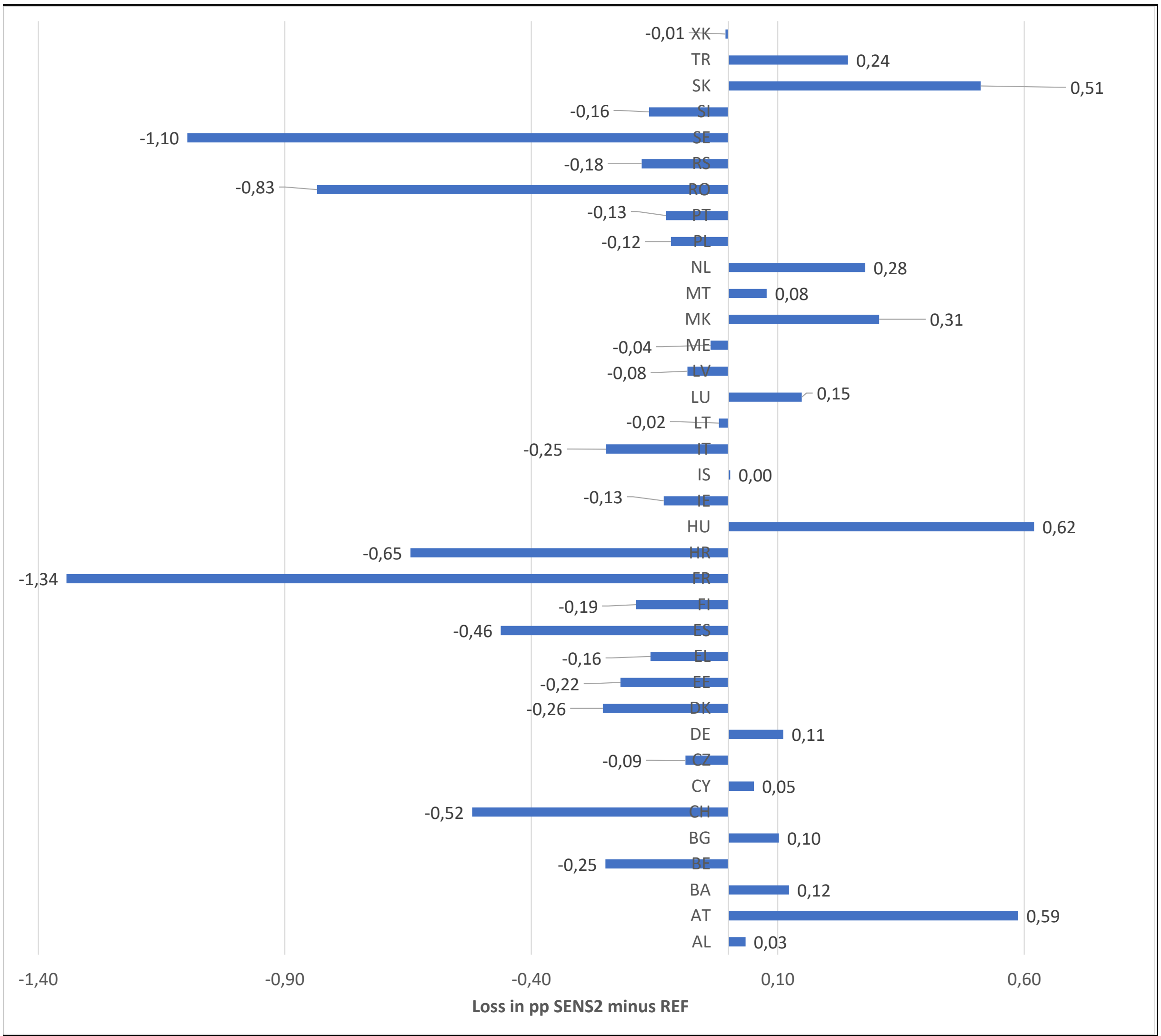

Figure 41 and Figure 42 show the difference in potato production loss in 2022, in percentage points (pp) at the country level, when subtracting REF from SENS2.

**Figure 41 Mapped difference in potato production loss in 2022 in percentage points (pp) (SENS2 minus REF)**




The differences range from -1.34 pp in France to +0.62 pp in Hungary. Differences exceeding 1 pp in absolute terms occur for 2 countries, France and Sweden.

**Figure 42 Difference in potato production loss in 2022 in percentage points (pp) (SENS2 minus REF)**




In the following two tables, the losses for potatoes are again aggregated over the whole European domain. Table 18 indicates the loss in million €, and Table 19 in percent.

**Table 18 Potato production loss in 2022 aggregated over Europe in million €2022 (REF, SENS1 and SENS2)**

| Economic loss in 2022 in million €2022 in Europe (*) | | |
|---|---|---|
| **REF** | **SENS1** | **SENS2** |
| 680 | 655 | 650 |
| (*) Sum over 36 countries | | |

The difference between REF and SENS1 amounts to 25 million €, and between REF and SENS2 to 30 million €. The difference between SENS1 and SENS2 is consequently 5 million €.

**Table 19 Potato production loss in 2022 aggregated over Europe in % (REF, SENS1 and SENS2)**

| Loss in 2022 in % in Europe (*) | | |
|---|---|---|
| **REF** | **SENS1** | **SENS2** |
| 5,61% | 5,39% | 5,39% |
| (*) Sum over 36 countries | | |

Aggregated over Europe, the differences between the losses expressed in percentage points and calculated in the sensitivity analysis are low: 0.21 pp between REF and SENS1, 0.22 % pp between REF and SENS2. They are close to zero between SENS1 and SENS2.

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