UK Centre for Ecology & Hydrology

NECR Reporting 2023 – Quantifying and mapping exceedances of ozone flux-based critical levels for vegetation in the UK in 2019 and 2020.

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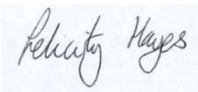
Signed 

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Executive Summary

The amended National Emissions Ceilings Directive (NECD; Directive (EU) 2016/2284, amendment of Directive 2003/35/EC) of the EU is aligning emission reduction commitments with those for the UN Convention on Long-range Transboundary Air Pollution (LRTAP), with the long-term objective to reduce air pollution to at or below the Convention's critical levels and loads for ecosystems. With respect to monitoring air pollutants, Article 9 of the Directive states that '*Member States shall ensure the monitoring of negative impacts of air pollution upon ecosystems based on a network of monitoring sites that is representative of their freshwater, natural and semi-natural habitats and forest ecosystem types, taking a cost-effective and risk-based approach*'. To comply with the requirements of Article 9, Member States may use the optional indicators listed in Annex V.

To meet the UK parallel requirements of Annex V of the amended NECD Directive by reporting on exceedances of flux-based critical levels for ozone, NECR, we mapped the modelled exceedances for vegetation for the years 2019 and 2020. We followed the same approach as previously used in an initial scoping study for the year 2015 (Mills et al., 2017), and subsequent studies investigating ozone impacts in the UK for the years 2014-16 (Sharps et al., 2019), 2017 (Sharps et al., 2020a), 2018 (Sharps et al., 2020b) and 2019 (Sharps et al., 2022). For the current report, a newer version of the EMEP model is used, therefore results are presented for 2019 (allowing comparison with the previous model version) and 2020.

The critical level exceedance data and ozone impacts on crop yield, annual increment of tree biomass and flower numbers in grassland were mapped and quantified by UK country using the latest flux-based methodology for wheat, potato, broadleaf woodland, conifers and flowering of wild plants.

Methods

We applied the most up-to-date approach for quantifying ozone critical level exceedance and impacts on vegetation using metrics that take into account the varying effects of climate and soil moisture on the cumulative uptake or flux of ozone into the leaf via the stomatal pores on the leaf surface (the Phytotoxic Ozone Dose above a threshold flux of Y, POD_Y). Ozone flux (accumulated uptake through the stomatal pores on the leaf surface expressed as POD_1SPEC and POD_6SPEC) was modelled for the UK in 2019 and 2020 using the EMEP4UK atmospheric chemistry transport model. Spatial data was collated at 5km x 5km resolution for the UK for crop area and production for wheat, potato and oilseed rape, and habitat distribution for managed broadleaf woodland, unmanaged beech woodland, managed coniferous woodland and perennial grassland (represented by acid, calcareous and dune grassland). For all crops and habitats where suitable critical levels exist, the areas where exceedance occurred were mapped for the UK and the areas of exceedance for the four countries were summed. The critical levels and methods used were those agreed at the 30th ICP Vegetation Task Force Meeting (February 2017, Poznan, Poland). In addition, effects of ozone on crop production in tonnes per grid square and associated losses in economic value (based on mean weekly crop prices for 2019) were mapped at 5km x 5km resolution by applying flux-based response functions to gridded flux data.

Results

The effects of ozone on vegetation growth were quantified by calculating and mapping effects on crop yield (quantity, economic value) and annual growth of living tree biomass and annual grassland biomass increment. As such, the percentage yield and biomass loss maps are indicative of the risk of effects on carbon flux and subsequent yield and biomass losses and do not provide actual monitored values for ozone effects.

In summary, calculation of the ozone impact on crops, trees and grassland in 2019 (using the updated version of the EMEP model) shows:

- Reduced UK wheat yield by 3.4%, based on POD_6SPEC, amounting to a production loss of 718,000 tonnes with an economic value of £114.7 million (at average weekly prices for 2019). The highest production losses were indicated for eastern counties of England, particularly Lincolnshire, Cambridgeshire, Norfolk and Suffolk.
- Reduced UK potato yield by 4.3%, resulting in 219,000 lost tonnes of potato tubers worth £40.45 million, with the highest production losses in Norfolk, Cambridgeshire, Bedfordshire and Hertfordshire.
- Reduced oilseed rape production by 4.9%, amounting to 85,000 tonnes of lost production, worth £27.72 million. The highest production losses were predicted for central England and parts of Yorkshire.
- Total economic losses for wheat, potato and oilseed rape in the UK of £182.85 million, with the majority of production losses (>97%) occurring in England.
- Calculated annual biomass increment losses for the UK for managed broadleaf woodland of 15.7% (and 17% for unmanaged). Impacts on managed and unmanaged broadleaf woodland tended to be greatest in the south-west of England, with additional patches of high biomass loss for managed broadleaf, for example in south-east England and south-west Wales.
- Reduced annual biomass increments of coniferous trees for the UK of 2.3%. Ozone reduced annual biomass increment of coniferous trees considerably less than broadleaf trees. The risk of potential effects across England was on average 2.5%, with some areas 2.75 - 3.25%, for example counties in the south-west.
- Reduced flower numbers in perennial grassland in the UK by 7.6%. Ozone had the potential to reduce flowering in wild plants primarily in England, with the areas at highest risk being mostly in eastern and south-eastern counties.
- Reduced annual total biomass increment in perennial grassland in the UK by 2.2%.

We provided maps and tables showing the exceedance of the ozone critical levels relevant for UK vegetation in 2019 (using the newer version of the EMEP model). In summary, we found that:

- Critical level exceedance was greatest for woodland habitats, with grasslands and crops having intermediate exceedance.
- UK average values for percentage of area exceeding critical levels do not provide the full picture on the extent of ozone impacts, as there are spatial differences in exceedances within the UK.

- For wheat, ozone critical level exceedance was only seen for England (44.4% of wheat growing area). There was no exceedance for wheat in Wales, Scotland or Northern Ireland.
- For potato, England showed exceedance of the critical level (65% of potato growing area), and Wales showed exceedance of 26%, with no exceedance for Scotland and Northern Ireland.
- Critical level exceedance for managed broadleaf woodlands was 100% for England, Wales and Scotland.
- Critical levels for unmanaged Beech woodland were exceeded (for 100% of the area) for England, Wales and Scotland.
- Critical levels for managed coniferous forest were exceeded in the UK in 2019, in England (99.9% of area), Wales (99.8% of area), Scotland (61.3% of area) and Northern Ireland (82.1% of area).
- The percentage of the grassland areas of England where the critical level for flowering was exceeded was 48.6%. The highest critical level exceedances were in eastern and southern England. Critical levels for this habitat were also exceeded for Wales (1.9%) but not for Scotland or Northern Ireland.
- The critical level for effects on the annual total biomass increment of grassland species was not exceeded in the UK in 2019.

For 2020, calculation of the ozone impact on crops, trees and grassland shows:

- Reduced UK wheat yield by 6.8%, based on POD_6SPEC, amounting to a production loss of 723,000 tonnes with an economic value of £125.4 million (at average weekly prices for 2020). The highest production losses were indicated for eastern counties of England, particularly Cambridgeshire, Norfolk and Suffolk.
- Reduced UK potato yield by 5.1%, resulting in 268,000 lost tonnes of potato tubers worth £47.5 million, with the highest production losses in Norfolk, Cambridgeshire, Bedfordshire, Hertfordshire and North Yorkshire.
- Reduced oilseed rape production by 7.3%, amounting to 70,000 tonnes of lost production, worth £23.64 million. The highest production losses were predicted for central England and parts of Yorkshire.
- Total economic losses for wheat, potato and oilseed rape in the UK of £196.53 million, with the majority of production losses (94%) occurring in England.
- Calculated annual biomass increment losses for the UK for managed broadleaf woodland of 16% (and 17.4% for unmanaged). Impacts on managed and unmanaged broadleaf woodland tended to be greatest in the south-west of England, with additional patches of high biomass loss for managed broadleaf, for example areas of southern and eastern England and parts of Wales.
- Reduced annual biomass increment losses of coniferous trees for the UK of 2.4%. Ozone reduced annual biomass increment of coniferous trees considerably less than broadleaf trees. The risk of potential effects across England was on average 2.7%, with some areas 2.75 - 3.25%, for example counties in the south-west.
- Reduced flower numbers in perennial grassland in the UK by 8.5%. Ozone had the potential to reduce flowering in wild plants primarily in England, with the areas at highest risk being mostly in central, eastern and south-eastern counties.

- Reduced annual total biomass increment in perennial grassland in the UK by 2.5%.

We provided maps and tables showing the exceedance of the ozone critical levels relevant for UK vegetation in 2020. In summary, we found that:

- Critical level exceedance was greatest for woodland habitats, with grasslands and crops having intermediate exceedance (although note, for wheat and potato, critical level exceedance of the crop area in England in 2020 was 95% and 86% respectively).
- UK average values for percentage of area exceeding critical levels do not provide the full picture on the extent of ozone impacts, as there are spatial differences in exceedances within the UK.
- For wheat, ozone critical level exceedance was seen for England (95% of wheat growing area), Wales (58%), Scotland (20%) and Northern Ireland (10%).
- For potato, England showed exceedance of the critical level (86% of potato growing area), and Wales showed exceedance of 30%, with no exceedance for Scotland and Northern Ireland.
- Critical level exceedance for managed broadleaf woodlands was 100% for England, Wales and Scotland.
- Critical levels for unmanaged Beech woodland were exceeded (for 100% of the area) for England, Wales and Scotland.
- Critical levels for managed coniferous forest were exceeded in the UK in 2020, in England (99.9% of area), Wales (99.8% of area), Scotland (61.1% of area) and Northern Ireland (92.6% of area).
- The percentage of the grassland areas of England where the critical level for flowering was exceeded was 52.3%. The highest critical level exceedances were in central, eastern and southern England. Critical levels for this habitat were also exceeded for Wales (13.8%), Scotland (0.3%) and Northern Ireland (0.1%).
- The critical level for effects on the annual total biomass increment of grassland species was not exceeded in the UK in 2020.

<u>Comparison between ozone impact results for 2019 using different model versions</u>

When the results between the two EMEP model versions were compared (using 2019 data), spatial patterns of ozone impacts were similar across the UK, i.e. areas with the greatest impact were in similar locations for both model versions, for all vegetation types. There were some differences between the 2019 results for the two model versions when looking at % losses and critical level exceedance, and the extent of this varied with vegetation type. The results using the newer model version (4.36) showed increased ozone impacts (flux, critical level exceedance and losses) when compared with the older version (4.17). This was most pronounced for broadleaf trees, (in terms of annual biomass increment losses). Ozone flux values were also greater for crops using the newer model version, which led to greater critical level exceedance (for wheat and potato) and greater estimates of production and economic losses, particularly for oilseed rape. Differences in ozone impact between the model versions were less pronounced for coniferous woodland and semi-natural grasslands.

<u>Comparison between 2019 and 2020 results (using the new EMEP model version)</u>

The results for 2019 and 2020 (using the newer model version 4.36) showed that there was not a big difference between years in terms of ozone impacts. The new model showed slightly higher fluxes in 2020 compared to 2019. Over the period 2014 to 2019 (which was only considered with the previous model version), 2019 was a low/medium year, and so it is likely that 2020 was a medium year compared to others in the 2014 – 2020 timespan. Generally, values were slightly higher for all vegetation types in 2020 compared to 2019, for example, ozone fluxes were higher in 2020 than in 2019. This in turn led to critical level exceedances also being higher, which was particularly noticeable for wheat (and potato to lesser extent). The vegetation type with the greatest differences between the 2019 and 2020 results was crops.

Sources of uncertainty

The analysis uses modelling methods approved for use by the LRTAP Convention and the EU, including the most up-to-date critical levels and response functions and the EMEP4UK model adapted for UK use from the extensively used EMEP model. Nevertheless, there are some sources of uncertainty associated with the following steps:

- Response functions and critical levels with the following order of robustness: crops>trees>grassland;
- EMEP4UK modelling including sources of emission data for the UK and countries influencing UK concentrations and climate data;
- Crop distribution and production data, converted to 2019 and 2020 from 2006 and 2008 data;
- Combining data sources of differing spatial resolution.

Further work

We have reported on modelled flux-based critical levels of ozone for vegetation. It would be desirable to validate the monitoring data with site-specific monitoring of ozone concentrations, climate data and soil type to calculate site-specific POD_Y values. Whilst we have reported on the key indicator "exceedances of flux-based critical levels" and impacts on "vegetation growth", reporting on "foliar injury" would require establishing a UK network for systematically monitoring ozone injury on vegetation and/or the development of a critical level for this effect by analysis of ICP Vegetation survey data and results from ozone exposure experiments. To gain a more comprehensive understanding of ozone impacts in the UK, we would need to conduct more ozone-exposure experiments to determine response functions for additional crops, native species and trees of relevance to the UK. Further development of modelling of POD_YSPEC for the UK would be beneficial too. Next year, the habitat data for woodland (deciduous and conifer), and grassland will be updated, using up-to-date land cover data.

1 Introduction

Objective

Report on the modelled exceedances of ozone flux-based critical levels for vegetation in the UK and impacts on crop yield, forest and grassland annual biomass increment and grassland flower number for the year 2019, as part of the UK reporting requirements previously for the amended European Union's National Emissions Ceilings Directive (NECD; Directive (EU) 2016/2284), Art. 9, and in the parallel NECR reporting requirements since 2020.

The amended National Emission Ceilings Directive (NECD; Directive (EU) 2016/2284, amendment of Directive 2003/35/EC) of the EU is aligning emission reduction commitments with those for the UN Convention on Long-range Transboundary Air Pollution (LRTAP), with the long-term objective of reducing air pollution to or below the Convention's critical levels and loads for ecosystems. With respect to monitoring air pollutant impacts on ecosystems, Article 9 of the Directive states that '*Member States shall ensure the monitoring of negative impacts of air pollution upon ecosystems based on a network of monitoring sites that is representative of their freshwater, natural and semi-natural habitats and forest ecosystem types, taking a cost-effective and risk-based approach*'. To comply with the requirements of Article 9, Member States may use the optional indicators listed in Annex V, with further guidance provided in a guidance document on ecosystem monitoring under Article 9 and Annex V.

Mills et al., (2017) carried out a scoping study to examine how Annex V of the amended NECD could be interpreted for ozone in a UK context. Data from the year 2015 was used as a test year for this study. The study developed and applied a methodology for UK reporting on ozone damage to vegetation growth and biodiversity, including exceedance of flux-based critical levels. The metric used in the study to quantify impacts is the Phytotoxic Ozone Dose (POD_Y) which is the hourly 'uptake' of ozone through the leaf pores (stomata) accumulated above a threshold flux Y during daylight hours for a species-relevant growth period. POD_Y is often referred to as the "flux" or "stomatal flux" of ozone and is determined by modelling how much ozone enters plants through the stomatal pores as they open and close in relation to leaf age and environmental conditions such as temperature, humidity, light intensity and soil water content. The stomatal flux approach is more biologically meaningful than older concentration-based approaches as climatic and plant factors may limit ozone uptake under dry conditions when concentrations are highest or lead to high uptake of moderate ozone concentrations under moist conditions (Mills et al., 2011b). A previous study showed that in Europe, locations of ozone injury, biomass or yield reduction in the field were better correlated with risk maps based on stomatal flux than on ozone concentration (Mills et al., 2011a).

Over the last 20 years, under the direction of the ICP Vegetation Programme Coordination Centre, the methodology for determining POD_Y has been developed and extended for a wide range of crops, trees and grassland species. For each of these species, critical levels have been defined for ozone effects on vegetation as the "cumulative flux of ozone into leaves above which direct adverse effects on sensitive vegetation may occur according to present knowledge”. Different Y values and parameterisations are used for the models for different species and biogeographical regions. The effect parameters for critical levels are yield quantity and quality for crops, total or above-ground annual biomass increment for trees and grasslands, and flower and seed number or weight for grasslands. In recent years, the ICP Vegetation has focussed on reviewing existing critical levels, revising them where necessary, and developing new critical levels. At the 30th ICP Vegetation Task Force Meeting in Poland (February 2017), 21 flux-based ozone critical levels were adopted for Europe (LRTAP Convention, 2017), with 8 of these suitable for application in UK climatic conditions.

We repeated the methodology used in the 2017 scoping study using data for the years 2014, 2015 and 2016, to provide information on the spatial and temporal variation in critical level exceedance and subsequent impacts on crops, trees and grasslands across the UK (Sharps et al., 2019). Results indicated spatial and temporal variation in ozone fluxes for the period 2014 - 2016. This seemed to be mainly driven by differences in meteorology. For some vegetation types, the areas of the country showing the highest ozone flux values varied with year. Critical level exceedances also varied with year, particularly for crops and perennial grasslands.

The study was repeated using data for the year 2017 (Sharps et al., 2020a). Results showed that compared to the period 2014-16, losses and critical level exceedance were greater in 2017 for crops (particularly for wheat and potato), and for semi-natural vegetation. For trees, results for 2017 were similar to those for 2014-16, with some spatial variation in ozone fluxes, losses and critical level exceedance between years. The study was then carried out using data for the year 2018 (Sharps et al., 2020b). Results showed that while losses and critical level exceedance remained similar for wheat (compared to 2017), values had increased again for both potato and oilseed rape, and also for semi-natural vegetation. For trees, results for 2018 were more similar to those for 2014-17, with some spatial variation in ozone fluxes, losses and critical level exceedance between years.

Lastly, the study was carried out using data for the year 2019 (Sharps et al., 2022). Losses and critical level exceedance were lower in 2019 for the crops wheat, potato and oilseed rape, and for semi-natural vegetation, compared to those of 2018. For trees, results for 2019 were more similar to those for 2018, with some spatial variation in ozone fluxes, losses and critical level exceedance between years.

Here, we use the same methodology as the previous studies (Mills et al., 2017; Sharps et al., 2019, 2020a, 2020b, 2022), reporting results from the EMEP4UK ozone model for the year 2019 and 2020. This year we use an updated version of the EMEP model, therefore we repeat the results for 2019 as a comparison exercise, to detect any potential changes in output due to changes in the model. We focus on the modelled exceedances of ozone flux-based critical levels for vegetation in the UK and impacts on crop yield, forest and grassland annual biomass increment and grassland flower number.

2 Methods

2.1 Modelling of the stomatal flux of ozone

POD_YSPEC is defined as:

- **POD_YSPEC:** a (group of) plant species-specific POD_Y that requires comprehensive input data and is suitable for detailed risk assessment.

The core of the leaf ozone flux model is the stomatal conductance (g_{sto}) multiplicative algorithm included in the DO_3SE model (https://www.sei.org/projects-and-tools/tools/do3se-deposition-ozone-stomatal-exchange/) and incorporated within the EMEP ozone deposition module (Simpson et al., 2012). The multiplicative algorithm has the following formulation:

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

Where g_{sto} is the actual stomatal conductance (mmol O_3 m^{-2} PLA s^{-1}), g_{max} is the species-specific maximum stomatal conductance (mmol O_3 m^{-2} PLA s^{-1}) and f_{min} represents the minimum value of the stomatal conductance. The parameters f_{phen}, f_{O3}, f_{light}, f_{temp}, f_{VPD} and f_{SW} are all expressed in relative terms (i.e. they take values between 0 and 1 as a proportion of g_{max}). These parameters allow for the modifying influence on stomatal conductance to be estimated for growth stages such as flowering or release of dormancy, or phenology (f_{phen}), O_3 concentration (f_{O3}, only used for crops), and four environmental variables: light (irradiance, f_{light}), temperature (f_{temp}), atmospheric water vapour pressure deficit (VPD, a measure of air humidity, f_{VPD}) and soil water (SW; soil water potential, f_{SW}, measure of soil moisture, replaced by f_{PAW} for crops where PAW is the plant available water content).

Each parameter modifies the maximum stomatal conductance in different ways, as illustrated for wheat in Figure 1. Mathematical functions have been developed for the DO_3SE model that describe the shape of each of these responses, with individual parameterisations set to represent species-specific and biogeographical region–specific differences, e.g. in the maximum temperature for stomatal conductance.

The EMEP-WRF model (Vieno et al., 2016), based on the official EMEP MSC-W model (Simpson et al., 2012) and called here EMEP4UK was used. The major difference between the EMEP MSC-W and the EMEP4UK models is the meteorological driver. The EMEP MSC-W model uses data from the European Centre for Medium Range Weather Forecasting Integrated Forecasting System (ECMWF-IFS) model whereas EMEP4UK uses the Weather Research and Forecast (WRF) model. The EMEP4UK model uses a latitude-longitude grid and 21 vertical layers with thickness varying from ~40 m at the surface to ~2 km at the top of the vertical boundary (~16 km). The height of the lowest surface layer used allows the EMEP4UK model to represent the strong gradient of concentrations such as NO_x in cities and therefore represent the titration of ozone by NO in these areas. The WRF model is used to calculate hourly 3D meteorological data used to drive the EMEP4UK model. The WRF model is initialised and nudges every 6 hours using the Global Forecast system final reanalysis (GFS-FNL) data (National Centers for Environmental Prediction, 2015).

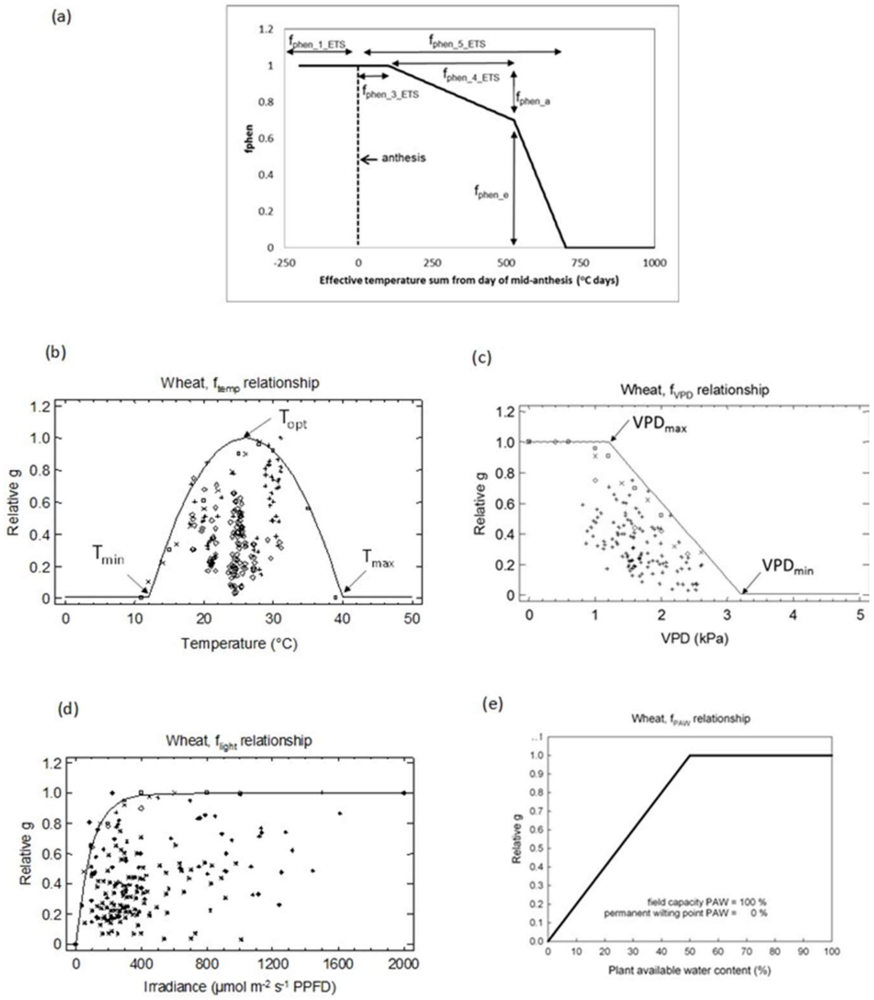

Figure 1: Illustration of the components of the DO$_3$SE stomatal flux model, showing for wheat how the stomatal conductance is modified by (a) phenology (growth stage), (b) temperature, (c) vapour pressure deficit - a measure of air humidity, (d), light and (e) plant available water - a measure of the soil water content.

The reports for the years 2014-2019 (Sharps et al., 2019 – 2022) used EMEP4UK version 4.17. The model version was kept consistent between years to allow comparison of results between reports. In the current report, we use the most up-to-date, stable version of EMEP4UK, which is version 4.36. The model is continuously updated, for example, resolution of bugs, updates to equations and changes in the atmospheric chemistry of the model. We will report results for both 2019 and 2020, allowing a comparison of the results between model versions 4.17 and 4.36 for 2019. For the 2019 runs, emissions and meteorological data (WRF version 4.2.2) were all kept the same as used by Sharps et al. (2022), to allow a direct comparison between the outputs of the two different model versions.

For 2019, anthropogenic emissions of NOx, NH_3, SO_2, primary $PM_{2.5}$, primary coarse PM, CO and non-methane volatile organic compounds (NMVOCs) for the UK are derived from the 2019 National Atmospheric Emission Inventory estimate (NAEI, http://naei.defra.gov.uk). The EMEP emission estimates at a resolution of 0.5°×0.5° provided by the Centre for Emission Inventories and Projections (CEIP, http://www.ceip.at/) are used for all non-UK emissions and based on the year 2019. Data for shipping emissions are a combination of NAEI for a buffer zone of 10 km off the coast (to avoid double counting in harbours) and official EMEP shipping emissions for the year 2019.

The same 2019 emissions datasets were then adjusted for 2020, with an ad-hoc monthly timing for the emissions used to account for the COVID lockdown. WRF version 4.2.2 was used for the 2020 meteorological data.

The EMEP4UK model (rv4.36) was parameterised for this study using ozone critical level parameterisations (see Annex, Tables 1&2 for input parameters used). Time periods for accumulation of PODySPEC match the Modelling and Mapping Manual (LRTAP Convention, 2017) specifications and are defined by SGS50 and EGS50 (Annex, Table 1). In 2022, a new EMEP4UK and WRF model domain (3km x 3km resolution, using polar stereo projection) replaced the previous ~5km x 5km domain. For the current report (and also Sharps et al., 2022), the modelled PODySPEC data were re-projected to British National Grid, and the data were resampled (using ArcGIS software, ArcMap v 10.6.1) to 5km x 5km resolution, in order to work with the 5km resolution habitat data and to allow results maps to be presented at the same scale as previous reports for comparison purposes. The bilinear option of the resampling method was chosen, which is suitable for continuous data and determines the new value of a cell based on a weighted distance average of the four nearest input cell centres.

2.2 Critical levels for ozone

Table 1: Stomatal flux-based critical levels used in this study.

Species	Effect parameter	POD metric	Potential effect at critical level (% reduction)	Critical level (mmol m^{-2} PLA)	Ref10 POD_6 (mmol m^{-2} PLA)[i]	Potential maximum rate of reduction (%) per mmol m^{-2} PLA of POD_6SPEC [ii]
Wheat	Grain yield	POD_6SPEC	5%	1.3	0.0	3.85
Potato	Tuber yield	POD_6SPEC	5%	3.8	0.0	1.34
Oilseed Rape	Seed yield	POD_6SPEC	NA	NA	NA	1.10
Beech and birch	Whole tree biomass [iii]	POD_1SPEC	4%	5.2	0.9	0.93
Norway spruce	Whole tree biomass [iii]	POD_1SPEC	2%	9.2	0.1	0.22
Temperate perennial grassland	Total biomass [iii,iv]	POD_1SPEC	10%	16.2	0.1	0.62
Temperate perennial grassland	Flower number[v]	POD_1SPEC	10%	6.6	0.1	1.54

[i] Ref10 POD_6 is the flux of ozone at a pre-industrial ozone concentration of 10 ppb; [ii] The % reduction for a given PODy is calculated using the following formula:

(POD_6SPEC – Ref10 POD_6SPEC) x potential maximum rate of reduction;

[iii] Annual increment of whole tree or total grassland biomass; [iv] Based on a combined function for the species: *Campanula rotundifolia* (harebell), *Dactylis glomerata* (cock's foot grass), *Leontodon hispidus* (rough hawkbit), *Ranunculus acris* (meadow buttercup);

[v] Based on a combined function for the species: *Campanula rotundifolia* (harebell), *Primula veris* (cowslip), *Potentilla erecta* (Tormentil), *Scabiosa columbaria* (small scabious).

The critical levels used in this study have been derived from exposure response relationships from experimental studies. Data included in the response functions were from experiments conducted in several countries and/or several independent studies, with the methodology and functions available in the revised chapter 3 (LRTAP Convention, 2017). We selected those most suited to the UK for application in this study from the list of critical levels available (Table 1).

A critical level has not been approved for oilseed rape as the response function only includes data from one experiment conducted in Belgium (De Bock et al., 2011). However, oilseed rape has been included in the analysis as it is one of the top five crops grown in the UK and the response function from the Belgian study is based on the most widespread cultivar in the UK, which is grown under similar climatic conditions.

2.3 Calculating critical level exceedances

Critical level exceedances were calculated for each habitat by first subtracting the pre-industrial ozone flux (Ref10 POD_6, Table 1) from the current (2019) ozone flux, and then calculating the amount of ozone flux above the critical level (Table 1). Exceedances were only calculated for areas where (a) the ozone flux was positive after subtracting the pre-industrial value, and (b) both ozone flux and habitat area data exist (i.e. there may be some small areas of habitat, particularly in coastal regions, where no flux data exist due to the coastal/land data masks used). The areas where the critical level was exceeded for each habitat was summarised by country and for the UK as a whole, and UK maps of areas of exceedance were produced.

2.4 Mapping crop and habitat distribution

2.4.1 Mapping the distribution of crop area and production

UK crop distribution data (area (ha) and production (tonnes), 10km x10km resolution) for the years 2006 and 2008 were produced for an earlier study for potato, wheat and oilseed rape (Mills et al., 2011c). The mean for the two years was calculated for each crop, for area (hectares) and production (tonnes). To align with the 2019 data used in this study, crop area and production data for the UK were obtained from Defra (wheat and oilseed rape), AHDB (Agriculture and Horticulture Development Board) (GB potatoes) and Northern Ireland's DAERA (Department of Agriculture, Environment and Rural Affairs) (NI potatoes) for 2006, 2008 and 2019. A conversion factor for 2019 was then calculated for each UK region (Scotland, Wales, Northern Ireland, North East England, North West England, Yorkshire and the Humber, East Midlands, West Midlands, Eastern Counties, South East England, South West England), at 1km x 1km scale, i.e. '2019 values/2006-08 mean value'. The 2006-08 crop production and distribution data were multiplied by the conversion factor (at 1km scale, with crop production divided equally between each of the 1km x 1km cells within each 10km x 10km cell). For the final maps, data were aggregated to 5km x 5km resolution.

The same methodology was followed for the 2020 dataset, using crop production and area data for 2020 from Defra, ADHB and DAERA. Note, due to data availability, in 2019 and 2020, AHDB combined potato data for North East and North West England, and also Wales and West Midlands. The previous 14 years of data (2005-2018) were therefore used to calculate an average value for how much greater production was in the North West than in the North East, and in West Midlands compared to Wales to calculate a final estimate of potato production and area for each region in 2019 and 2020.

All maps include only cells where the crop area was >1ha within each 1km x 1km cell (for wheat and oilseed rape) and >0.5ha within each 1km x 1km cell (potato). For Northern Ireland, there were no oilseed rape areas >1ha within any of the 1km x 1km cells. Data processing was done using Python version 2.7.16 and maps were created using R version 4.3.1 (R Core Team, 2023).

2.4.2 Defining habitat areas for woodlands and grasslands

For the impact assessments for biodiversity, habitat distribution maps created under Defra contract AQ0826 were used. These maps define the areas of habitats sensitive to nitrogen pollution and were derived from a combination of UKCEH Land Cover Map 2000 (Fuller et al., 2002) and ancillary data sets, e.g. species data, Forestry Commission inventory data, National Vegetation Classification maps (Hall et al., 2015). It should be noted that these habitat distribution maps and areas were generated for use in UK critical loads research and only include areas where data exist for the calculation and derivation of critical loads; they may differ from other national habitat distribution maps or estimates of habitat areas. These maps provide habitat area data at 1km x 1km resolution and for this study, the area data were aggregated to 5km x 5km resolution. The habitat distributions used and corresponding species-based critical levels are provided in Table 2. For Northern Ireland there was a lack of data for mapping all of the different categories of woodland mapped for critical loads (Hall et al., 2015), and therefore woodland for this region is only mapped as either managed conifers or unmanaged mixed (conifer and/or broadleaf) woodland. This means there are no areas in Northern Ireland mapped as managed broadleaf or unmanaged beech woodland.

Table 2: Critical levels applied by habitat

Habitat distribution	Species-based critical level applied[1]	Critical level effect parameter[1]
Managed (productive) coniferous woodland	Norway spruce	Whole tree biomass
Managed (productive) broadleaf woodland	Beech and birch	Whole tree biomass
Unmanaged* beech woodland	Beech and birch	Whole tree biomass
Semi-natural grassland (comprising acid, calcareous and dune grassland)	Temperate perennial grassland	Flower number
Semi-natural grassland (comprising acid, calcareous and dune grassland)	Temperate perennial grassland	Total biomass

*"unmanaged" = "managed" for biodiversity or amenity, but not timber production
[1]See table 1

2.5 Calculating losses due to ozone

2.5.1 Crops

POD_6SPEC (wheat, oilseed rape and potato) data from the EMEP4UK model (at 5km x 5km resolution) were used to map the maximum potential yield loss for each crop, using the following formula and species-specific values in Table 1:

Yield loss = (POD_Y – Ref10 POD_Y) * % reduction per mmol m^{-2} POD_Y

Production loss (tonnes) was then calculated using the following equation:

Production loss = Production * (Yield loss/100)

Calculations were made at 1km x 1km scale, then production loss values (tonnes) were summed for each 5km x 5km cell, therefore maps are at 5km x 5km resolution.

Data on the economic value of crops in the UK were obtained from the Agriculture and Horticulture Development Board (AHDB, http://www.ahdb.org.uk/), with weekly mean values calculated across the year of 2019, to allow for the fluctuating nature of the crop prices. The average crop price (£ per tonne) was based on weekly delivered spot prices for wheat, for regions across England, Central Scotland and Northern Ireland (£159.75); weekly delivered spot price (average for regions in England and Scotland) for oilseed rape (£324.64); and weekly GB average prices (average of free-buy and contract purchases bought direct from growers) for potato (£184.20). Following the same methodology for 2020, the average weekly delivered spot price for wheat (£ per tonne) was £173.39 and for oilseed rape was £337.81; and weekly GB average prices for potato were £177.04. For potatoes, price data for both years were calculated from a sample of 22 purchasing companies across GB, including some in Scotland and Wales.

2.5.2 Trees and grassland

The percentage reduction in the annual increment of total biomass or flower number was calculated using the following formula:

% reduction = (POD_1SPEC – Ref10 POD_1SPEC) x rate of reduction (%)

The effects calculated in this way are indicative of the extent of risk.

3 Results

Note: All maps (Figures 2 - 21) are presented at the end of the results section to avoid breaking up the text.

3.1 Impacts of ozone on crop production in the UK in 2019 and 2020

Three major UK crops with a combined area of ~2.5 million hectares were considered in this study: wheat, potato and oilseed rape. Results are presented here for 2019 and 2020, using the new version of the EMEP model (version 4.36), and 2019 results are also compared with those from the previous model version (4.17).

Wheat

2019 (new model version)

Wheat is grown most extensively in England. In 2019, 44% was grown in areas exceeding the ozone critical level of 1.3mmol m^{-2}. The average yield loss was 4.1% and the loss in production was 711,000 tonnes with an economic value of £113.64 million (Table 3). In Wales, Scotland and N. Ireland, there were no areas where the critical level was exceeded (Table 3, Figure 2). Overall, our analysis indicated that 41% of the UK wheat production in 2019 was in areas where the critical level was exceeded. The average yield loss for the UK was 3.4% resulting in a production loss of 718,000 tonnes with an economic value of £114.68 million. The highest ozone fluxes in 2019 were in England, in the eastern counties of Lincolnshire, Norfolk, Suffolk and Cambridgeshire, and there were patches of higher values in the counties of Essex and Kent (Figure 2). The highest production losses were indicated for eastern counties of England, particularly Lincolnshire, Cambridgeshire, Norfolk and Suffolk (Figure 3). These were areas where ozone flux values above the critical level coincided with high levels of wheat production per 5km x 5km grid square (Figures 2&3). Economic losses were therefore also predicted to be highest in areas of eastern England (Fig 3).

Comparison between old and new model version (2019 data)

The results for wheat in 2019 using the older version of the EMEP model (version 4.17, Sharps et al., 2022) showed a similar spatial pattern in terms of the highest levels of ozone flux and yield losses being in eastern areas of England, however overall, the losses estimated using the newer version of the model were higher, for example, using (older) version 4.17, the area of critical level exceedance for the UK was 0.98%, average UK yield loss was 1.9% and total production losses were 389,000 tonnes. Using the newer model version, ozone flux values were slightly higher across much of central, southern and eastern England. The differences in flux value were not large, for example, more areas with values of 1.25 – 2.25 mmol m^{-2} in south-east England using version 4.36, whereas these areas had values of 1 – 1.75mmol m^{-2} using the older version. However, as the critical level for wheat is 1.3mmol m^{-2}, these changes led to greater areas of critical level exceedance with the newer model version.

2020 (new model version)

In 2020, wheat production and crop area in the UK were considerably lower than in 2019, (15876 thousand tonnes of wheat production in 2019 compared to 9396 thousand tonnes production in 2020; see Figs. 2-5). This is thought to be due to poor weather conditions at the time of planting, resulting in farmers planting more spring crops. Ozone flux levels were also higher in 2020 across much of England and Wales (Fig. 4), with 95% of the wheat grown in England grown in areas exceeding the critical level (Table 4). The average yield loss was 7.5% for England and the loss in production was 690,000 tonnes with an economic value of £119.75 million (Table 4). Critical levels were also exceeded in other parts of the UK in 2020 (57.9% of wheat area for Wales, 20.4% for Scotland and 10.4% for N. Ireland) (Table 4, Figure 4). The average yield loss for the UK was 6.8% resulting in a production loss of 723,000 tonnes with an economic value of £125.39 million. As wheat production was lower in 2020, total losses due to ozone weren't much greater than those estimated for 2019, however the difference in average estimated yield loss for the UK (3.4% in 2019 and 6.8% in 2020) shows that if wheat production had been higher, losses would also have been considerably higher). Whereas in 2019 ozone flux values were highest in the east of England, in 2020 values were highest across many areas of England and in parts of south Wales too (Fig. 4). This in turn led to potential yield losses for wheat of 7.5 – 10.5% across many areas of central and eastern England in 2020 (Fig. 4), compared to the highest yield loss estimates in 2019 being mostly 5 - 7.5% in easter and south-eastern England in 2019 (Fig. 2), with some very small patches of 7.5 – 10% losses in eastern counties such as Essex. In 2020, the highest production losses were indicated for eastern counties of England, particularly Cambridgeshire, Norfolk and Suffolk (Figure 5). These were areas where ozone flux values above the critical level coincided with high levels of wheat production per 5km x 5km grid square (Figures 4&5). Economic losses were therefore also predicted to be highest in areas of eastern England (Fig 5).

Table 3: Impacts of ozone on wheat in 2019, including critical level exceedance, production and economic losses, determined using POD_6SPEC.

Country	Wheat (POD_6SPEC)						
	Total area (ha)	Total area exceeding critical level (ha)	Exceeded area (%)	Production (thousand tonnes)	Production loss (thousand tonnes)	Yield loss (%, average)	Economic loss (£ Million)
England	1655397	734644	44.4	14831	711	4.1	113.64
Wales	22479	0	0	162	2.46	1.3	0.39
Scotland	102150	0	0	851	4.01	0.4	0.64
NI	6970	0	0	32	0.09	0.3	0.014
UK	1786996	734644	41.1	15876	717.86	3.4	114.68

Table 4: Impacts of ozone on wheat in 2020, including critical level exceedance, production and economic losses, determined using POD_6SPEC.

Country	Wheat (POD_6SPEC)						
	Total area (ha)	Total area exceeding critical level (ha)	Exceeded area (%)	Production (thousand tonnes)	Production loss (thousand tonnes)	Yield loss (%, average)	Economic loss (£ Million)
England	1249290	1185985	94.9	8542	690	7.5	119.75
Wales	20632	11948	57.9	111	5.50	4.7	0.95
Scotland	89241	18234	20.4	721	26.29	3.3	4.56
NI	6025	627	10.4	22	0.78	3.6	0.14
UK	1365187	1216794	89.1	9396	723.18	6.8	125.39

Potato

Potato is classed as moderately sensitive to ozone and is thus less sensitive than wheat (Mills et al., 2007).

2019 (new model version)

In 2019, using the newer version of the EMEP model, across the UK potato production areas, the mean yield loss was 4.3%, resulting in 219,000 lost tonnes of potato tubers worth £40.45 million. In England, 65% of the potato growing areas had ozone fluxes that exceeded the critical level of 3.8 mmol m^{-2}. Critical level exceedance for potato was 26.1% in Wales, with no exceedance in Scotland and N. Ireland (Table 5, Figure 6). The average yield loss in England was 5.5% and the loss in production was 200,000 tonnes with an economic value of £36.91 million (Table 5). The highest values for ozone flux were seen in eastern and southern England, and in patches of south-east Wales (Figure 6). However, areas with the highest levels of ozone flux often do not coincide with areas with high potato production. Maps show pockets of high potato production and economic losses, for example in parts of Norfolk, Cambridgeshire, Bedfordshire and Hertfordshire (Figure 7).

Comparison between old and new model version (2019 data)

As for wheat, ozone flux was on a similar scale using the two versions of the model but generally higher across the majority of the UK, particularly in eastern and south-eastern areas of the UK. The spatial pattern remained the same, i.e. the highest flux values were in the southern half of the UK. The area of critical level exceedance using the newer version of the model was considerably greater for England and Wales (65% compared to 2.5% for England), in comparison to the 2019 results for potato using the older model version (Sharps et al., 2022). Average yield loss for the UK was also greater using the newer version (4.3% compared to 2.6%) as was production loss (219,000 tonnes compared to 130,000 tonnes).

2020 (new model version)

For 2020, (version 4.36), the area exceeding the critical level for potatoes was higher for England (86%) and Wales (30%) compared to the results for 2019, while in Scotland and Northern Ireland, there was no exceedance of the critical level. The area of potato crop planted in the UK was slightly reduced in 2020 (Fig. 8), while total production was slightly increased, compared to 2019. In England, average yield loss due to ozone for potato was 6.3% in 2020, amounting to 240,000 tonnes of lost production, worth £42.51 million (Table 6). Across the UK potato production areas, the mean yield loss was 5.1%, resulting in 268,000 lost tonnes of potato tubers worth £47.50 million. Therefore, compared to 2019, total potato losses in the UK due to ozone were overall slightly higher in 2020. The highest values for ozone flux were seen for similar areas of England as in 2019 (Fig. 8), in eastern and southern areas. However, flux values were slightly higher in central England in 2020, leading to increased estimates of yield losses in this area (4-6% in 2019, 6-10% in 2020). As for 2019, areas with the highest levels of ozone flux often do not coincide with areas with high potato production and economic losses (Fig. 9) and maps show areas of high production and economic losses in parts of Norfolk, Cambridgeshire, Bedfordshire, Hertfordshire and North Yorkshire (Figure 9).

Table 5: Impacts of ozone on potato in 2019, including critical level exceedance, production and economic losses, determined using POD_6SPEC.

Country	Potato (POD_6SPEC)						
	Total area (ha)	Total area exceeding critical level (ha)	Exceeded area (%)	Production (thousand tonnes)	Production loss (thousand tonnes)	Yield loss (%, average)	Economic loss (£ Million)
England	97940	63808	65.1	3542	200.35	5.5	36.91
Wales	1936	505	26.1	31	1.37	4.3	0.25
Scotland	25058	0	0	960	16.25	1.6	2.99
NI	3415	0	0	107	1.60	1.5	0.296
UK	128350	64313	50.1	4640	219.57	4.3	40.45

Table 6: Impacts of ozone on potato in 2020, including critical level exceedance, production and economic losses, determined using POD_6SPEC.

Country	Potato (POD_6SPEC)						
	Total area (ha)	Total area exceeding critical level (ha)	Exceeded area (%)	Production (thousand tonnes)	Production loss (thousand tonnes)	Yield loss (%, average)	Economic loss (£ Million)
England	94654	81012	85.6	3680	240.14	6.3	42.51
Wales	1807	548	30.3	34	1.62	4.8	0.29
Scotland	25056	0	0	963	24.22	2.5	4.29
NI	3339	0	0	107	2.33	2.2	0.41
UK	124856	81560	65.32	4784	268.30	5.1	47.50

Oilseed rape

Oilseed rape is also classified as moderately sensitive to ozone. A critical level has not been approved for oilseed rape as the response function only includes data from one experiment conducted in Belgium. As the oilseed rape cultivar tested is commonly grown in the UK, we have provided maps showing the potential yield losses for this crop as a result of ozone in 2019 and 2020 (Figures 10-13).

2019 (new model version)

In 2019, using version 4.36, the average yield loss for the UK was estimated at 4.9%, amounting to 85,000 tonnes of lost production, worth £27.72 million (Table 7). Ozone flux values were highest in England, particularly in eastern counties, including Lincolnshire, Norfolk, Suffolk and Cambridgeshire (Figure 10). Oilseed rape growing in north-east Scotland primarily had potential yield losses of 2-4%, while in England and Wales, estimated yield losses were higher, between 4 and 7.5% (Figure 10). The highest production and economic losses (>100 tonnes and >£50,000 per 5km x 5km square respectively) were predicted for central/eastern England and parts of North Yorkshire, where higher levels of ozone flux coincided with areas of high oilseed rape production per 5km x 5km square (Figure 11).

Comparison between old and new model version (2019 data)

As for the other crops, spatially, the areas where the greatest losses in the country are predicted for oilseed rape remain the same using the two different versions of the model. However, in comparison to results for 2019 using the older model version, (Sharps et al., 2022), results using the newer version showed greater flux values and losses for oilseed rape, (average UK yield loss of 1.3% for version 4.17). This crop showed the greatest difference in flux values between the model versions, with maximum values of 1.25 – 2mmol m^{-2} for vr. 4.17 and 5 – 7 mmol m^{-2} for vr. 4.36. Estimated yield losses were more similar to potato and wheat using the newer model version. Total production losses for the UK using version 4.17 were 24,000 tonnes and economic losses were £7.78 million.

<u>2020 (new model version)</u>

In 2020, oilseed rape estimated yield losses due to ozone were increased further, however, as for wheat, production and planted area for this crop decreased compared to 2019. Therefore, while the average yield loss for the UK was estimated at 7.3%, total production and economic loss for the UK were slightly lower than estimates for 2019 (70,000 tonnes of lost production, worth £23.64 million) (Table 8). Ozone flux in 2020 was greater than in 2019 across many parts of the UK and was highest (7-9mmol m^{-2}) across eastern and southern England, as well as in parts of central England and south-west Wales (Fig.12). This is compared to 2019, when the highest flux values were 5-7mmol m^{-2} and were mostly found on the eastern side of England (Fig. 10). This in turn led to higher values for potential yield losses due to ozone, in the areas where oilseed rape crops are grown (Fig. 12), with the majority of grid squares in England showing estimates of 7.5-9.75% yield loss for this crop in 2020. This can be compared to 2019, where the highest yield loss estimates were 5-7.5%, primarily in areas of northern, central, eastern and south-eastern England (Fig. 10). In terms of production losses and economic losses due to ozone, maps for 2019 and 2020 are similar, with the highest losses found in areas where high crop production and high ozone flux coincide (Figs. 11&13), for example in parts of central and eastern England.

Table 7: Impacts of ozone on oilseed rape in 2019, including production and economic losses, determined using POD_6SPEC. Note: A critical level has not been derived for oilseed rape.

Country	Oilseed rape (POD_6SPEC)						
	Total area (ha)	Total area exceeding critical level (ha)	Exceeded area (%)	Production (thousand tonnes)	Production loss (thousand tonnes)	Yield loss (%, average)	Economic loss (£ Million)
England	499404	NA	NA	1567	82.10	5.1	26.66
Wales	5458	NA	NA	8	0.32	3.9	0.10
Scotland	30412	NA	NA	82	2.95	3.6	0.96
NI	663	NA	NA	NA	NA	NA	NA
UK	535938	NA	NA	1657	85.37	4.9	27.72

NA: Not applicable

Table 8: Impacts of ozone on oilseed rape in 2020, including production and economic losses, determined using POD_6SPEC. Note: A critical level has not been derived for oilseed rape.

Country	Oilseed rape (POD_6SPEC)						
	Total area (ha)	Total area exceeding critical level (ha)	Exceeded area (%)	Production (thousand tonnes)	Production loss (thousand tonnes)	Yield loss (%, average)	Economic loss (£ Million)
England	338725	NA	NA	845	66.66	7.9	22.52
Wales	3311	NA	NA	3	0.25	7.2	0.085
Scotland	29508	NA	NA	80	3.06	3.8	1.03

NI	693	NA	NA	NA	NA	NA	NA
UK	372239	NA	NA	928	69.97	7.3	23.64

3.2 Impacts of ozone on broad habitats in the UK in 2019 and 2020

Using the updated version of the EMEP model, critical level exceedance was determined for managed broadleaf woodland, unmanaged beech woodland, managed coniferous woodland and (semi-)natural grasslands, represented by acid, calcareous and dune grassland.

Managed broadleaf woodlands

This habitat is widespread across the UK, with most counties having some grid squares with 5-10% cover, and some regions such as southern counties of England (Hampshire, Surrey and West Sussex) having large forested areas with 10 - 20%, and sometimes >30% land cover for this habitat type (Figure 14).

2019 (new model version)

In 2019, using version 4.36 of the EMEP model, the ozone critical level of 5.2 mmol m^{-2} was exceeded in 100% of the area of this habitat in England, Wales and Scotland (Table 9a). Therefore, the overall exceeded area for the UK was 100%, with an average indicative biomass increment loss of 15.7%. The level of ozone flux (and therefore exceedance) was greatest for woodland areas in south-west England (Cornwall and Devon), patches of the south-west coast of Wales and in south-east England (Kent) (Figure 14). Predicted biomass increment loss was highest in south-west England (18-22%), with other patches of high losses, for example in south-west Wales and south-east England (Figure 14). Estimated losses were lowest in Scotland, with values of 10-12% predicted for Northern Scotland.

Comparison between old and new model version (2019 data)

Exceedance of the critical level was widespread across the country using the older version of the model (e.g. 100% in England and 99.7% in Wales), therefore there was not a great difference between the model versions in this respect. Also, as for the other vegetation types, the spatial pattern of ozone flux levels, critical level exceedance and biomass losses was the same across the UK for both model versions, with the lowest values in the north of Scotland, and the highest levels in the south-west of England. However, ozone flux values and therefore biomass increment losses for managed broadleaf were considerably higher using the newer version of the EMEP model compared to the previous model version. This was the case across the UK. The average biomass increment loss for this habitat for the UK increased from 6.9% to 15.7% using the newer model version (7.4% to 16.6% for England).

2020 (new model version)

In 2020, losses were on a similar scale to those predicted for 2019 using the newer version of the model. The area of managed broadleaf woodland where the critical level was exceeded was 100% for England, Wales and Scotland, and the average indicative biomass increment loss was 16% (Table 10a). As for 2019, the level of ozone flux was greatest for woodland areas in the south - west of England and Wales, with patches of high values in south-east England (Fig. 15), but the higher flux values also reached into central England in 2020, and also areas of eastern England (Norfolk, Lincolnshire) and areas of central and north Wales. The critical level of 5.2 mmol m^{-2} for POD_1SPEC was exceeded across the country in both years, with the highest values >20 mmol m^{-2}. The maps for critical level exceedance and average biomass increment loss follow the same pattern as for ozone flux, with values in Scotland very similar to 2019, but higher values in some parts of England and Wales (Fig. 15).

Unmanaged beech woodland

This relatively sparsely located habitat can be found (mostly <5% of the grid square area) in pockets across Wales and England, particularly in south-east England where the percentage area per square is slightly higher (5-20%) (Figure 16).

2019 (new model version)

Using the newer version of the EMEP model, in 2019, the ozone critical level was exceeded in 100% of the area of this habitat in England, Wales and Scotland (Table 9b). For the UK overall, the average indicative biomass increment loss was 17%. The level of exceedance was greatest in the south-west of England, where in some areas biomass increment losses of 18 - 22% were predicted (Figure 16).

Comparison between old and new model version (2019 data)

For both model versions, critical level exceedance for this habitat was 100% for England, Wales and Scotland. The areas of the UK where the estimated losses were highest also remained the same for both versions of the model - south-west and south-east England and south-west Wales (Fig. 16). However, ozone flux levels and biomass increment losses were considerably greater using version 4.36 compared to the previous model version, across the UK. Using the older version of the model, the average biomass increment loss was 7.6% (7.7% for England, 7.6% for Wales and 7.2% for Scotland) (Sharps et al., 2022).

2020 (new model version)

In 2020, losses were on a similar scale to those predicted for 2019 using the newer version of the model. The area of unmanaged broadleaf woodland where the critical level was exceeded was 100% for England, Wales and Scotland, and the average indicative biomass increment loss was 17.4% (Table 10b). For the different nations, losses were slightly higher in Wales in 2020, compared to 2019, at 17.4% compared to 16.8%, whereas for Scotland the losses were slightly lower in 2020 (16.2% in 2019, 15.7% in 2020). As for managed broadleaf woodland, flux values in 2020 were higher in parts of central and eastern England, and areas of central and north Wales (Fig. 17). As this habitat is more sparse than managed broadleaf woodland, these higher levels of flux only impacted critical level exceedance and biomass losses in certain parts of the UK. Biomass losses (%) were higher in 2020 in patches of south-west England (Gloucestershire, Wiltshire, Somerset), in south-east Wales, and in east/south-east England (Buckinghamshire, Bedfordshire and Hertfordshire), going from 16 - 18% in 2019 to 18 - 22% in 2020 (Figs. 16&17).

Managed coniferous woodland

As coniferous species are less sensitive to ozone than broadleaf species, the critical level is higher at 9.2 mmol m^{-2}. Using the new version of the EMEP model for 2019, the critical level was exceeded for 99.9% (England), 99.8% (Wales), 61.3% (Scotland) and 82.1% (N. Ireland) of managed coniferous woodland area in the UK (Table 9c,

Figure 18). Average indicative biomass increment losses were much lower than for broadleaf woodland, with all estimated losses being below ≤ 2.5%.

2019 (new model version)

In 2019, the majority of grid squares in England and Wales suggested predicted losses of 2.25 – 3.25%, with the highest losses in the south-west of England and Wales (Fig. 18). In Northern Ireland, the majority of losses were estimated at 2.25%, while losses in Scotland were highest in the south (2.25 – 2.75%) and lowest in the north (≤ 1.75%).

Comparison between old and new model version (2019 data)

When the results for 2019 were compared between model versions, the biggest difference was that the critical level was not exceeded in any part of the UK for the version 4.17, whereas the updated model suggested exceedance of the critical level in many areas across the UK. Ozone flux values were considerably higher using the new model version, however as this habitat type is not as sensitive to ozone, this did not have as great an impact on % biomass increment loss as for deciduous trees. When estimates of losses were compared, there was only a slight difference, with 1.3% (UK average) for version 4.17 and 2.3% for the updated model version. The spatial pattern of biomass losses was also similar between the two model versions, with the lowest values in the north of Scotland, and the highest in the south-west of England and Wales.

2020 (new model version)

In 2020, ozone impacts on coniferous woodland were estimated to be very similar to those in 2019. The critical level was exceeded for 99.9% (England), 99.8% (Wales), 61.1% (Scotland) and 92.6% (N. Ireland) of managed coniferous woodland area in the UK (Table 10c, Figure 19). Comparison of the flux maps for the two years for this habitat show that ozone flux values were slightly higher in 2020 across many parts of England (for example, central and eastern areas) and Wales (Figs.18&19). This in turn led to higher values for biomass losses in these areas of the UK for example many grid squares in central England with estimated losses increasing from 2.25 – 2.5% to 2.5–2.75% in 2020. Losses estimated for this habitat are still considerably lower than for broadleaf habitat. Overall, the average indicative biomass increment losses values were slightly higher in 2020 in England (2.7% compared to 2.5%) and Wales (2.7% compared to 2.5%), however the overall average for the UK was 2.4%, only 0.1% higher than in 2019 (Tables 9c &10c).

Table 9: Impacts of ozone on woodland habitats in the UK in 2019, determined using POD_1SPEC for beech and birch (applied to managed broadleaf woodland and unmanaged beech woodland) and Norway spruce (applied to managed coniferous woodland).

Country	(a) Managed broadleaf woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	556341	556341	100	16.6
Wales	80621	80621	100	16.6
Scotland	108705	108705	100	13.3
NI	NA	NA	NA	NA
UK	745667	745667	100	15.7

Country	(b) Unmanaged Beech woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	58053	58053	100	17.1
Wales	5821	5821	100	16.8
Scotland	312	312	100	16.2
NI	NA	NA	NA	NA
UK	64186	64186	100	17
Country	(c) Managed coniferous woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	171274	171053	99.9	2.5
Wales	105263	105001	99.8	2.5
Scotland	511583	313355	61.3	2.1
NI	50148	41151	82.1	2.2
UK	838268	630560	75.2	2.3

Table 10: Impacts of ozone on woodland habitats in the UK in 2020, determined using POD_1SPEC for beech and birch (applied to managed broadleaf woodland and unmanaged beech woodland) and Norway spruce (applied to managed coniferous woodland).

Country	(a) Managed broadleaf woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	556341	556341	100	17.2
Wales	80621	80621	100	17.2
Scotland	108705	108705	100	13
NI	NA	NA	NA	NA
UK	745667	745667	100	16
Country	(b) Unmanaged Beech woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	58053	58053	100	17.5
Wales	5821	5821	100	17.4
Scotland	312	312	100	15.7
NI	NA	NA	NA	NA
UK	64186	64186	100	17.4
Country	(c) Managed coniferous woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	171274	171274	99.9	2.7
Wales	105263	105263	99.8	2.7
Scotland	511583	511583	61.1	2.1
NI	50148	50148	92.6	2.2
UK	838268	838268	75.8	2.4

(Semi-) natural grasslands (acidic, calcareous and dune)

It is important to note that the critical levels for grassland are set at an effect of 10%, which is higher than the effect levels for other vegetation types (5% for crops, 4% for broadleaf trees and 2% for coniferous trees). This is because the response functions for grassland are less robust due to the greater inter-species variation in response to ozone (See Section 4.1) and lower effect values are not currently justified.

Grassland - flowering

2019 (new model version)

In 2019, the ozone critical level for flowering of ozone-sensitive grassland species (6.6 mmol m^{-2}) was exceeded in England (48.6%) and Wales (1.9%), with no exceedance of the critical levels in Scotland or Northern Ireland, and an average value of 15.68% for the UK (Table 11a, Figure 20).The indicative risk analysis suggested an average of 7.6% loss in flower number for the UK, with the highest losses (13-15%) occurring mostly in areas of eastern and south-east England (Figure 20). This could potentially affect plant species composition and/or diversity.

Comparison between old and new model version (2019 data)

When the results for 2019 are compared between the two model versions, the values for critical level exceedance and average % flower number losses were slightly higher for the updated model version (4.36), with an average loss for the UK of 6.3% for version (4.17) (Sharps et al., 2022). For the older model version, the critical level was also only exceeded in England (32%). Ozone flux levels for the two model versions were on a similar scale for this habitat, but were generally higher across the UK, particularly in south-east England (Fig. 20; Sharps et al., 2022). However, the ozone impacts followed a similar spatial pattern across the UK, with values increasing from the north to the south of the UK, and the highest values in the south-east of England.

2020 (new model version)

In 2020, the area of critical level exceedance (for % flower number) for perennial grassland was greater than in 2019, with 52.3% for England, 13.8% for Wales, 0.3% for Scotland and 0.1% for Northern Ireland, and an average value of 19.1% for the UK (Table 12a). The average % flower number losses were also greater in 2020, compared to 2019, for all nations (Tables 11a, 12a), with an average of 8.5% loss in flower number for the UK in 2020. Maps indicated that ozone flux values were slightly higher in many parts of the UK in 2020 compared to 2019, particularly in central and southern England (Figs. 20&21). This led to higher values for critical level exceedance across central/southern England and also greater values for % flower number losses in this area. For example, increases in critical level exceedance from <1 in 2019 to 2-3.5 in 2020, and increases in % flower number losses from 11-13% in 2019 to 13.15.5% in 2020.

Grassland – total biomass

2019 (new model version)

The critical level for effects of ozone on grassland annual increment of total biomass is higher at 16.2 mmol m^{-2} and, using the new version of the EMEP model for 2019, was not exceeded anywhere for this habitat in the UK (Table 11b; maps not presented). Hence, biomass losses were well below 10% (as defined by the critical level), with an average value of 2.2% for the UK.

Comparison between old and new model version (2019 data)

When the 2019 results were compared between model versions, the critical level was not exceeded for either version, and the average total biomass losses (%) for the UK were slightly higher using the new version (2.2% for version 4.36 and 1.5% for version 4.17).

2020 (new model version)

In 2020, the critical level was still not exceeded in any area of the UK, and the average biomass losses were similar to 2019, with an average UK value of 2.5% (Table 12b).

Table 11: Impacts of ozone on (a) flowering and (b) total biomass of grassland habitats in the UK in 2019, determined using POD_1SPEC for ozone-sensitive grassland species, and including the broad habitats of acid, calcareous and dune grassland.

Country	(a) Grassland flower number			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	603884	293239	48.6	10.4
Wales	334078	6411	1.9	7.8
Scotland	846649	188	0	4.6
NI	126405	0	0	6.4
UK	1911016	299838	15.68	7.6
Country	(b) Grassland total biomass			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	603884	0	0	3.1
Wales	334078	0	0	2.2
Scotland	846649	0	0	1.2
NI	126405	0	0	1.7
UK	1911016	0	0	2.2

Table 12: Impacts of ozone on (a) flowering and (b) total biomass of grassland habitats in the UK in 2020, determined using POD_1SPEC for ozone-sensitive grassland species, and including the broad habitats of acid, calcareous and dune grassland.

Country	(a) Grassland flower number			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	603909	315800	52.3	11.3
Wales	334078	46174	13.8	9.3
Scotland	848417	2839	0.3	5.3
NI	126408	127	0.1	7.6
UK	1912812	364941	19.1	8.5
Country	(b) Grassland total biomass			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	603790	0	0	3.5
Wales	334078	0	0	2.8

Scotland	848092	0	0	1.5
NI	126408	0	0	2.1
UK	1912368	0	0	2.5

3.3 Results summary

Comparison between ozone impact results for 2019 using different model versions

When the results between the two EMEP model versions were compared (using 2019 data), spatial patterns of ozone impacts were similar across the UK, i.e. areas with the greatest impact were in similar locations for both model versions, for all vegetation types. There were some differences between the 2019 results for the two model versions when looking at % losses and critical level exceedance, and the extent of this varied with vegetation type. The results using the newer model version (4.36) showed increased ozone impacts (flux, critical level exceedance and losses) when compared with the older version (4.17). This was most pronounced for broadleaf trees, (in terms of annual biomass increment losses). Ozone flux values were also greater for crops using the newer model version, which led to greater critical level exceedance (for wheat and potato) and greater estimates of production and economic losses, particularly for oilseed rape. Differences in ozone impact between the model versions were less pronounced for coniferous woodland and semi-natural grasslands.

Comparison between 2019 and 2020 results (using the new EMEP model version)

The results for 2019 and 2020 (using the newer model version 4.36) showed that there was not a big difference between years in terms of ozone impacts. The new model showed slightly higher fluxes in 2020 compared to 2019. Over the period 2014 to 2019 (which was only considered with the previous model version), 2019 was a low/medium year, and so it is likely that 2020 was a medium year compared to others in the 2014 – 2020 timespan. Generally, values were slightly higher for all vegetation types in 2020 compared to 2019, for example, ozone fluxes were higher in 2020 than in 2019. This in turn led to critical level exceedances also being higher, which was particularly noticeable for wheat (and potato to lesser extent). The vegetation type with the greatest differences between the 2019 and 2020 results was crops.

3.4 Ozone impacts maps for crops, trees and grasses

Wheat (POD_6SPEC for grain yield)

(Note: Where possible, map scales have been kept the same as for the previous 2019 report for comparison purposes).

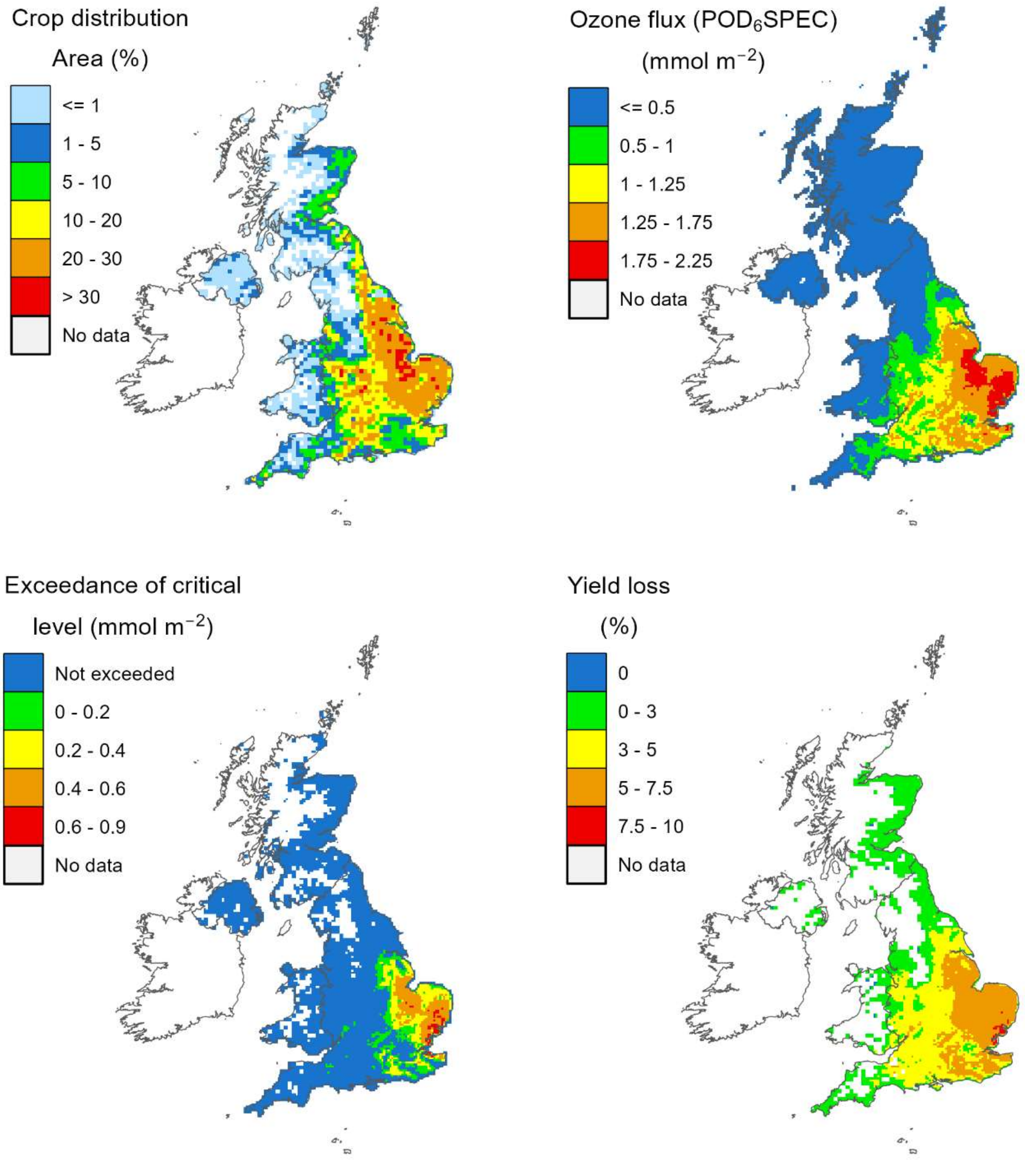

Figure 2: Impacts of ozone on wheat production in 2019 calculated using POD_6SPEC (EMEP model 4.36). (a) Distribution of wheat presented as the percentage of each 5km x 5km grid square sown with wheat; (b) POD_6SPEC (mmol m^{-2}) (**critical level = 1.3 mmol m^{-2}**); (c) Exceedance of the critical level; (d) Percentage yield loss.

Wheat (POD_6SPEC for grain yield)

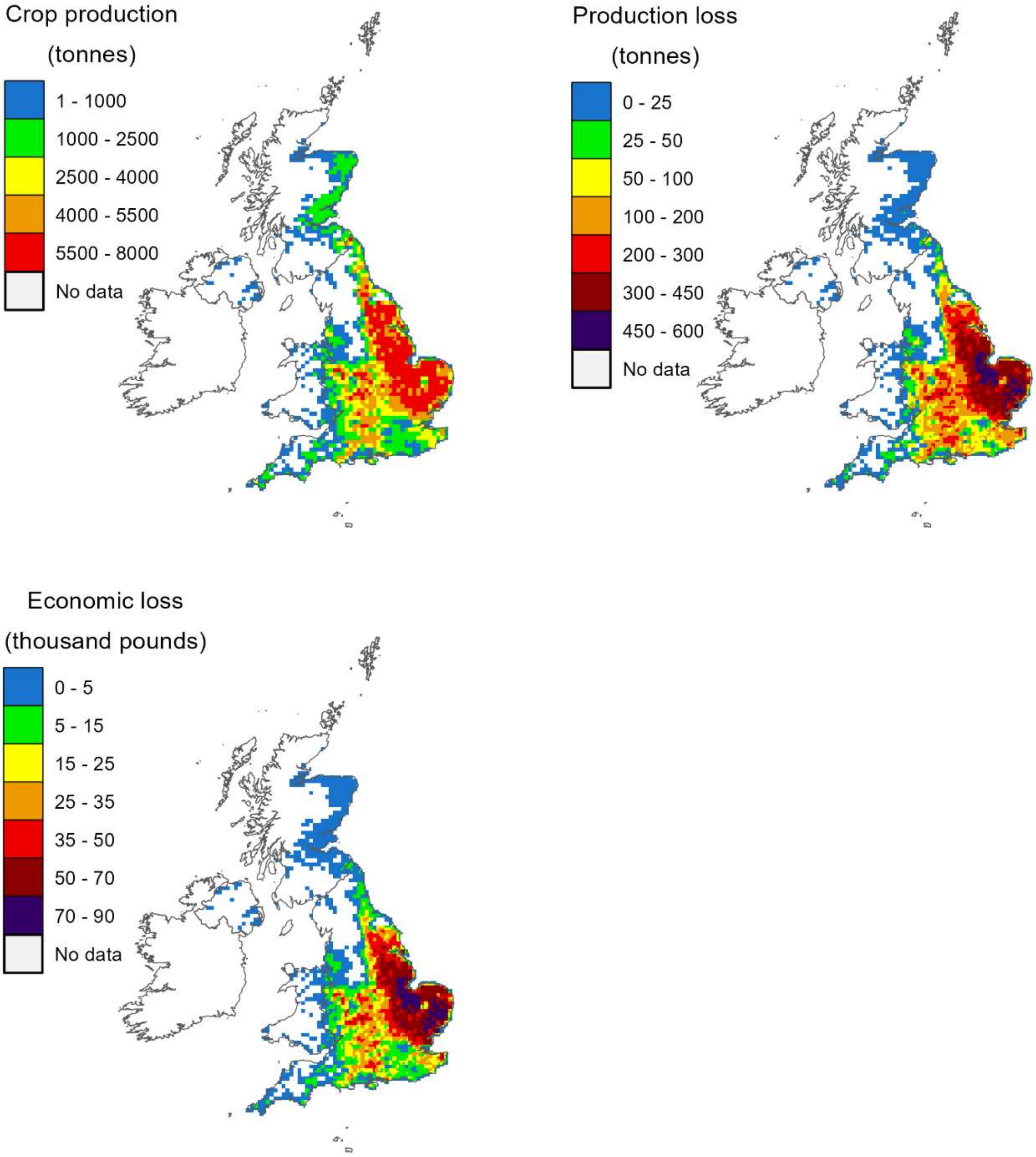

Figure 3: Impacts of ozone on wheat production in 2019 calculated using POD_6SPEC (EMEP model 4.36). (a) Wheat production in the UK in tonnes per 5km x 5km grid square; (b) Production loss due to ozone in tonnes per 5km x 5km grid square; and (c) Economic loss in thousand £UK per 5km x 5km grid square, based on mean price in 2019.

Wheat (POD_6SPEC for grain yield)

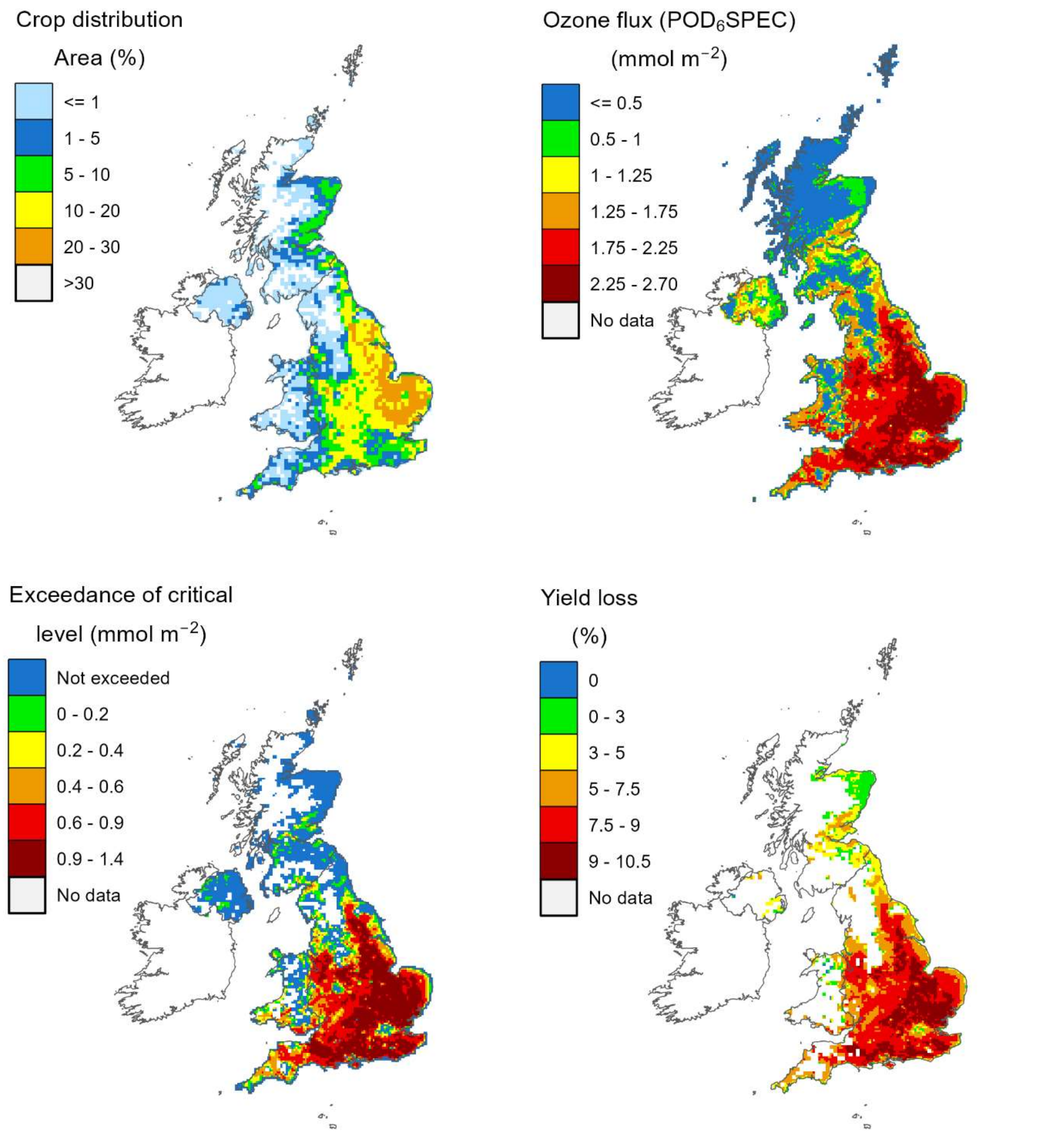

Figure 4: Impacts of ozone on wheat production in 2020 calculated using POD_6SPEC (EMEP model 4.36). (a) Distribution of wheat presented as the percentage of each 5km x 5km grid square sown with wheat; (b) POD_6SPEC (mmol m^{-2}) (**critical level = 1.3 mmol m^{-2}**); (c) Exceedance of the critical level; (d) Percentage yield loss.

Wheat (POD_6SPEC for grain yield)

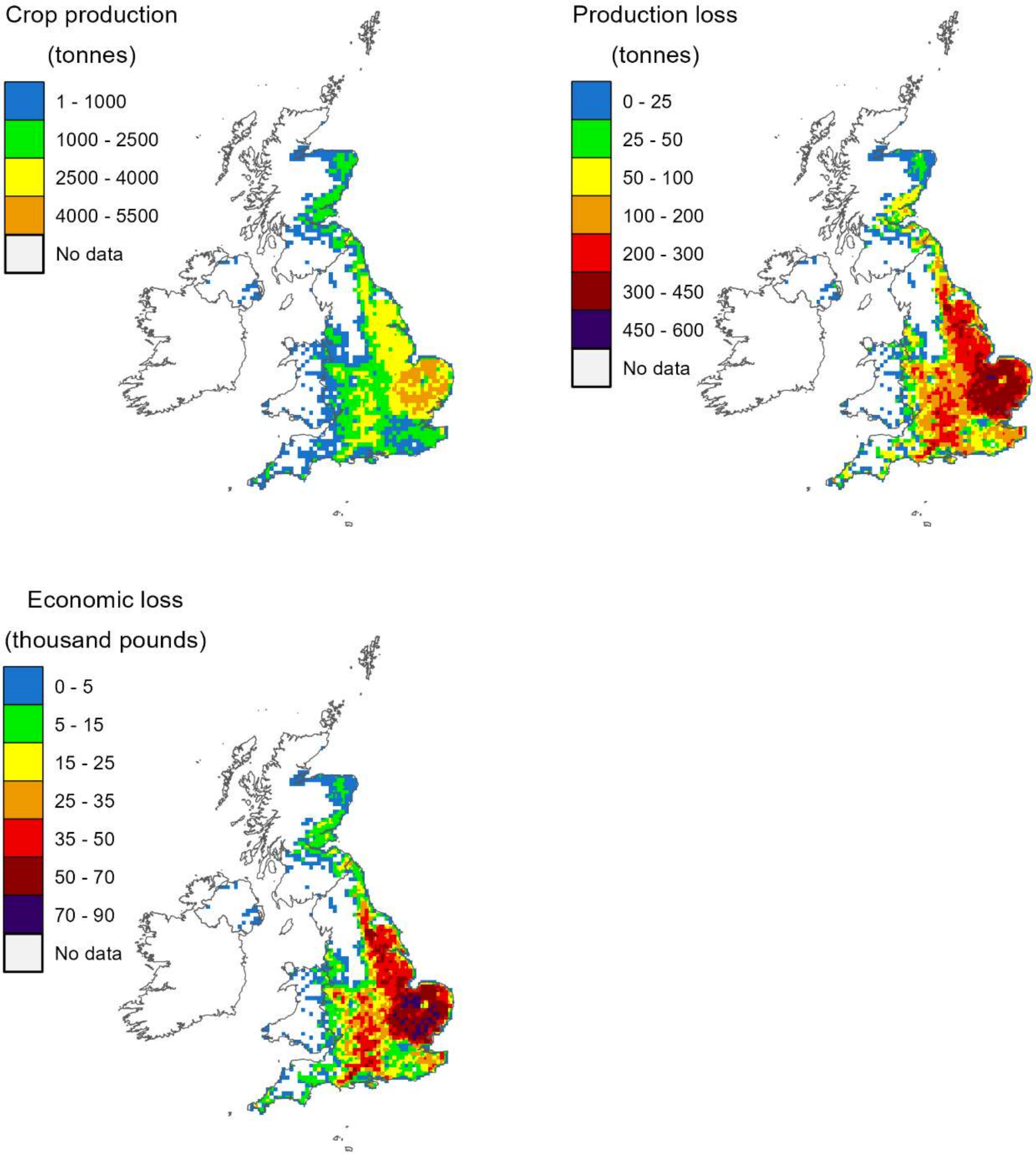

Figure 5: Impacts of ozone on wheat production in 2020 calculated using POD_6SPEC (EMEP model 4.36). (a) Wheat production in the UK in tonnes per 5km x 5km grid square; (b) Production loss due to ozone in tonnes per 5km x 5km grid square; and (c) Economic loss in thousand £UK per 5km x 5km grid square, based on mean price in 2020.

Potato (POD_6SPEC for tuber yield)

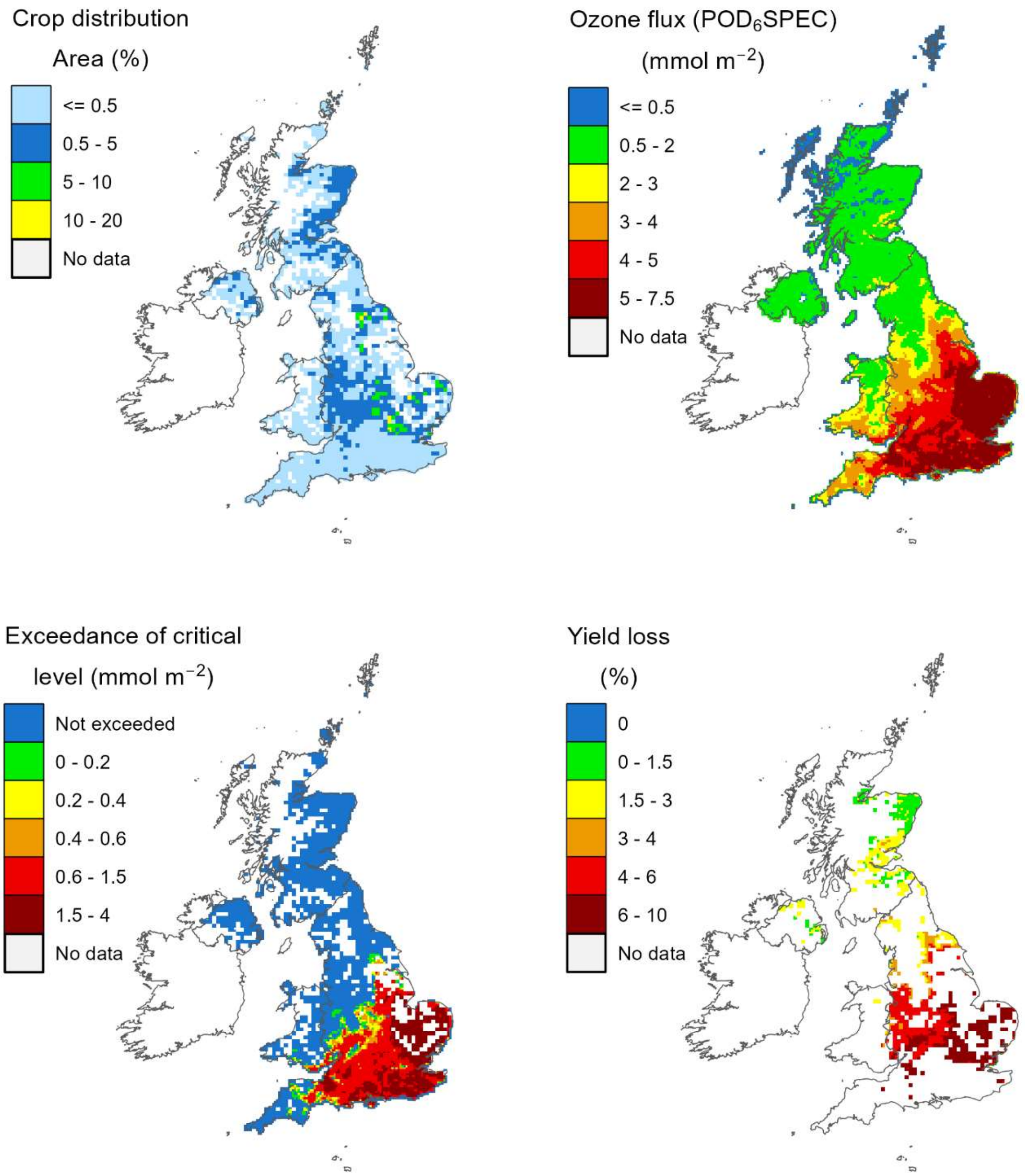

Figure 6: Impacts of ozone on potato production in 2019 calculated using POD_6SPEC (EMEP 4.36). (a) Distribution of potato presented as the percentage of each 5km x 5km grid square sown with potato; (b) POD_6SPEC (mmol m^{-2}) (**critical level = 3.8 mmol m^{-2}**); (c) Exceedance of the critical level; (d) Percentage yield loss.

Potato (POD_6SPEC for tuber yield)

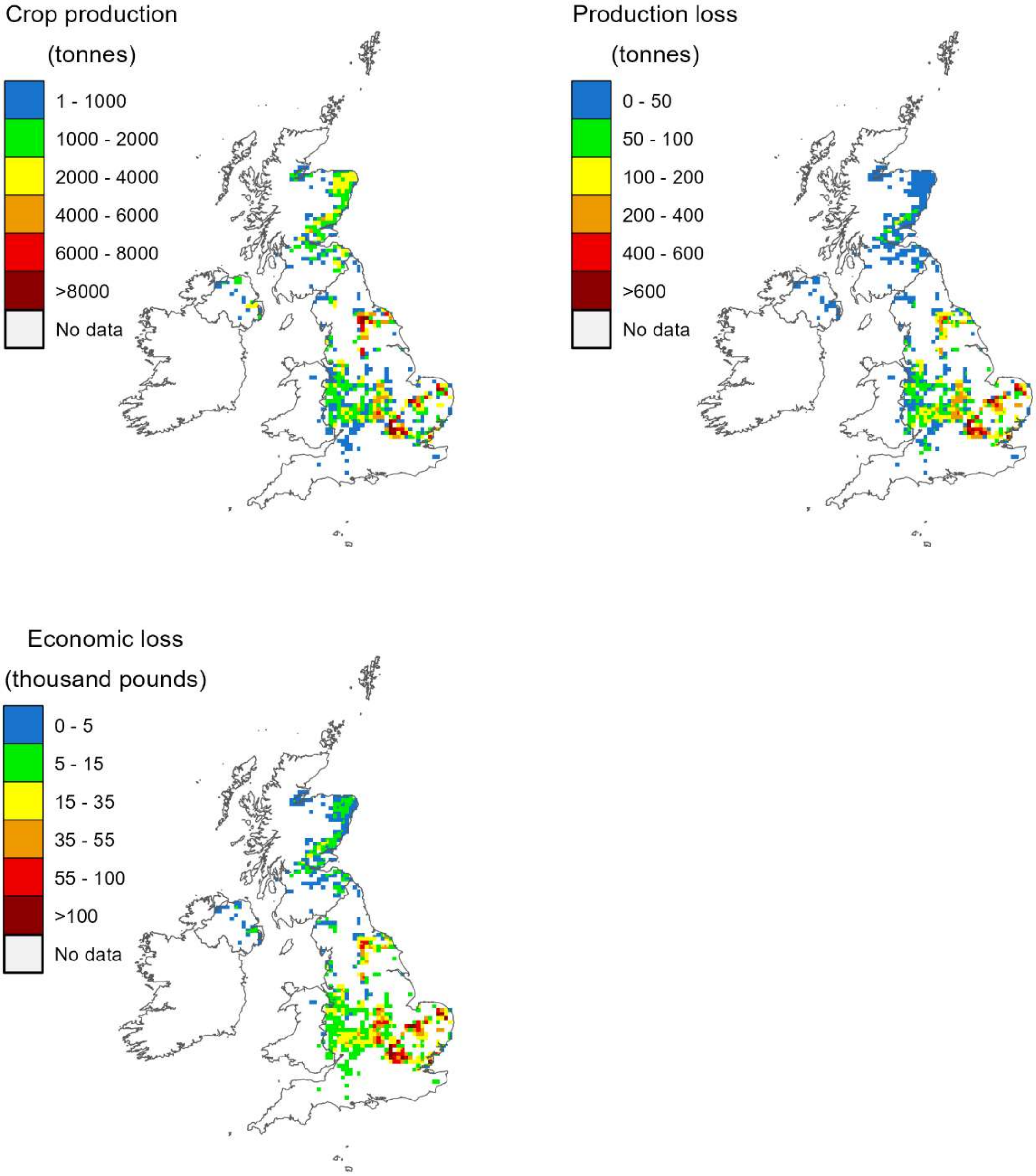

Figure 7: Impacts of ozone on potato production in 2019 calculated using POD_6SPEC (EMEP 4.36). (a) Potato production in the UK in tonnes per 5km x 5km grid square; (b) Production loss due to ozone in tonnes per 5km x 5km grid square; and (c) Economic loss in thousand UK£ per 5km x 5km grid square, based on mean price in 2019.

Potato (POD_6SPEC for tuber yield)

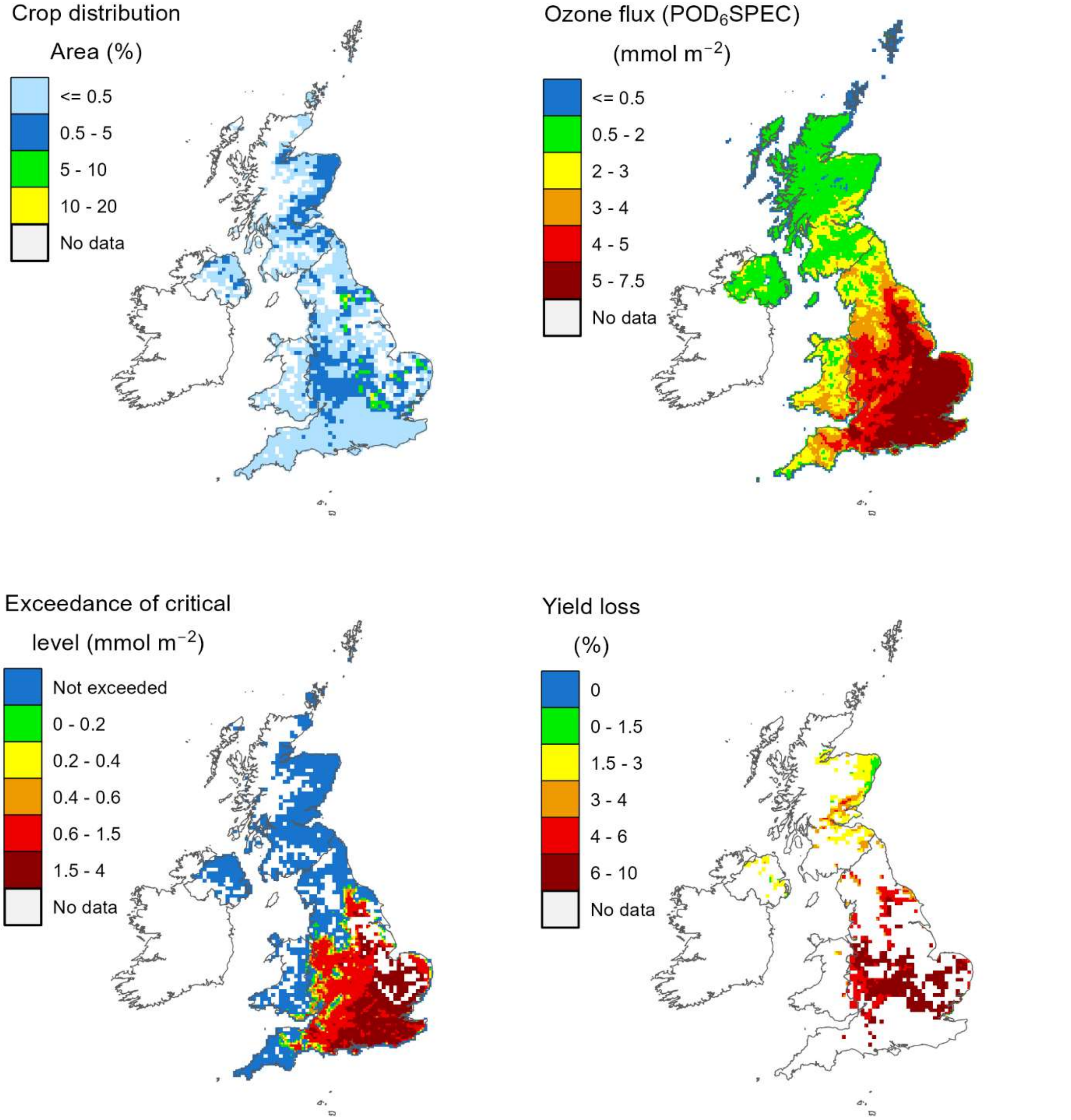

Figure 8: Impacts of ozone on potato production in 2020 calculated using POD_6SPEC (EMEP 4.36). (a) Distribution of potato presented as the percentage of each 5km x 5km grid square sown with potato; (b) POD_6SPEC (mmol m^{-2}) (**critical level = 3.8 mmol m^{-2}**); (c) Exceedance of the critical level; (d) Percentage yield loss.

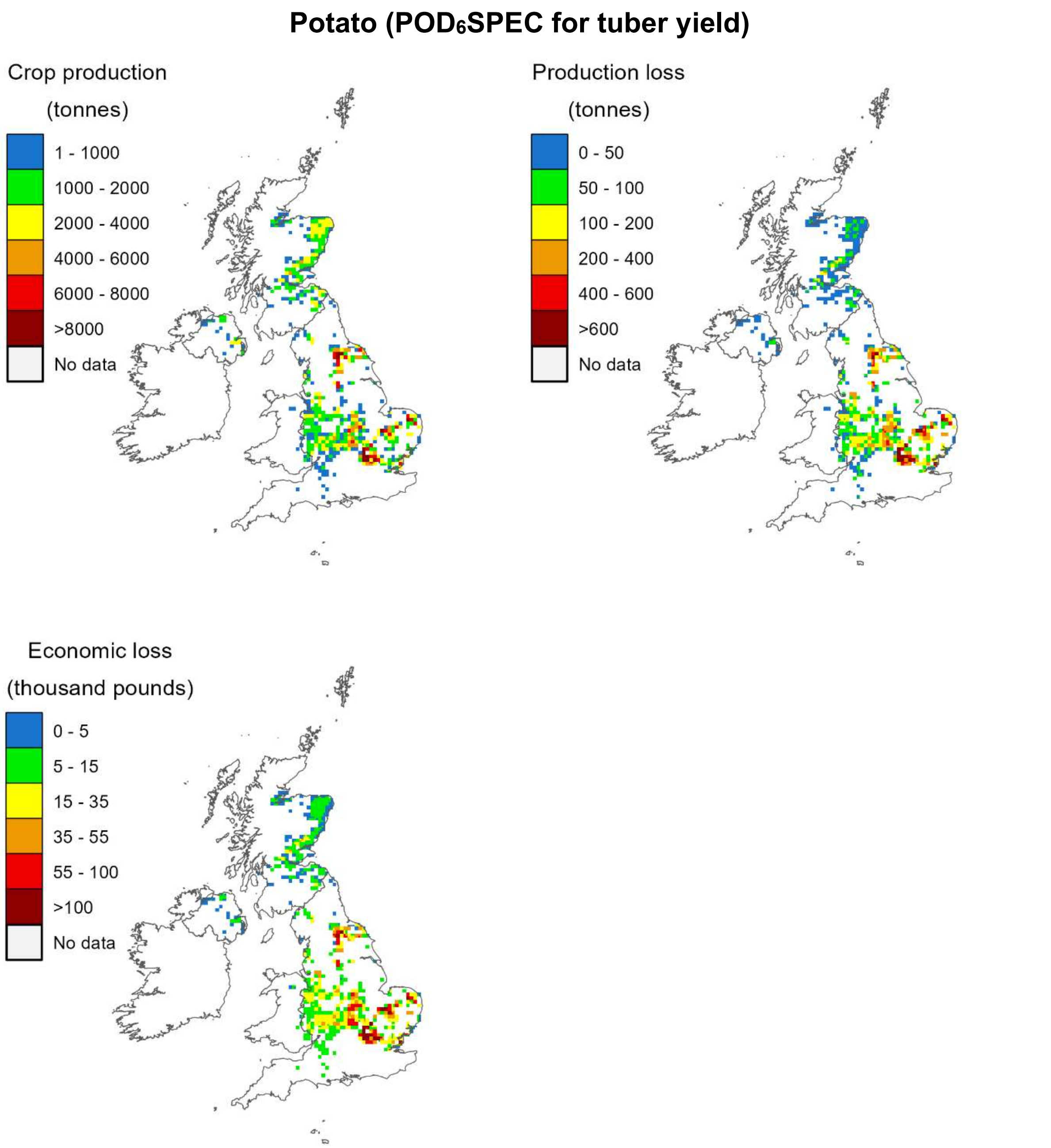

Figure 9: Impacts of ozone on potato production in 2020 calculated using POD_6SPEC (EMEP 4.36). (a) Potato production in the UK in tonnes per 5km x 5km grid square; (b) Production loss due to ozone in tonnes per 5km x 5km grid square; and (c) Economic loss in thousand UK£ per 5km x 5km grid square, based on mean price in 2020.

Oilseed rape (POD_6SPEC for grain yield)

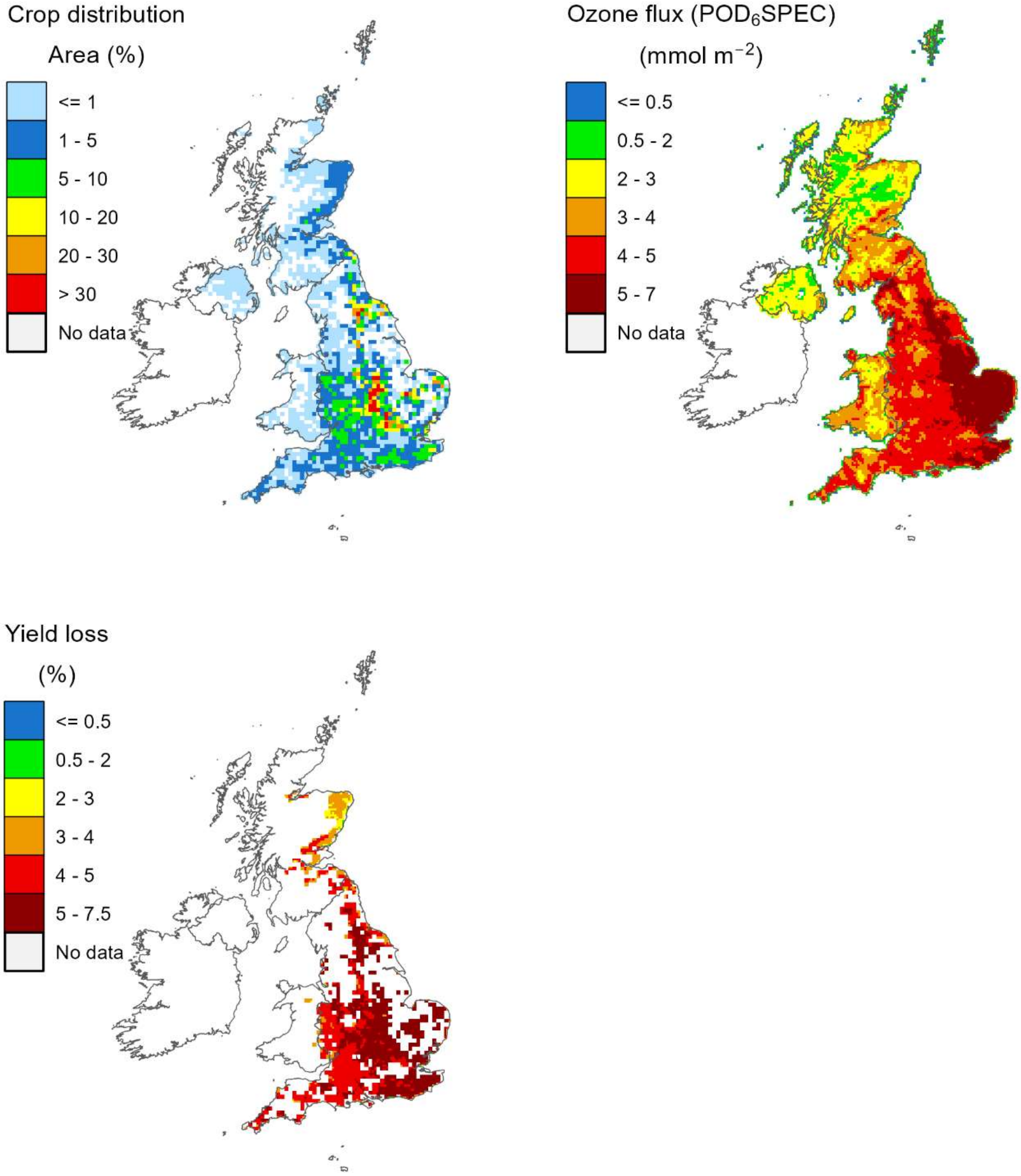

Figure 10: Impacts of ozone on oilseed rape production in 2019 calculated using POD_6SPEC (EMEP 4.36). (a) Distribution of oilseed rape presented as the percentage of each 5km x 5km grid square sown with oilseed rape; (b) POD_6SPEC (mmol m^{-2}); (c) Percentage yield loss.

Oilseed rape (POD_6SPEC for grain yield)

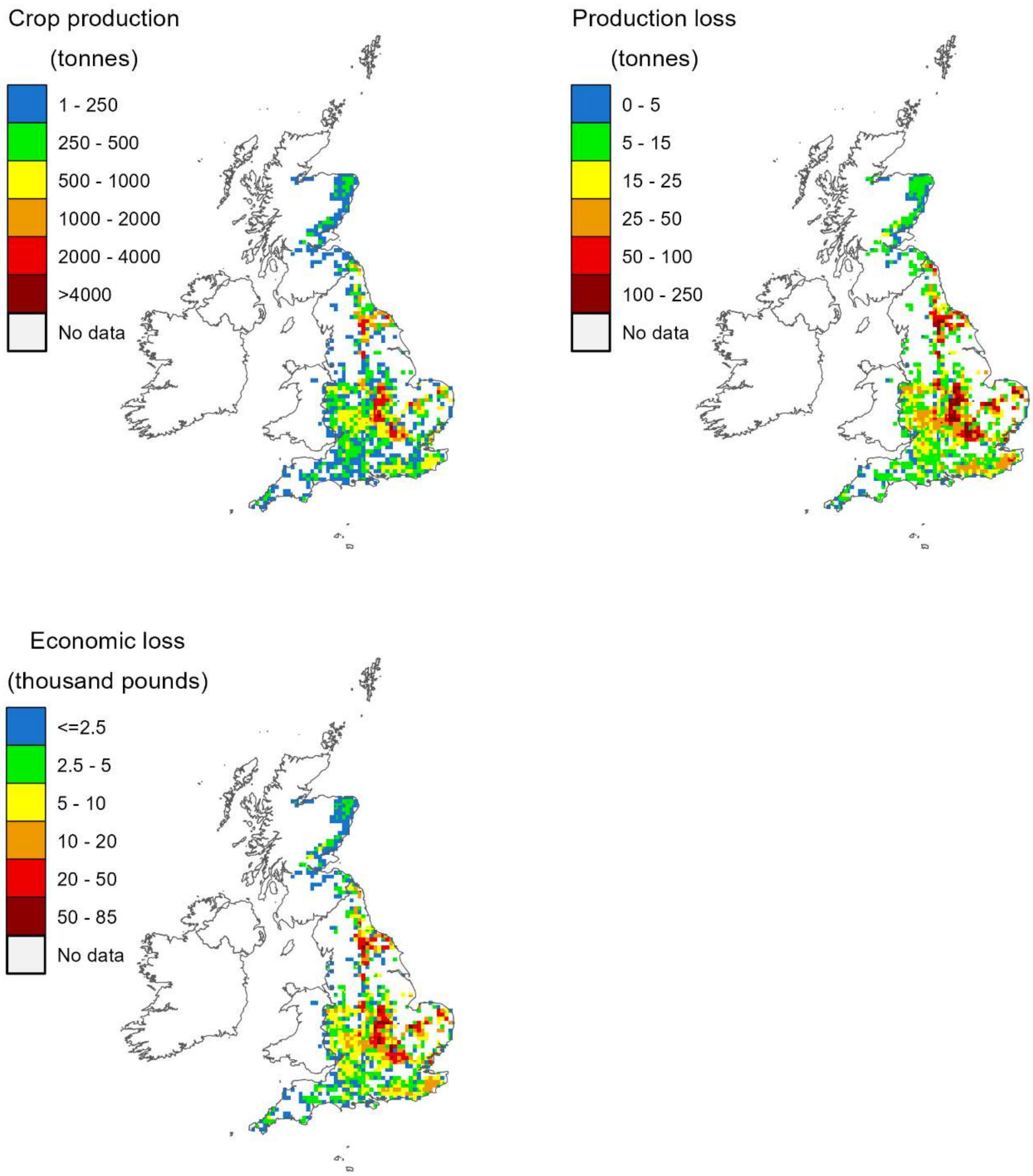

Figure 11: Impacts of ozone on oilseed rape production in 2019 calculated using POD_6SPEC (EMEP 4.36). (a) Oilseed rape production in the UK in tonnes per 5km x 5km grid square; (b) Production loss due to ozone in tonnes per 5km x 5km grid square; and (c) Economic loss in thousand UK£ per 5km x 5km grid square, based on mean price in 2019.

Oilseed rape (POD_6SPEC for grain yield)

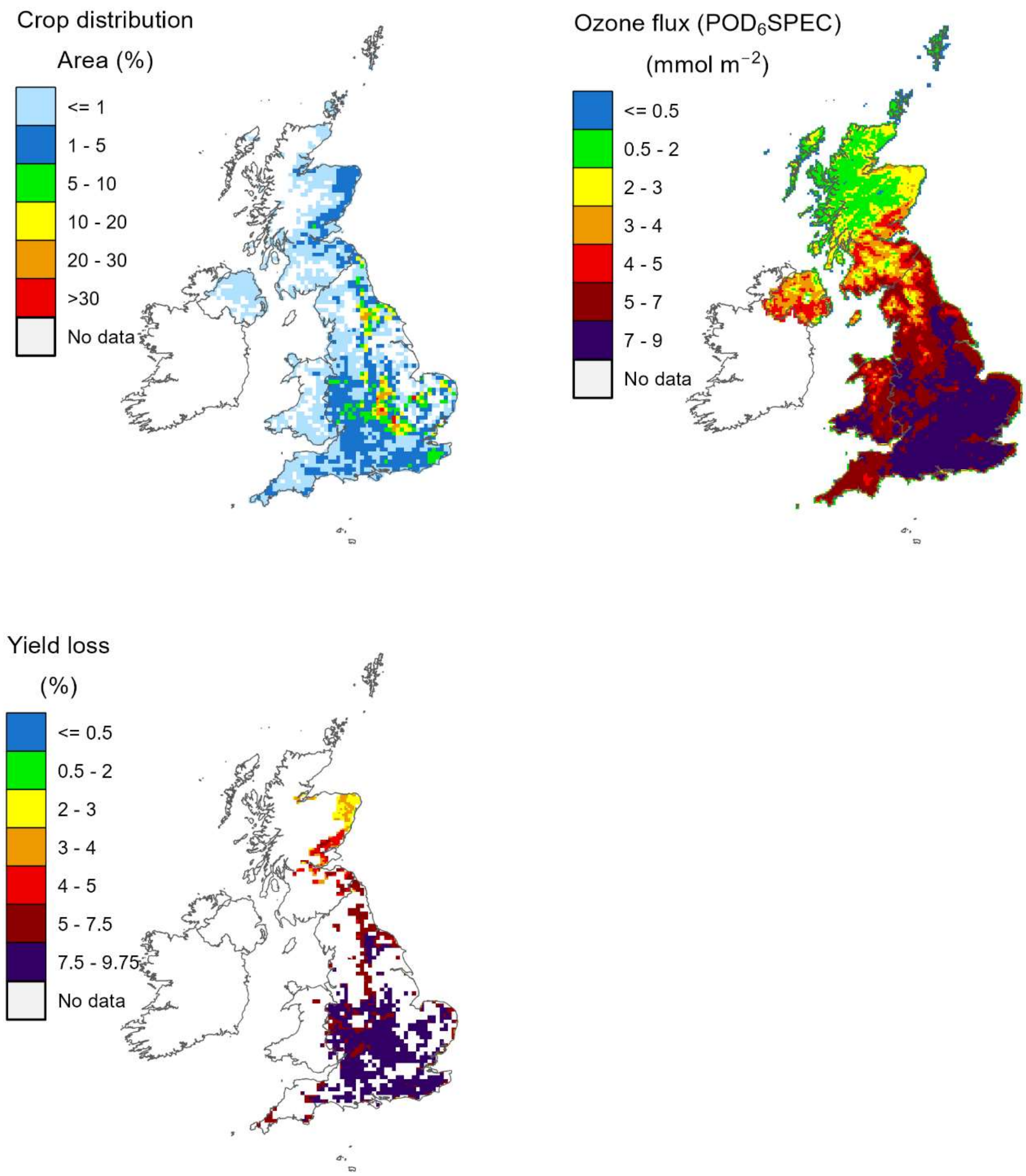

Figure 12: Impacts of ozone on oilseed rape production in 2020 calculated using POD_6SPEC (EMEP 4.36). (a) Distribution of oilseed rape presented as the percentage of each 5km x 5km grid square sown with oilseed rape; (b) POD_6SPEC (mmol m^{-2}); (c) Percentage yield loss.

Oilseed rape (POD_6SPEC for grain yield)

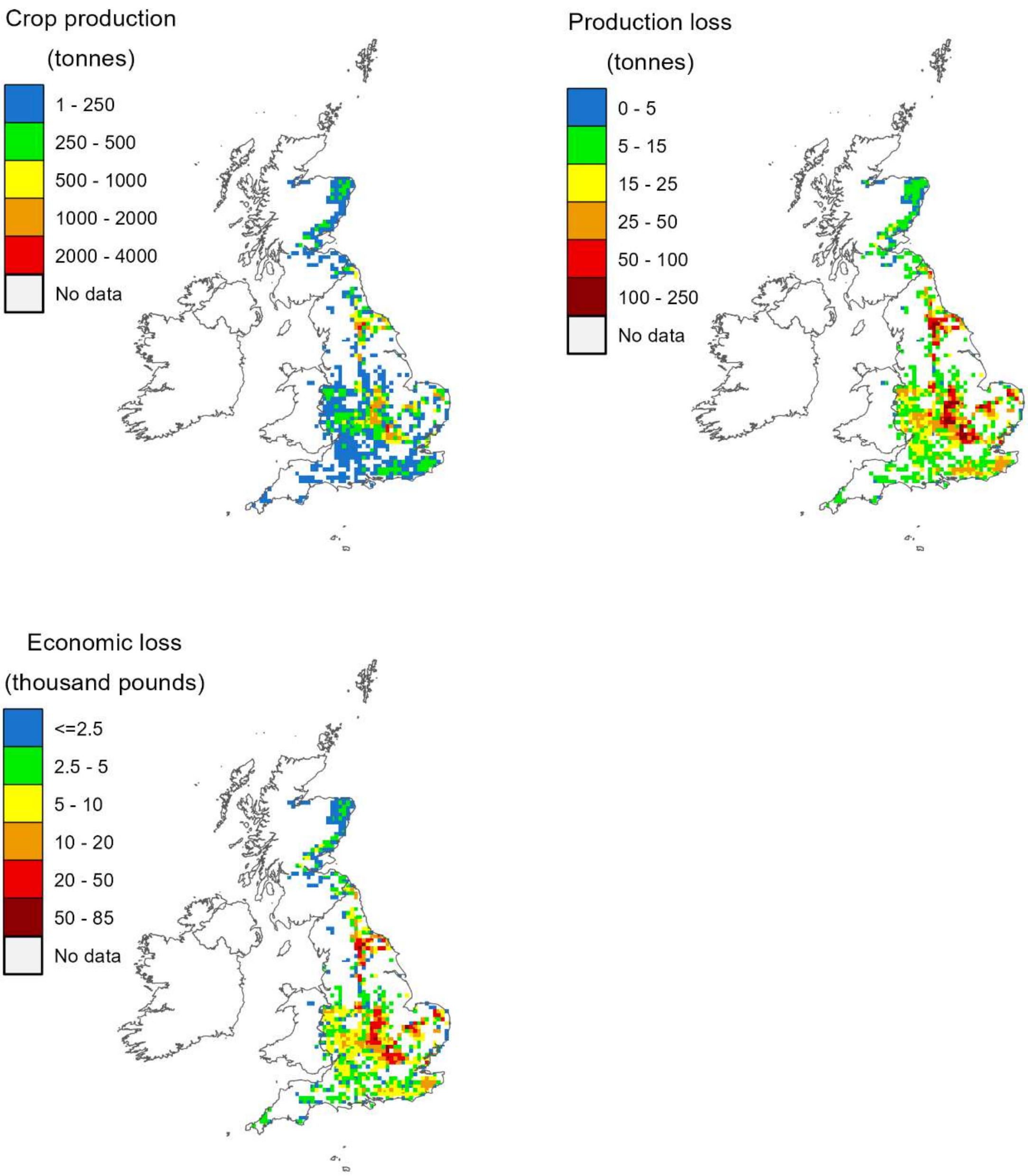

Figure 13: Impacts of ozone on oilseed rape production in 2020 calculated using POD_6SPEC (EMEP 4.36). (a) Oilseed rape production in the UK in tonnes per 5km x 5km grid square; (b) Production loss due to ozone in tonnes per 5km x 5km grid square; and (c) Economic loss in thousand UK£ per 5km x 5km grid square, based on mean price in 2020.

Managed broadleaved woodland (POD_1SPEC for biomass increment)

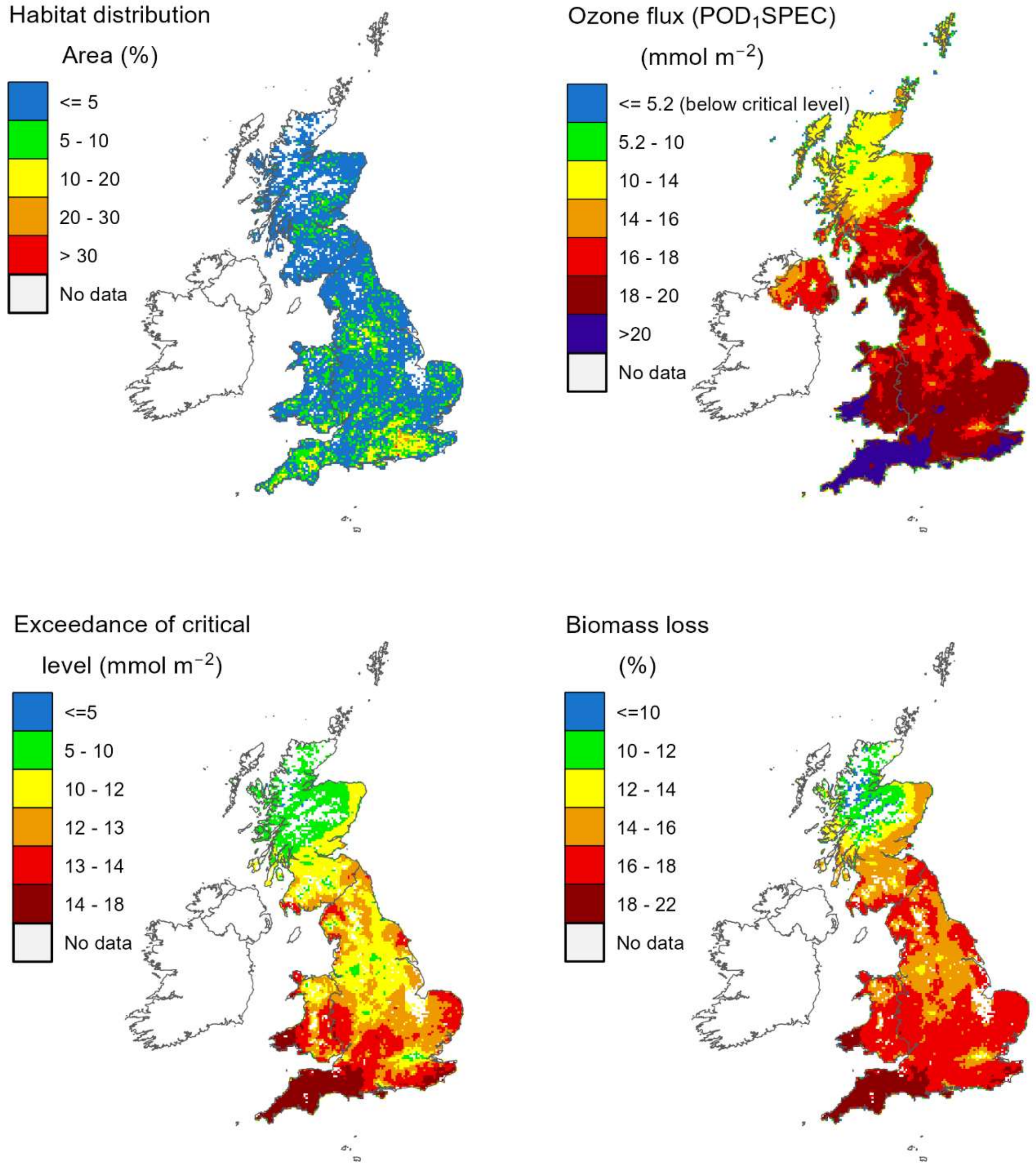

Figure 14: Impacts of ozone on managed broadleaf woodland in 2019 calculated using POD_1SPEC (EMEP 4.36). (a) Distribution of managed broadleaf woodland as the percentage area of each 5km x 5km grid square; (b) POD_1SPEC (mmol m^{-2}), all squares coloured blue have POD_1SPEC values below the **critical level of 5.2 mmol m^{-2}**; (c) exceedance of the critical level; (d) Percentage biomass loss (indicative risk only).

Managed broadleaved woodland (POD_1SPEC for biomass increment)

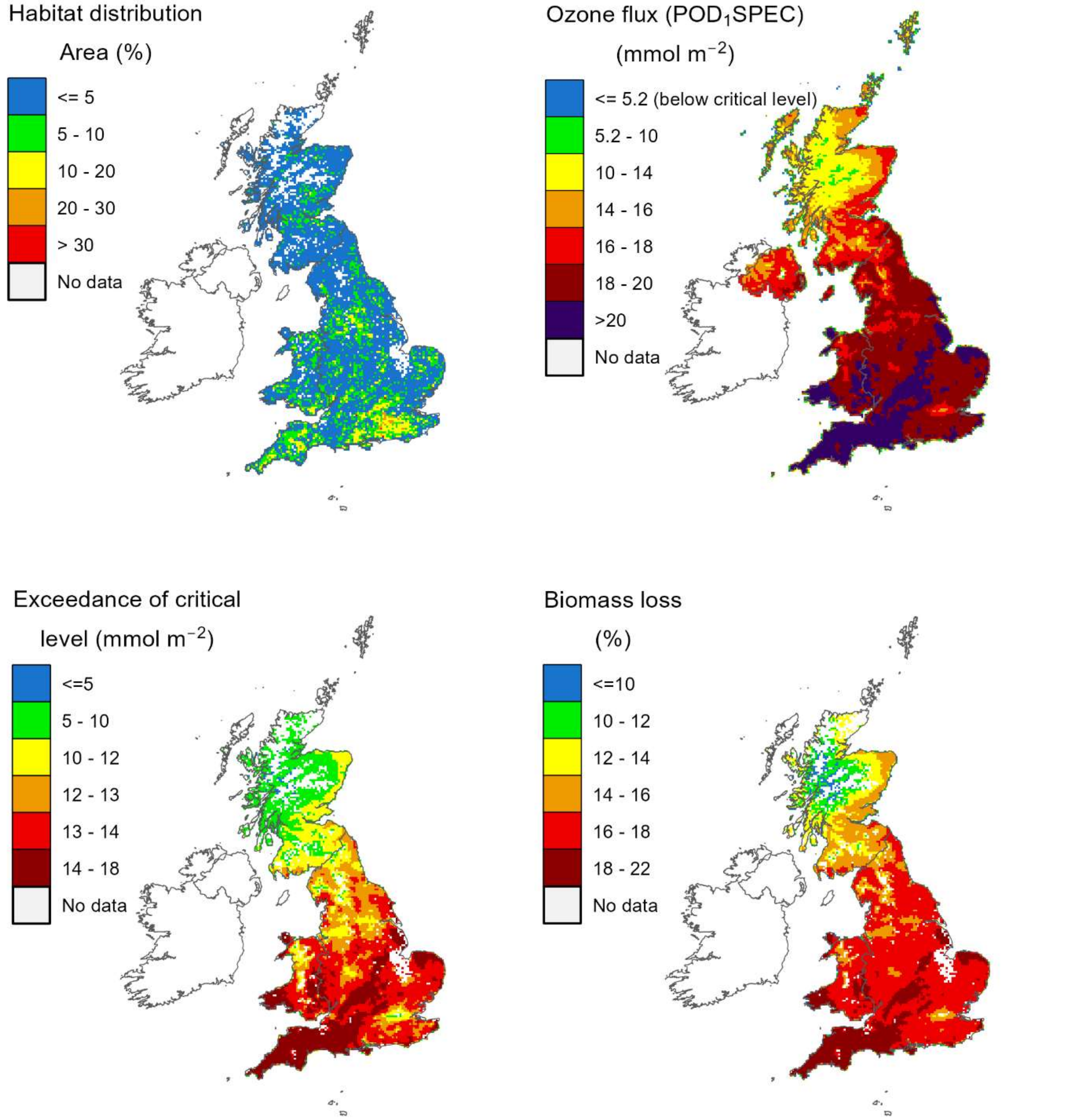

Figure 15: Impacts of ozone on managed broadleaf woodland in 2020 calculated using POD_1SPEC (EMEP 4.36). (a) Distribution of managed broadleaf woodland as the percentage area of each 5km x 5km grid square; (b) POD_1SPEC (mmol m^{-2}), all squares coloured blue have POD_1SPEC values below the **critical level of 5.2 mmol m^{-2}**; (c) exceedance of the critical level; (d) Percentage biomass loss (indicative risk only).

Unmanaged Beech woodland (POD_1SPEC for biomass increment)

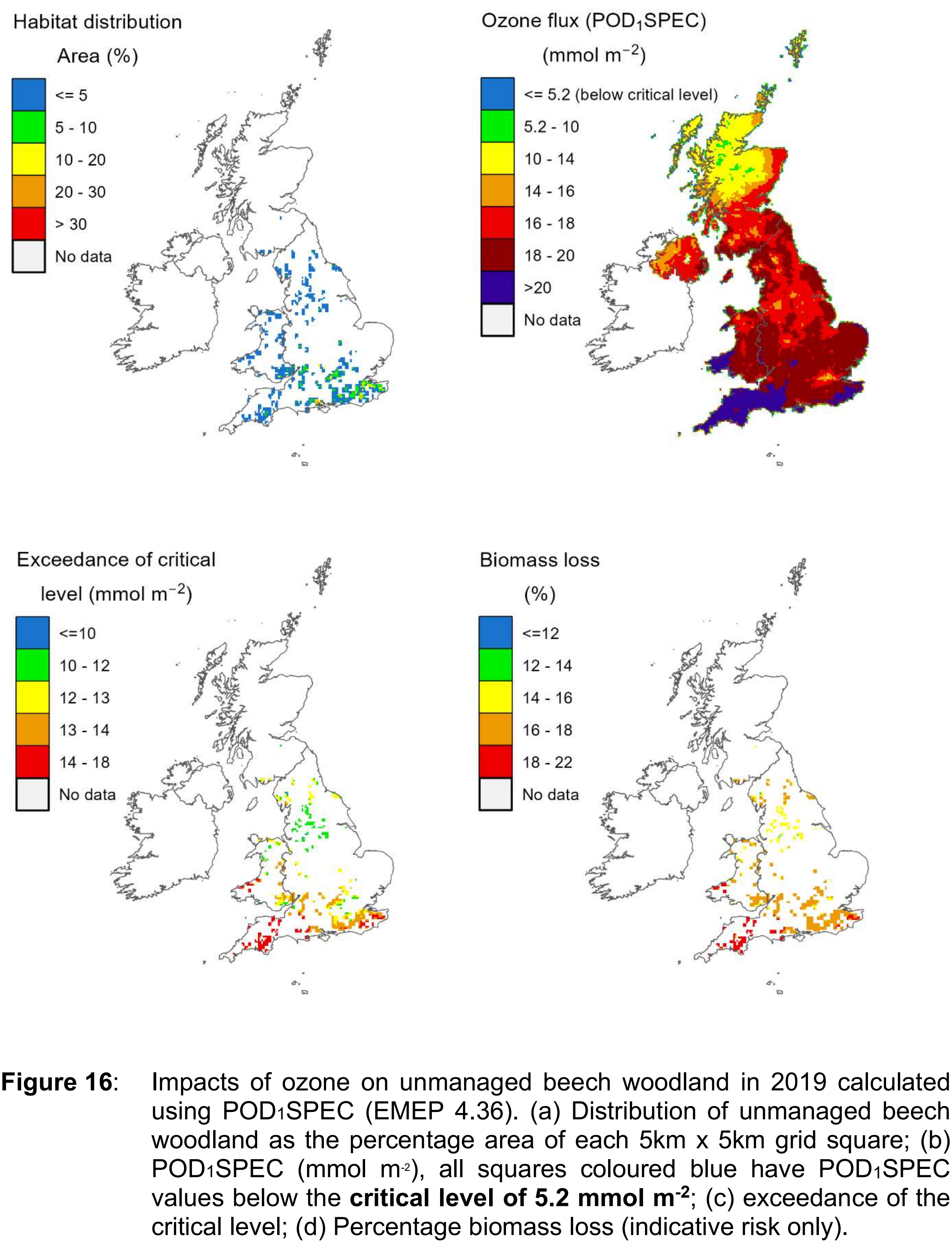

Figure 16: Impacts of ozone on unmanaged beech woodland in 2019 calculated using POD_1SPEC (EMEP 4.36). (a) Distribution of unmanaged beech woodland as the percentage area of each 5km x 5km grid square; (b) POD_1SPEC (mmol m^{-2}), all squares coloured blue have POD_1SPEC values below the **critical level of 5.2 mmol m^{-2}**; (c) exceedance of the critical level; (d) Percentage biomass loss (indicative risk only).

Unmanaged Beech woodland (POD_1SPEC for biomass increment)

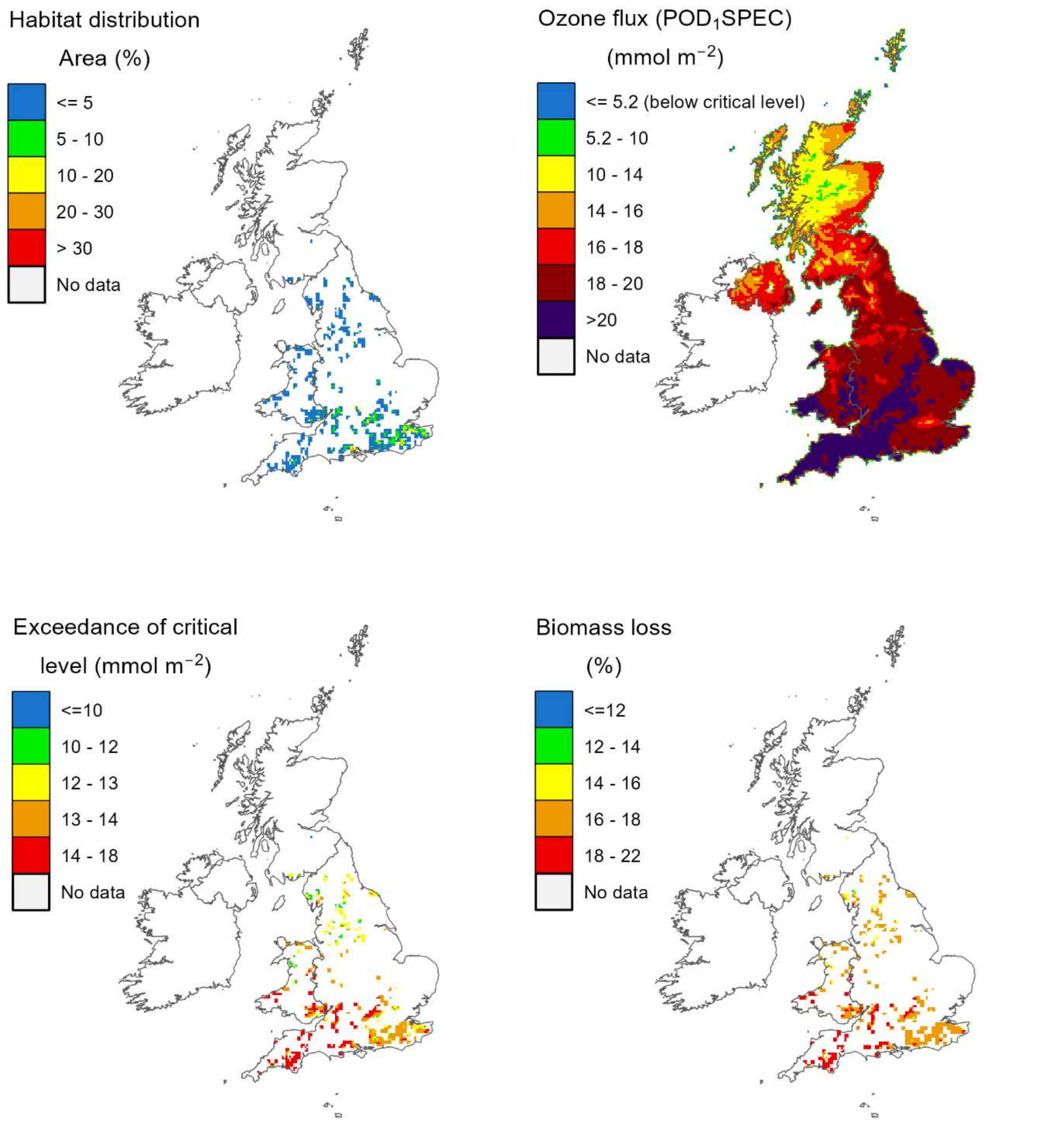

Figure 17: Impacts of ozone on unmanaged beech woodland in 2020 calculated using POD_1SPEC (EMEP 4.36). (a) Distribution of unmanaged beech woodland as the percentage area of each 5km x 5km grid square; (b) POD_1SPEC (mmol m^{-2}), all squares coloured blue have POD_1SPEC values below the **critical level of 5.2 mmol m^{-2}**; (c) exceedance of the critical level; (d) Percentage biomass loss (indicative risk only).

Managed coniferous woodland (POD$_1$SPEC for biomass increment)

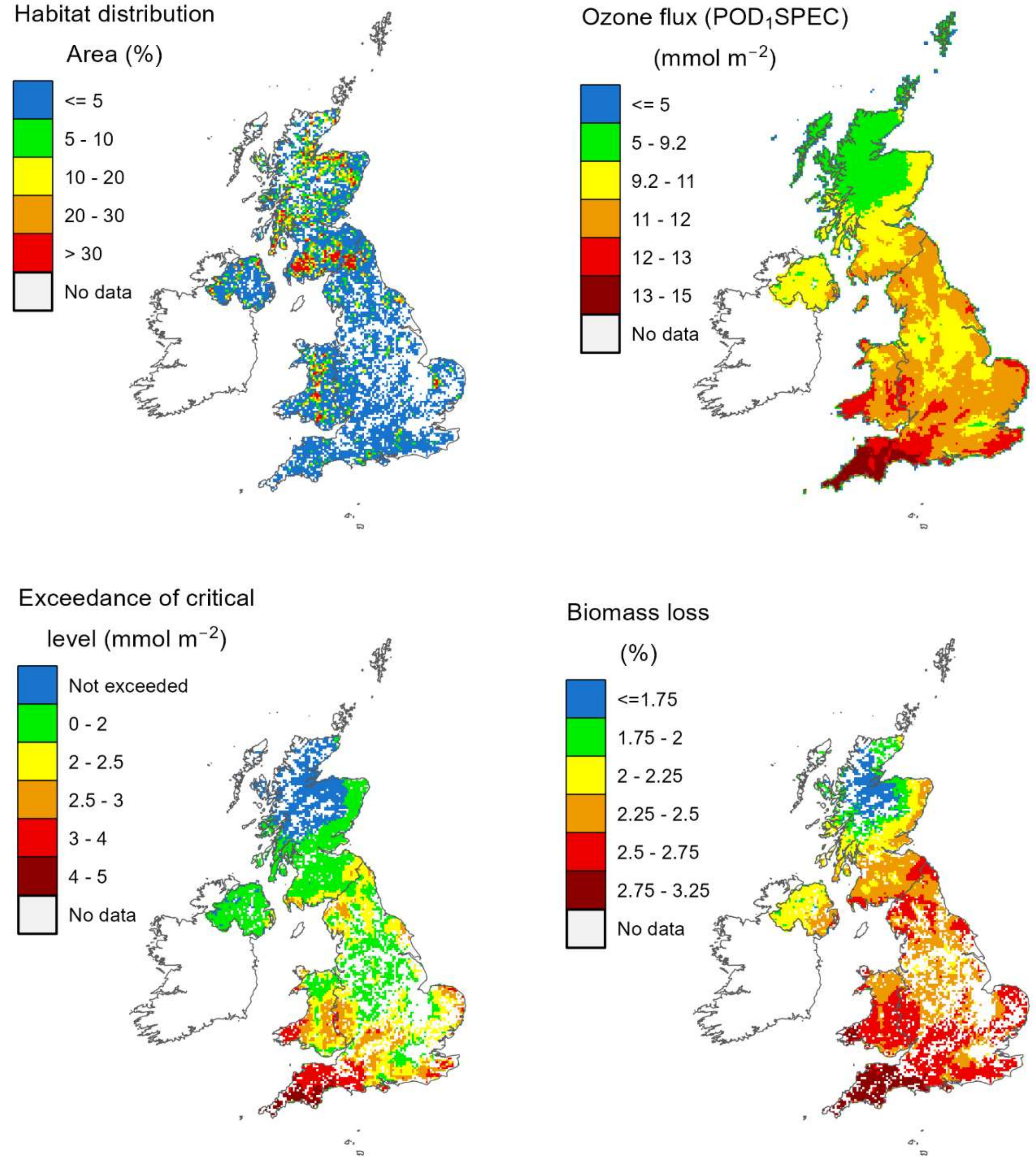

Figure 18: Impacts of ozone on managed coniferous woodland in 2019 calculated using POD$_1$SPEC (EMEP 4.36). (a) Distribution of managed coniferous woodland as the percentage area of each 5km x 5km grid square; (b) POD$_1$SPEC (mmol m^{-2}) (**critical level = 9.2 mmol m^{-2}**); (c) exceedance of the critical level; (d) Percentage yield loss (indicative risk only).

Managed coniferous woodland (POD_1SPEC for biomass increment)

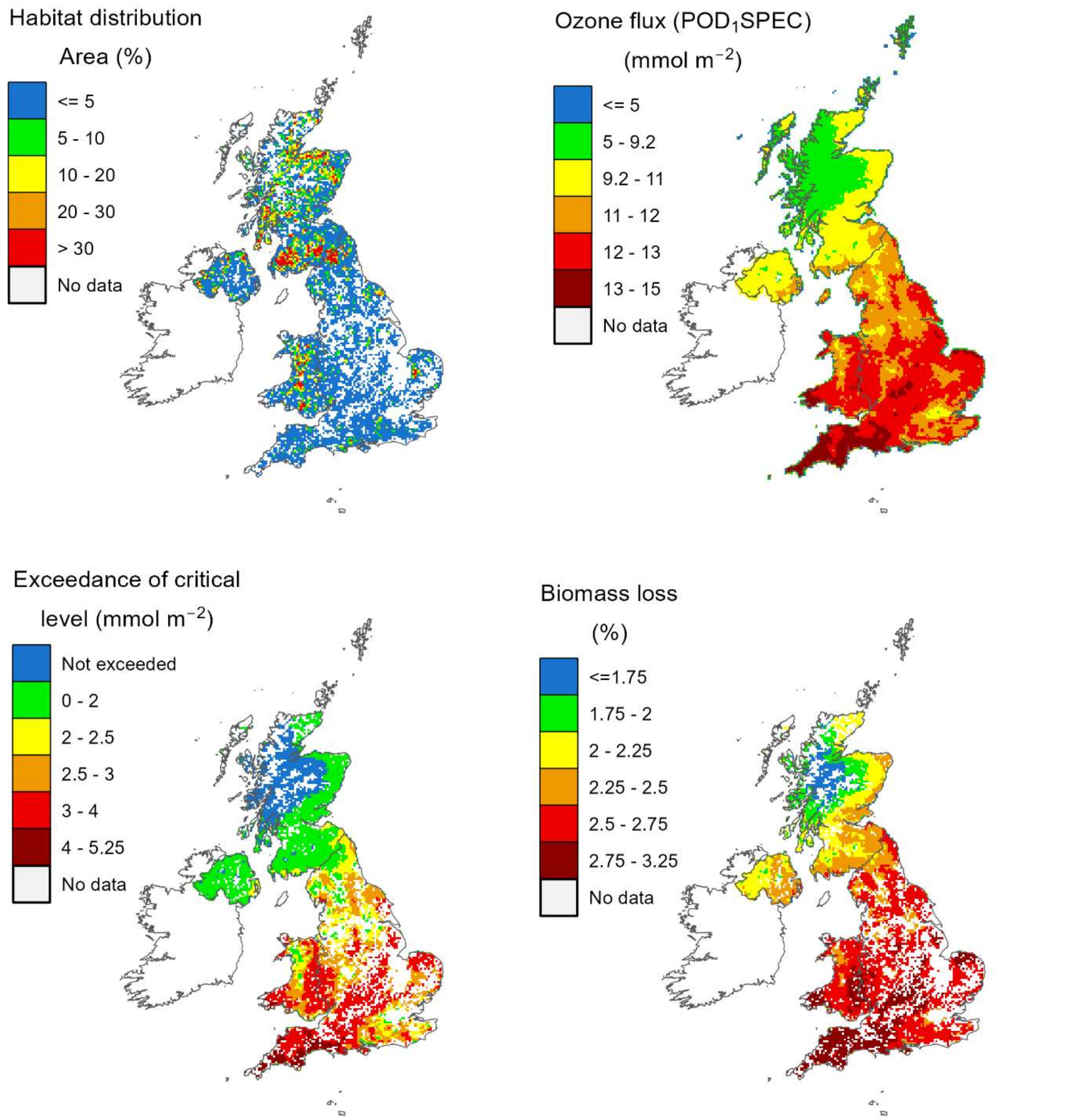

Figure 19: Impacts of ozone on managed coniferous woodland in 2020 calculated using POD_1SPEC (EMEP 4.36). (a) Distribution of managed coniferous woodland as the percentage area of each 5km x 5km grid square; (b) POD_1SPEC (mmol m^{-2}) (**critical level = 9.2 mmol m^{-2}**); (c) exceedance of the critical level; (d) Percentage yield loss (indicative risk only).

Perennial grassland (POD_1SPEC for flower numbers)

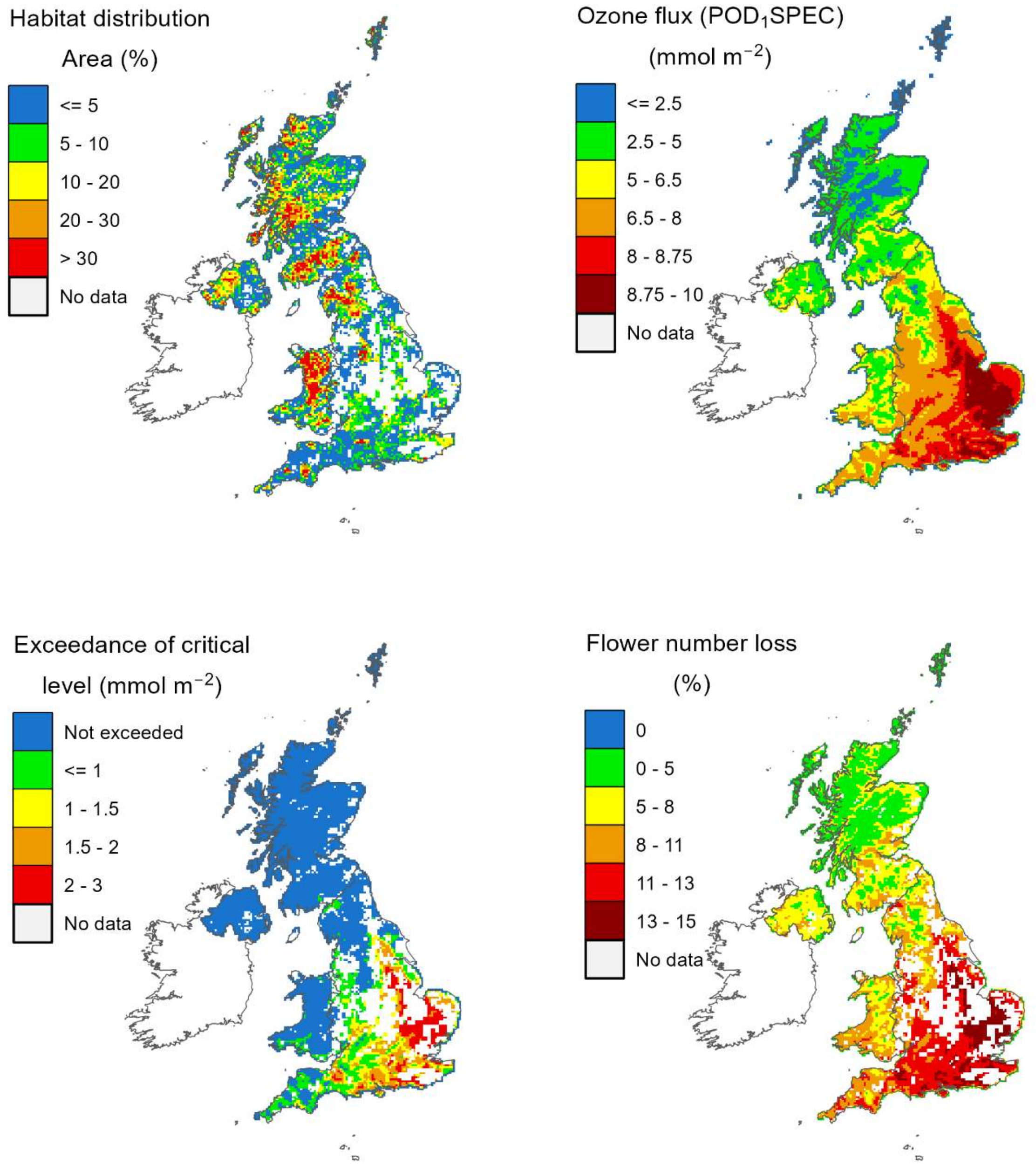

Figure 20: Impacts of ozone on perennial (semi-natural) grassland in 2019 calculated using POD_1SPEC (EMEP 4.36). (a) Distribution of grassland as the percentage area of each 5km x 5km grid square; (b) POD_1SPEC (mmol m^{-2}) (**critical level = 6.6 mmol m^{-2}**); (c) Exceedance of the critical level; (d) Percentage flower number loss (indicative risk only).

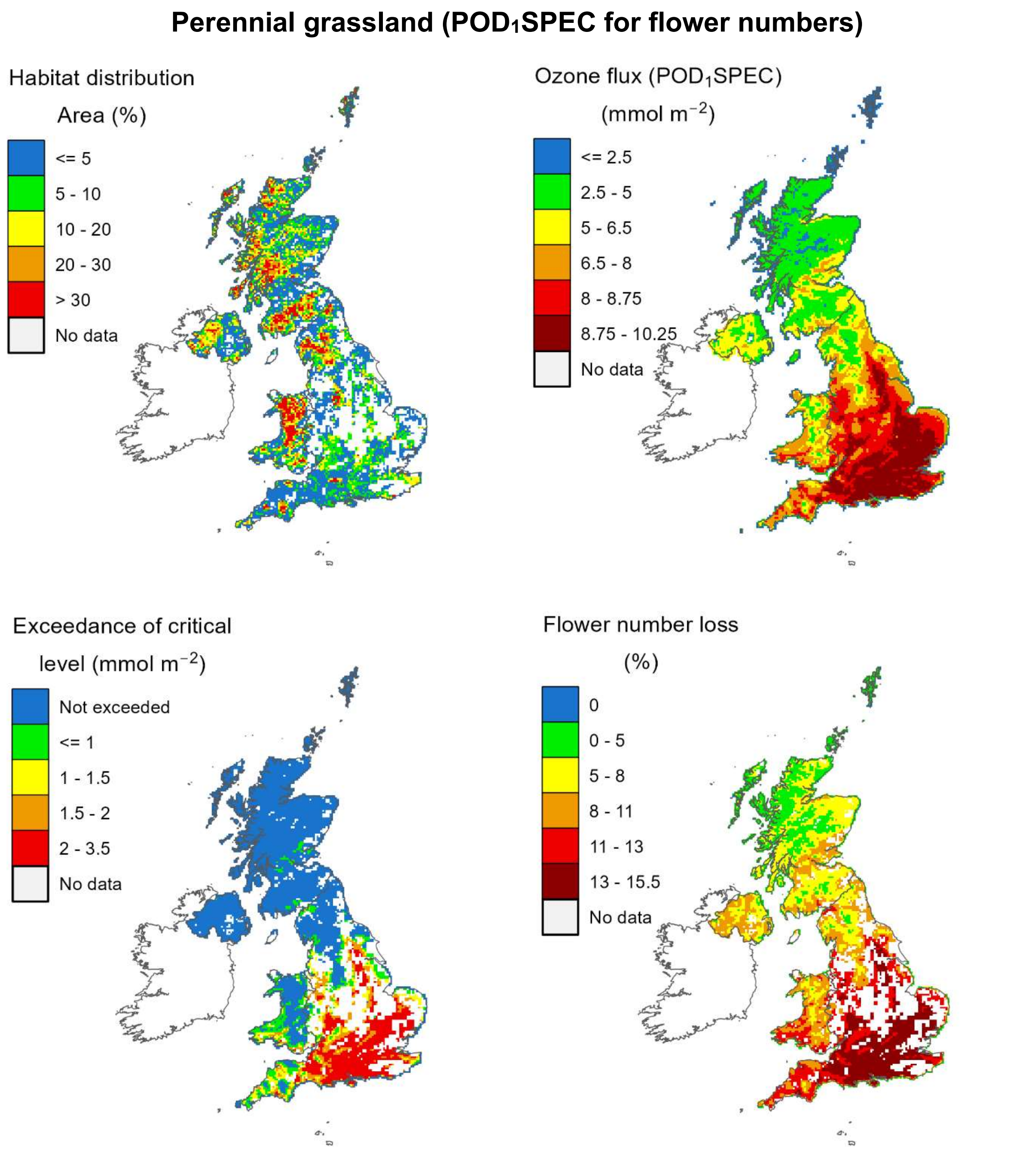

Figure 21: Impacts of ozone on perennial (semi-natural) grassland in 2020 calculated using POD_1SPEC (EMEP 4.36). (a) Distribution of grassland as the percentage area of each 5km x 5km grid square; (b) POD_1SPEC (mmol m^{-2}) (**critical level = 6.6 mmol m^{-2}**); (c) Exceedance of the critical level; (d) Percentage flower number loss (indicative risk only).

4 Discussion

4.1 Spatial and temporal variation in ozone flux

The previous reports spanning the period 2014–19 (Sharps et al., 2019, 2020a, 2020b, 2022) showed spatial and temporal variation in ozone flux values for the UK, with examination of model inputs suggesting that these patterns were primarily due to changes in meteorology (for example, temperature). Also the EMEP-WRF model calculates the PODy values from hourly data, and as it is a threshold, the episodic nature of ozone plays a key role in the temporal and spatial distribution.

EMEP annual reports provide a summary of ozone levels across Europe for each year (https://www.emep.int/publ/common_publications.html#2019). The EMEP report for 2018 (EMEP, 2020) reported that there were special meteorological conditions in 2018 with a remarkably hot and dry summer in large areas, most pronounced in northern parts of Europe. Hot, dry, sunny conditions can lead to increased ozone concentrations.

Long-term time series of EMEP ozone levels show a general downward trend (e.g. for ozone metrics such as SOMO35 and AOT40), which reflects reduced precursor emissions over the last two decades. Ozone levels in 2018 were lower than in 2003 (another extreme temperature year), which suggests that this may be due to lower emissions levels. However, weather extremes, which do seem to be occurring more frequently with time, can counteract the benefits of emission reductions. The elevated levels of ozone in the summer of 2018 indicate that efficient abatement of surface ozone depends not only on the reduction of ozone precursor emissions but on future climate change. While summer heat waves can lead to higher levels of surface ozone, drought conditions can also result in reduced ozone uptake into plants (due to the closing of stomata). Therefore, it is important to use ozone flux rather than metrics such as AOT40 to assess the potential impact of ozone, as the former takes soil moisture levels into account.

In 2019, there were four main ozone episodes in Europe over the summer, with June being the warmest June on record (for Europe and globally) and a short intense heat wave in July (EMEP, 2021). National temperature records for July were set in the UK (38.7 ◦C) and peak ozone levels were measured. In the UK, an hourly maximum level of 119 ppb was seen at Sibton in Suffolk on 25th July, the highest level measured at this site since 1996. The year 2020 was a “fairly modest year” with regard to ozone episodes (EMEP, 2022). As in previous years, ozone metrics (mean daily maximum O_3, SOMO35 and AOT40) in 2020 all show a distinct gradient with levels increasing from north to south in Europe, reflecting the dependence of ozone on the photochemical conditions. In connection with a heatwave in the north-west of Europe in late July/early August high ozone levels were observed in the Belgium, Netherlands, Luxembourg and the south-east of UK.

The vegetation types studied can respond to ozone levels differently in a particular year (for example higher losses estimated for wheat than potato). In addition to ozone concentration and meteorological conditions, there are a number of factors influencing the ozone impact for each vegetation type, including the sensitivity to ozone, critical level for ozone, rate of stomatal conductance and length of accumulation period. Crops with slightly different growing seasons and ozone accumulation periods can have differing levels of ozone uptake. In addition, even if estimates of ozone flux for a vegetation type or crop are high, the highest values may not coincide with the distribution of the habitat or for crops, areas with high levels of production.

The summer in 2020 was slightly warmer and wetter than average, although not exceptional. Growing conditions were difficult for farmers that year, with the wettest February on record. Although this was followed by a dry spring, the soil was very wet, meaning that many farmers were unable to plant seeds, and the dry weather following meant that germination levels were poor/delayed. This led to lower production for wheat and oilseed rape in particular.

As crops in particular are more sensitive to ozone (see Table 1, Potential maximum rate of reduction (%) per mmol m^{-2} PLA of PODySPEC), increases in ozone flux can be expected to have greater effects on estimates of yield and production loss. Also, the g_{max} values for crops are greater compared to those for trees (Annex, Table 2), therefore changes in ozone level can be expected to have a greater impact on crops. The use of Met Office data allows a closer examination of UK temperature changes during the year, and differences between years (Annex, Figures 1&2). The summer mean temperature in 2018 was greater than for both 2019 and 2020, which show more similar values across the UK (Annex, Figure 1). As 2019 and 2020 were not extreme years in terms of temperature, the monthly mean temperatures provide more of an indication of how conditions may have differed for the key crops of interest in this report, rather than looking at the summer mean values (Annex, Fig. 2).

In 2020, wheat showed an increase in critical level exceedance and yield loss compared to 2019. The monthly mean temperature maps for the wheat accumulation period (May and June) show that temperatures were higher across many parts of the UK in 2020 compared to 2019 (Annex, Fig. 2). Similarly, ozone flux and yield loss estimates for oilseed rape were higher in 2020 than in 2019. The Met Office data show that temperatures were higher in April, May and June 2020 (accumulation period for this crop), compared to 2019 (Annex, Fig. 2), particularly in the southern half of England and Wales. Ozone impacts on potatoes were more similar between 2019 and 2020, and the monthly temperature maps help to explain why this might be (Annex, Fig. 2). The key months in the accumulation period for potato are June and July, and UK temperatures were only slightly higher in June 2020 and generally lower in July 2020, compared to the values for 2019.

For the woodland habitat types, ozone impacts did not vary greatly between 2019 and 2020, with critical levels exceeded in all areas for broadleaved woodland in 2019 and 2020, and values for ozone flux and the % annual biomass increment losses only slightly higher in 2020. For managed coniferous woodland, critical level exceedance and annual biomass increment losses were also similar between 2019 and 2020. For grassland, the reduction in flower number due to ozone was slightly greater in 2020 compared to 2019. While the g_{max} for this habitat is lower (more similar to trees than crops), the sensitivity to ozone is slightly greater than for trees (Table 1). The accumulation period is mid-April to mid-July and the warmer temperatures at this time in 2020 would have contributed to higher ozone concentrations and uptake.

4.2 Comparison between model versions

For previous reports on ozone impacts on vegetation in the UK (Sharps et al., 2019, 2020a, 2020b, 2022), the EMEP4UK model version used was 4.17, with the version kept the same for each report, to allow the only factors which changed to be the meteorology and emissions for each year. However, the EMEP model is continuously updated, due to developers correcting bugs and also updates in the equations. For this current report, the most recent, stable, version of the model was used (version 4.36). The model was run for the years 2019 and 2020, to allow comparison between the results for 2019 using the previous and updated model versions, and then for the results for 2020 to be compared to those for 2019, using the updated version.

Each year, EMEP produces a status report, which includes an update chapter outlining any important changes in the code for the original EMEP MSC-W model. Two particular changes that are relevant for the model versions used here are outlined in the EMEP status reports for 2019 and 2020 (EMEP, 2019; EMEP, 2020). The 2019 report outlines a change in the way PAR (Photosynthetically Active Radiation) was calculated between versions 4.17 and version 4.33. The radiation scheme of Weiss and Norman (1985) was introduced when updating version 4.16 to give better estimates of diffuse versus direct photosynthetically active radiation (PAR), and to fix a bug in the calculations of these variables which had been identified in previous model versions. PAR is used in modelling both stomatal uptake and biogenic VOC emissions. Unfortunately, this bug-fix contained itself a bug in the units used in the stomatal uptake (DO_3SE) module, so that calculated PAR levels were too low, for model version 4.16 onwards. Although this change had very limited impact on most results and pollutants, the effects on calculations of phytotoxic ozone dose (POD) were found to be large in some cases, especially for forests. While ozone itself (surface concentration) was hardly affected by this change, POD_1 values for deciduous forests were about 30% lower with version 4.17 than with version 4.15. Interestingly, the POD metrics for crops were not as sensitive to this change in the model, however, the light response coefficients used in the calculation of stomatal conductance (gsto) are quite different for crops and forests, such that gsto for forests is more likely to be limited by low PAR values than crops. Also, the accumulation season for POD_1 extends into the spring and autumn and thus includes more periods when light-levels act to limit gsto.

Results in the current report also indicate a difference between the three crops studied, for example, ozone flux values were considerably higher for oilseed rape using the newer model version (compared to the previous version), but less so for wheat. This could be due to the difference in accumulation period used for the crops, with oilseed rape having the longest period in the parameterisation table (90 days) (Annex, Table 1). The light response coefficients also differ between the three crops, with oilseed rape having the lowest value (Annex, Table 2). Grasslands have less of a difference in 2019 results between the EMEP model versions, (compared to deciduous trees and crops). This vegetation type has a shorter accumulation period than trees (90 days), and the light coefficient values are more similar to the values for crops, but g_{max} is lower for grasslands than for crops, therefore ozone uptake (flux) at a given ozone concentration could be expected to be lower than for crops.

The bug in the units for PAR was corrected for model version 4.33 onwards. As illustrated in Figure 22, comparing outputs between version 4.32 and 4.33 of the model, the impact of the change was mainly apparent for forests. The net result of fixing this bug was to restore POD levels to very similar levels to those seen in the 4.15 model version. The figure also shows that the correlation coefficient between new and old model versions is very high (≥ 0.996). In addition to the changes outlined in the calculation of PAR, there have been some other changes to the model, for example, there were some chemistry changes and the emissions speciation of NMVOCs (Non-methane Volatile Organic Carbon, which are ozone precursors) were updated for version 4.35. Therefore, the differences seen in the ozone impact results for 2019 using the two different model versions can be explained due to the changes between the versions.

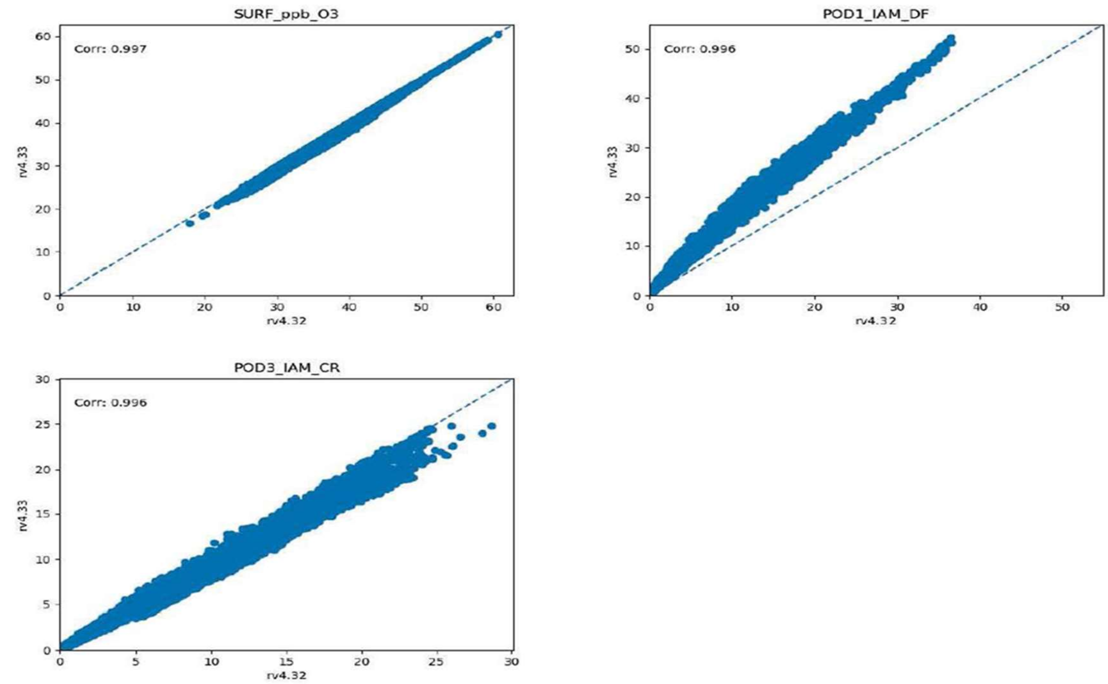

Figure 22: Comparison of model versions rv4.33 and rv4.32 for mean ozone (top-left), POD1 for IAM deciduous forests (top-right) and POD_3IAM for crops (bottom). The dashed line represents the 1:1 line. Calculations are for the year 2012, using the 50km version of the EMEP MSC-W model. (Taken from EMEP Status Report 2019, Chapter 10, Fig. 10.1).

The results for deciduous forests show the greatest differences, which fits with the changes described in the EMEP status reports.

Overall, in comparison to the results reported for the UK for previous years, it seems that ozone impacts, particularly on deciduous trees, are more severe than those calculated in the model version used to calculate impacts for 2014-2019. As forest ecosystems have the greatest C sink capacity of any vegetation type, and hold the largest amount of biomass C, ozone impacts on tree biomass have the potential to have major repercussions for the C cycle and carbon sequestration in the UK. This in turn could impact climate change policy as the terrestrial biosphere removes approximately a third of all present-day anthropogenic CO_2 emission (Seiler et al., 2022). It should be noted however that the maps in the current report predict effects on the living biomass annual increment of young trees and several more stages are required to analyse effects on timber production or carbon sequestration in trees.

Büker et al. (2012) investigated the reduction of sequestered C in the living biomass of trees due to ozone in Europe for the year 2000, as predicted by flux-based deposition modelling approaches (using the DO_3SE model). The tree biomass C reduction was calculated as the difference between the current C stored in trees and the C that would have been stored if ozone would not have had an impact on tree growth. The reduction in sequestered carbon varied with a number of factors, including the climate and pollution data used, and also the ozone metric (AOT40 or PODy). However, in absolute terms, the amount of C reduction in Eu-27+NO+CH in 2000 as compared to the baseline was between 1249 and 1929 Mt C using the POD_Y approach. The authors recommended that global climate change modelling should incorporate the impacts of ozone on vegetation to more accurately predict the impacts of the future climate on C sequestration.

One further caveat to be considered is that the EMEP results presented in the current report are interim results, as another version of the model is shortly to be officially released (version 5.0), with more updates to the code potentially impacting PODy values, for example the photolysis system has been revised. Therefore, the results from the newest version of the model need to be examined to see if this trend for increased losses due to ozone, particularly for deciduous trees, continues.

4.3 Sources of uncertainty in the analysis

The analysis presented uses modelling methods approved for use by the LRTAP Convention and the EU (LRTAP Convention, 2017), including the most up-to-date critical levels and response functions and the EMEP4UK model adapted for UK use from the extensively used EMEP model. Quality assurance and quality control checks were also carried out by EMEP4UK modellers on completion of the model runs. This process includes checking for warnings or errors in output files, cross checking the total emissions of air pollutants per country against values from a reference run and creating initial maps to check for extreme or unusual values.

Nevertheless, there are some sources of uncertainty in this analysis, associated with the steps described below.

4.3.1 Response functions and critical levels

The response functions used to derive critical levels have varying degrees of certainty, depending on vegetation type (LRTAP Convention, 2017). The linear relationship between POD_YSPEC and effect and associated critical level is the most robust for wheat yield (Adjusted R^2 = 0.83, $p<0.001$). The function includes data from Belgium, Finland, Italy and Sweden and has been tested for modern wheat varieties (Grünhage et al., 2012). Although not tested with recent varieties, the critical level for potato has also been derived from a robust response relationship (Adjusted R^2= 0.80, $p<0.001$, Pleijel et al., 2007), based on data from countries with similar climates to the UK (Belgium, Finland, Germany and Sweden). Of the crops included here, the response function for oilseed rape is the least robust (R^2 = 0.24, De Bock et al., 2011), being based on exposure of one variety (cv. Ability) to ozone in open top chambers in Belgium for three growing seasons. Although this function did not meet the ICP Vegetation criteria for establishing a critical level, we have included this crop in our analysis because the function is based on the most widespread cultivar of oilseed rape grown in the UK.

The response functions used to derive critical levels for effects of ozone on trees are based on ozone exposure experiments conducted with young trees under 10 years old (Büker et al., 2015). Whilst both functions used are highly statistically significant ($p<0.001$), there is more scatter of the data in these functions than those for crops, with the birch/beech total biomass function having an Adjusted R^2 of 0.67 and the Norway spruce total biomass function having an Adjusted R^2 of 0.31. Both functions contain data from Sweden and Switzerland, with added data from Finland contributing to the birch/beech function and from France contributing to the Norway spruce function. Unfortunately, very few studies have been performed under field conditions with mature trees due to the cost of such experiments, meaning there is insufficient data available to derive critical levels for mature trees. Whilst the uncertainty in interpreting responses of mature trees from functions derived using young trees is acknowledged, there is strong support for the critical levels from epidemiological analysis of tree trunk growth in Switzerland (Braun et al., 2010, 2014). Analysis of the spatial extent of critical level exceedance provided here provides a strong indication of the areas in the UK where woodland is most at risk from adverse impacts of ozone on annual biomass increment. As discussed, the maps of total biomass annual increment for trees should be interpreted with caution as these are predicting effects on the living biomass annual increment of young trees and further steps are required to analyse potential effects on timber production or carbon sequestration.

Deriving critical levels for grasslands is more difficult because the number of species tested for ozone sensitivity represents only a small fraction of the 4000+ species present in Europe, and the range of responses varies from negative to positive effects on annual biomass increment and flowering (e.g. Hayes et al., 2007). The ICP Vegetation Task Force took the approach of defining criteria for ozone sensitive species based on a study by Bergmann et al., (2015) and developing flux-effect relationships for species with a negative response to ozone. The temperate grassland response functions for flower and biomass effects contained data from experiments conducted over 3 or 4 years respectively in the UKCEH solardomes using UK grassland species. Both functions contain data for iconic UK species such as buttercup, harebell and cowslip (Table 1) which makes the findings very relevant in a UK biodiversity context. Although highly significant ($p<0.001$), the response functions for annual biomass increment (Adjusted R^2 = 0.34) and flowering (Adjusted R^2 = 0.30) are less robust than those for deciduous trees and crops and have higher effect critical levels of 10% to account for the lower certainty. It was agreed that these critical levels could be applied in a biodiversity context with the caveat that the experiments were only designed to test for effects on growth and flowering and not for changes in biodiversity.

4.3.2 Modelling PODySPEC

The WRF model has been validated against observations for other years (Vieno et al., 2010) and a simple evaluation for the meteorology has also been carried out for this work. The official EMEP MSC-W model results and EMEP4UK qualitatively agree well on annual average concentration for SO_2, NO_2, and $PM_{2.5}$. Ozone values differ slightly between the two models. The soil-moisture index used in the EMEP4UK model has been developed for the ECMWF meteorological driver. This may add uncertainties when used with the WRF model. In addition, the differing spatial scales for EMEP4UK (originally 5km, now 3km) and EMEP MSC-W (10km) may play a role in any differences between model outputs.

In 2022, a new EMEP and WRF model domain (3km x 3km resolution, using polar stereo projection) was introduced to replace the previous 5km x 5km domain. For this study, the PODySPEC data was re-projected to British National Grid, and the data were resampled to 5km x 5km resolution, in order to work with the 5km resolution habitat data and to allow results maps to be presented at the same scale as previous reports for comparison purposes. While this method has the potential to add some uncertainty to the final PODySPEC values, ozone levels would not be expected to vary greatly in adjoining grid squares. This is in comparison to other pollutants such as ammonia, which can show local fluctuations. Therefore taking the mean PODy value per 5km square should provide a good representation of the ozone uptake overall.

4.3.3 Mapping habitat area, production and economic losses

For crop production data, we had to scale an existing dataset for 2006 – 2008 (Mills et al., 2011c) to 2019/20. The finest scale data that could be found for this conversion was regional production totals per crop which will have introduced some uncertainty into the analysis, and there may be some areas that were growing a crop in 2019/20 but were not doing so in 2006/08 and vice versa. Furthermore, the regional totals for each crop may also vary depending on how many farms per region were surveyed. As the 2006 – 2008 database was at 10km x 10km resolution, some error was introduced by assuming that the crop production and distribution is spread equally across each 10km x 10km cell in order to achieve the desired 5km x 5km resolution.

For future studies, it would be beneficial to update the UK crop production spatial dataset for wheat, potato and oilseed rape. The original dataset was created using a combination of crop statistics on extent and yield, and land cover data (Mills et al., 2011c). This was beyond the scope of the current report.

The habitat distribution maps for forest and grassland were generated for critical loads research (see Section 2.4.2) and intended to provide national-scale pictures of the main habitat types required for national-scale critical loads mapping and modelling activities. As such they may not include every small area of each sensitive habitat at the regional or local scale. There are uncertainties associated with the maps; two of the main reasons are:

- There are uncertainties in all the datasets used (land cover, forest land use, species distributions, National Vegetation Classification classes, soils).
- The maps are based on a combination of data sets at different resolutions (e.g. land cover at 1km x 1km, species distributions at 10km x 10km); the habitat distribution maps have been aggregated from 1km x 1km to 5km x 5km resolution for this study.

Further information on the methods and data used to derive the habitat maps can be found in Hall et al., (2015). We plan to update the habitat distribution data for the UK (currently based on land cover data for the year 2000) for both forest habitats and grasslands next year, using up-to-date land cover data, and also the Forestry Commission National Forest Inventory dataset. As the current report focuses on a comparison between the different EMEP model versions, the habitat data were kept consistent, to avoid introducing any further sources of variation in the outputs.

5 Conclusions

This study was undertaken to build on the initial scoping study to investigate the ozone impact on UK vegetation in by Mills et al., (2017), the study examining three consecutive years (2014 – 2016) of ozone data for the UK (Sharps et al., 2019) and the studies for the year 2017 (Sharps et al., 2020a), 2018 (Sharps et al., 2020b) and 2019 (Sharps et al., 2022). The study provides information to meet the UK parallel requirements of Annex V of the amended NECD Directive by reporting on exceedances of flux-based critical levels for ozone (NECR), contributing to the assessment of exceedances of ozone flux-based critical levels and ozone damage to crop yield, vegetation growth and biodiversity of terrestrial ecosystems for the years 2019 and 2020.

The effects of ozone on vegetation growth were quantified by calculating and mapping effects on crop yield (quantity, economic value) and annual growth of living tree biomass and annual grassland biomass increment. As such, the percentage yield and biomass loss maps are indicative of the risk of effects on carbon flux and subsequent yield and biomass losses and do not provide actual monitored values for ozone effects.

For the current report, a newer version of the EMEP model was used, with results for 2019 compared with the version used for previous reports, and also results for 2020 presented, again using the new EMEP model version.

In summary, the comparison between the sets of results for 2019 from the two different model versions (4.17 and 4.36) showed that the spatial pattern of ozone impacts remained similar however ozone impacts were increased using the newer model version, with the extent of this varying between vegetation types. EMEP status reports (outlining changes in the model) suggest that these differences are due primarily to correction of a bug found in the calculation of PAR, which affected POD results for deciduous trees. These high predictions for % losses in annual increment of tree biomass (15.7% mean for the UK) due to ozone have the potential to have repercussions for the C cycle and carbon sequestration in the UK. However, as the calculations and results presented predict effects on young trees, several more stages are required to analyse effects on timber production or carbon sequestration in trees.

When comparing results for 2019 and 2020 (using the new model version), there was generally not a big difference between years in terms of ozone impacts, with values slightly higher for all vegetation types in 2020 compared to 2019, and the greatest differences seen for crops (wheat and oilseed rape). Over the period 2014 to 2019 (which was only considered with the previous model version), 2019 was a low/medium year in terms of ozone impacts, and so it is likely that 2020 was a medium year compared to others in the 2014 – 2020 timespan. Examination of monthly mean temperature data from the Met Office for the growing season (April to August) suggested that the differences between 2019 and 2020 resulted from higher ozone flux during this period in 2020, due to slight increases in temperature.

Overall, results suggest that ozone impacts on vegetation in the UK may be more severe than previously reported (using the old version of the EMEP model), particularly for deciduous forest. However, the EMEP results presented in the current report are interim results, as another version of the model is shortly to be officially released (version 5.0), with more updates to the code potentially impacting PODy values, for example the photolysis system has been revised. Therefore, the results from the newest version of the model need to be examined to see if this trend for increased losses due to ozone continues.

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7 Annex

Table 1: Input parameterisation for land-cover definitions for EMEP4UK

Name	code	type	PFT	hveg	Alb	eNH4	SGS50	DSGS	EGS50	DEGS	LAImin	LAImax	SLAIlen	ELAIlen	BiomasD	Eiso	Emtl	Emtp
#				m	(%)		day	days/d	day	days/d	m2/m2	m2/m2	days	days	g/m2	ug/g/h	ug/g/h	ug/g/h
#-------------------------	#SKIP																	
#DATA:																		
temp_conif	CF	ECF	CF	20	12	0	0	0	366	0	5	5	1	1	1000	1	0.5	2
temp_decid	DF	EDF	DF	20	16	0	100	1.5	307	-2	0	4	20	30	320	15	2	2
med_needle	NF	ECF	NF	8	12	0	0	0	366	0	4	4	1	1	500	4	0.2	4
med_broadleaf	BF	EDF	BF	15	16	0	0	0	366	0	4	4	1	1	300	0.1	10	0.2
temp_crop	TC	ECR	NOLPJ	1	20	1	123	2.57	213	2.57	0	3.5	70	20	700	0.1	0.2	0.2
med_crop	MC	ECR	NOLPJ	2	20	1	123	2.57	237	2.57	0	3	70	44	700	0.1	0.2	0.2
root_crop	RC	ECR	NOLPJ	1	20	1	130	0	250	0	0	4.2	35	65	700	0.1	0.2	0.2
moorland	SNL	SNL	C3PFT	0.5	14	0	0	0	366	0	2	3	192	96	200	5	0.5	0.5
grass	GR	SNL	C3PFT	0.3	20	1	0	0	366	0	2	3.5	140	135	400	0.1	0.5	0.5
medscrub	MS	SNL	C4PFT	2	20	0	0	0	366	0	2.5	2.5	1	1	150	8	0.5	2
wetlands	WE	SNL	NOLPJ	0.5	14	0	0	0	366	0	-1	-1	-1	-1	150	2	0.5	0.5
tundra	TU	SNL	NOLPJ	0.5	15	0	0	0	366	0	-1	-1	-1	-1	200	5	0.5	0.5
desert	DE	BLK	NOLPJ	0	25	0	0	0	366	0	-1	-1	-1	-1	0	0	0	0
water	W	BLK	NOLPJ	0	8	0	0	0	366	0	-1	-1	-1	-1	0	0	0	0
ice	ICE	BLK	NOLPJ	0	70	0	0	0	366	0	-1	-1	-1	-1	0	0	0	0
urban	U	BLK	NOLPJ	10	18	0	0	0	366	0	-1	-1	-1	-1	50	0	0	0
IAM_CR	IAM_CR	ECR	NOLPJ	1	20	1	123	2.57	213	2.57	3.5	3.5	1	1	700	0	0	0
IAM_DF	IAM_DF	EDF	NOLPJ	20	16	0	105	1.5	297	-2	0	4	15	30	0	0	0	0
IAM_MF	IAM_MF	EMF	NOLPJ	8	12	0	0	0	366	0	5	5	1	1	0	0	0	0
NEUR_SPRUCE	NEUR_SPF	ECF	NOLPJ	20	12	0	105	1.5	297	-2	5	5	1	1	0	0	0	0
NEUR_BIRCH	NEUR_BIR	EDF	NOLPJ	20	16	0	105	1.5	297	-2	0	4	15	30	0	0	0	0
ACE_PINE	ACE_PINE	ECF	NOLPJ	20	12	0	105	1.5	297	0	5	5	1	1	0	0	0	0
ACE_OAK	ACE_OAK	EDF	NOLPJ	20	16	0	105	1.5	297	-2	0	4	15	30	0	0	0	0
ACE_BEECH	ACE_BEEC	EDF	NOLPJ	20	16	0	105	1.5	297	-2	0	4	15	30	0	0	0	0
CCE_SPRUCE	CCE_SPRU	ECF	NOLPJ	20	12	0	0	0	366	0	5	5	1	1	0	0	0	0
CCE_BEECH	CCE_BEEC	EDF	NOLPJ	25	16	0	105	1.5	297	-2	0	5	15	30	0	0	0	0
MED_OAK	MED_OAK	EMF	NOLPJ	15	12	0	0	0	366	0	3	5	100	166	0	0	0	0
MED_PINE	MED_PINE	EMF	NOLPJ	10	12	0	0	0	366	0	1	2	100	166	0	0	0	0
MED_BEECH	MED_BEE(	EMF	NOLPJ	20	12	0	105	1.5	297	-2	0	5	15	30	0	0	0	0
IAM_CR_NO_PS	IAM_CR_N	ECR	NOLPJ	1	20	1	105	0	195	0	3.5	3.5	1	1	700	0	0	0
WHEAT_NO_PS	WHEAT_N	ECR	NOLPJ	1	20	1	141	2.57	183	0	3.5	3.5	1	1	700	0	0	0
WHEAT_NO_P	WHEAT_N	ECR	NOLPJ	1	20	1	141	2.57	183	0	3.5	3.5	1	1	700	0	0	0
WHEAT	WHEAT	ECR	NOLPJ	1	20	1	141	2.57	183	0	3.5	3.5	1	1	700	0	0	0
POTATO	POTATO	ECR	NOLPJ	1	20	1	146	0	216	0	0	4.2	35	65	700	0	0	0
LETTUCE	LETTUCE	ECR	NOLPJ	0.3	20	1	152	0	194	0	3.5	3.5	1	1	700	0	0	0
OILSEED_RAPE	OILSEED_F	ECR	NOLPJ	1	20	1	91	0	181	0	3.5	3.5	1	1	700	0	0	0
PASTURE_GRASS	PASTURE_	SNL	C3PFT	0.3	20	1	105	0	195	0	2	3.5	140	135	400	0	0	0
PASTURE_FORB	PASTURE_	SNL	C3PFT	0.3	20	1	105	0	195	0	2	3.5	140	135	400	0	0	0
#END																		
#Aug2012 changed:																		
#L_E temp_crop	TC	ECR	NOLPJ	1	20	1	123	2.57	213	2.57	0	3.5	70	22	700	0.1	0.2	0.2
#EGS med_crop	MC	ECR	NOLPJ	2	20	1	123	2.57	213	2.57	0	3	70	44	700	0.1	0.2	0.2
#LAImin	Ls	Le:IAM_CI	IAM_CR	ECR	NOLPJ	1	20	1	123	2.57	213	2.57	0	3.5	70	22	700	0

User notes for Annex, Table 1

h = Height of vegetation, Alb = Albedo, ENH4 = Flag for possible Nhx fluxes
SGS50 = Start of growing season (days) At 50 deg. N
DSGS = D(SGS)/d(Lat)., DEGS = D(EGS)/d(lat)
#,
DEGS = d(EGS)/d(lat)
#,
LAImax - give as -1 if bulk resistance
SLAIlen = days from LAImin to LAImax at start of season
ELAIlen = days from LAImax to LAImin at end of season
(Set SLAIlen and ELAIlen to 1 for vegetation with constant LAI)
BVOC biomass loosely based upon Simpson et al., (1999)*
BVOC data only used outside Europe as defaults
#,
types - used in deposition system, e.g, to define areas where N-dep to conif forest is calculated
ECF - conif forest
EDF - decid forest
SNL - seminatural
W - Water
BLK - bulk - simple bulu surface resistance used
type B indicates that surface resistance will be calculated simply
using bulk formula

*(Simpson, D., Winiwarter, W., Börjesson, G., Cinderby, S., Ferreiro, A., Guenther, A., Hewitt, C.N., Janson, R., Khalil, M.A.K., Owen, S. and Pierce, T.E., 1999. Inventorying emissions from nature in Europe. *Journal of Geophysical Research: Atmospheres*, *104*(D7), pp.8113-8152.)

Table 2: Input parameterisation for DO_3SE within EMEP4UK

#Code	gmax	fmin	f_phen	#	#	#	#	#	Astart	Aend	flight	ftemp	#	#	Surface	Res.	fVDP	#	VPD	fSWP	#	rootd	Lw
#Code	#	#	fac	fac	fac	fac	len	len	(rel-SGS)	(rel_EGS)	#	min	opt	max	RgsS	RgsO	max	min	Crit	SWPmax	PWP	m	m
#	#	#	a	b	c	d	e	f	days	days	#	#	#	#	#	#	#	#	#	#	#	#	#
CF	140	0.1	0.8	0.8	0.8	0.8	1	1	0	0	0.006	0	18	36	500	200	0.5	3	-1	-0.76	-1.2	1.2	-1
DF	150	0.1	0	0	1	0	20	30	0	0	0.006	0	20	35	500	200	1	3.25	-1	-0.55	-1.3	0.9	-1
NF	200	0.13	1	1	0.2	1	130	60	80	35	0.013	8	25	38	500	200	1	3.2	-1	-0.4	-1	0.9	-1
BF	200	0.02	1	1	0.3	1	130	60	80	35	0.009	1	23	39	500	200	2.2	4	-1	-1.1	-2.8	0.9	-1
TC	300	0.01	0.1	0.1	1	0.1	0	45	0	0	0.0105	12	26	40	150	200	1.2	3.2	8	-0.3	-1.1	0.7	0.02
MC	300	0.019	0.1	0.1	1	0.1	0	45	0	0	0.0048	0	25	51	150	200	1	2.5	-1	-0.11	-0.8	0.7	-1
RC	360	0.02	0.2	0.2	1	0.2	20	45	0	0	0.0023	8	24	50	150	200	0.31	2.7	10	-0.44	-1	0.7	0.04
SNL	60	0.01	1	1	1	1	1	1	0	0	0.009	1	18	36	500	400	1.3	3	-1	-9.99	-99.9	0.7	-1
GR	270	0.01	1	1	1	1	0	0	0	0	0.009	12	26	40	350	1000	1.3	3	-1	-0.49	-1.5	0.8	-1
MS	200	0.01	1	1	0.2	1	130	60	80	35	0.012	4	20	37	500	200	1.3	3.2	-1	-1.1	-3.1	0.8	-1
WE	-1	-1	-1	-1	-1	-1	0	-1	0	0	-1	-1	-1	-1	50	400	-1	-1	-1	-1	-99	-1	-1
TU	-1	-1	-1	-1	-1	-1	0	-1	0	0	-1	-1	-1	-1	500	400	-1	-1	-1	-1	-99	-1	-1
DE	-1	-1	-1	-1	-1	-1	0	-1	0	0	-1	-1	-1	-1	1000	2000	-1	-1	-1	-1	-99	-1	-1
W	-1	-1	-1	-1	-1	-1	0	-1	0	0	-1	-1	-1	-1	1	2000	-1	-1	-1	-1	-99	-1	-1
ICE	-1	-1	-1	-1	-1	-1	0	-1	0	0	-1	-1	-1	-1	1000	2000	-1	-1	-1	-1	-99	-1	-1
U	-1	-1	-1	-1	-1	-1	0	-1	0	0	-1	-1	-1	-1	400	400	-1	-1	-1	-1	-99	-1	-1
IAM_CR	500	0.01	0.1	0.1	1	0.1	0	45	0	0	0.0105	12	26	40	150	200	1.2	3.2	8	-9.99	-99.9	0.7	0.02
IAM_DF	150	0.1	0	0	1	0	15	20	0	0	0.006	0	21	35	500	200	1	3.25	-1	-9.99	-99.9	0.9	0.07
IAM_MF	175	0.02	1	1	0.3	1	130	60	80	35	0.009	2	23	38	500	200	2.2	4	-1	-9.99	-99.9	0.9	0.035
#																							
NEUR_SPRUCE	112	0.1	0	0	1	0	20	30	0	0	0.006	0	20	200	500	200	0.8	2.8	-0.76	-1.2	1.2	0.8	0.008
NEUR_BIRCH	196	0.1	0	0	1	0	20	30	0	0	0.0042	5	20	200	500	200	0.5	2.7	-0.55	-1.3	0.9	5	0.05
ACE_PINE	180	0.1	0.8	0.8	1	0.8	40	40	0	0	0.006	0	20	36	500	200	0.6	2.8	-0.7	-1.5	1.2	0.8	0.008
ACE_OAK	230	0.06	0	0	1	0	20	30	0	0	0.003	0	20	35	500	200	1	3.25	-0.5	-1.2	0.9	5	0.05
ACE_BEECH	150	0.1	0	0	1	0	15	20	0	0	0.006	0	21	35	500	200	1	3.25	-0.8	-1.5	0.9	7	0.07
CCE_SPRUCE	125	0.16	1	1	1	1	1	1	0	0	0.01	0	14	35	500	200	0.5	3	-0.05	-0.5	1.2	0.8	0.008
CCE_BEECH	150	0.13	0	0	1	0.4	20	20	0	0	0.006	5	16	33	500	200	1	3.1	-0.05	-1.25	0.9	7	0.07
MED_OAK	180	0.02	1	1	0.3	1	130	60	80	35	0.012	1	23	39	500	200	2.2	4	-1	-4.5	9.99	5.5	0.055
MED_PINE	215	0.15	1	1	0	1	130	60	80	35	0.013	10	27	38	500	200	1	3.2	-0.5	-1	9.99	0.8	0.008
MED_BEECH	145	0.02	0	0	1	0	15	20	0	0	0.006	4	21	37	500	200	1	4	-2	-3.8	0.9	7	0.07
IAM_CR_NO_PS	500	0.01	1	1	1	1	0	0	0	0	0.0105	12	26	40	150	200	1.2	3.2	8	-9.99	-99.9	0.7	0.02
WHEAT_NO_PS	500	0.01	1	1	1	1	0	0	0	0	0.0105	12	26	40	150	200	1.2	3.2	8	-9.99	-99.9	0.7	0.02
WHEAT_NO_P	500	0.01	1	1	1	1	0	0	0	0	0.0105	12	26	40	150	200	1.2	3.2	8	-0.3	-1.1	0.7	0.02
WHEAT	500	0.01	0.1	0.1	1	0.1	0	45	0	0	0.0105	12	26	40	150	200	1.2	3.2	8	-0.3	-1.1	0.7	0.02
POTATO	750	0.01	0.1	0.1	1	0.1	0	45	0	0	0.005	13	28	39	150	200	2.1	3.5	-1	-9.99	-99.9	0.7	0.04
LETTUCE	790	0.05	0.1	0.1	1	0.1	0	45	0	0	0.005	10	31.5	42	150	200	3.2	5.3	-1	-9.99	-99.9	0.4	0.04
OILSEED_RAPE	490	0.02	0.1	0.1	1	0.1	0	45	0	0	0.0027	5	22	39	150	200	1.5	3.5	-1	-9.99	-99.9	0.7	0.04
PASTURE_GRASS	190	0.1	0.1	0.1	1	0.1	0	45	0	0	0.01	10	24	36	350	1000	1.75	4.5	-1	-9.99	-99.9	0.8	0.02
PASTURE_FORB	210	0.1	0.1	0.1	1	0.1	0	45	0	0	0.02	10	22	36	350	1000	1.75	4.5	-1	-9.99	-99.9	0.8	0.04
#Note 45 for Aend gives discont. Change to 35																							
#IAM_MF	175	0.02	1	1	0.3	1	130	60	80	35	0.009	2	23	38	500	200	2.2	4	-1	-9.99	-99.9	0.9	0.035
#	#	#	a	b	c	d	e	f	days	days	#	#	#	#	#	#	#	#	#	#	#	#	#

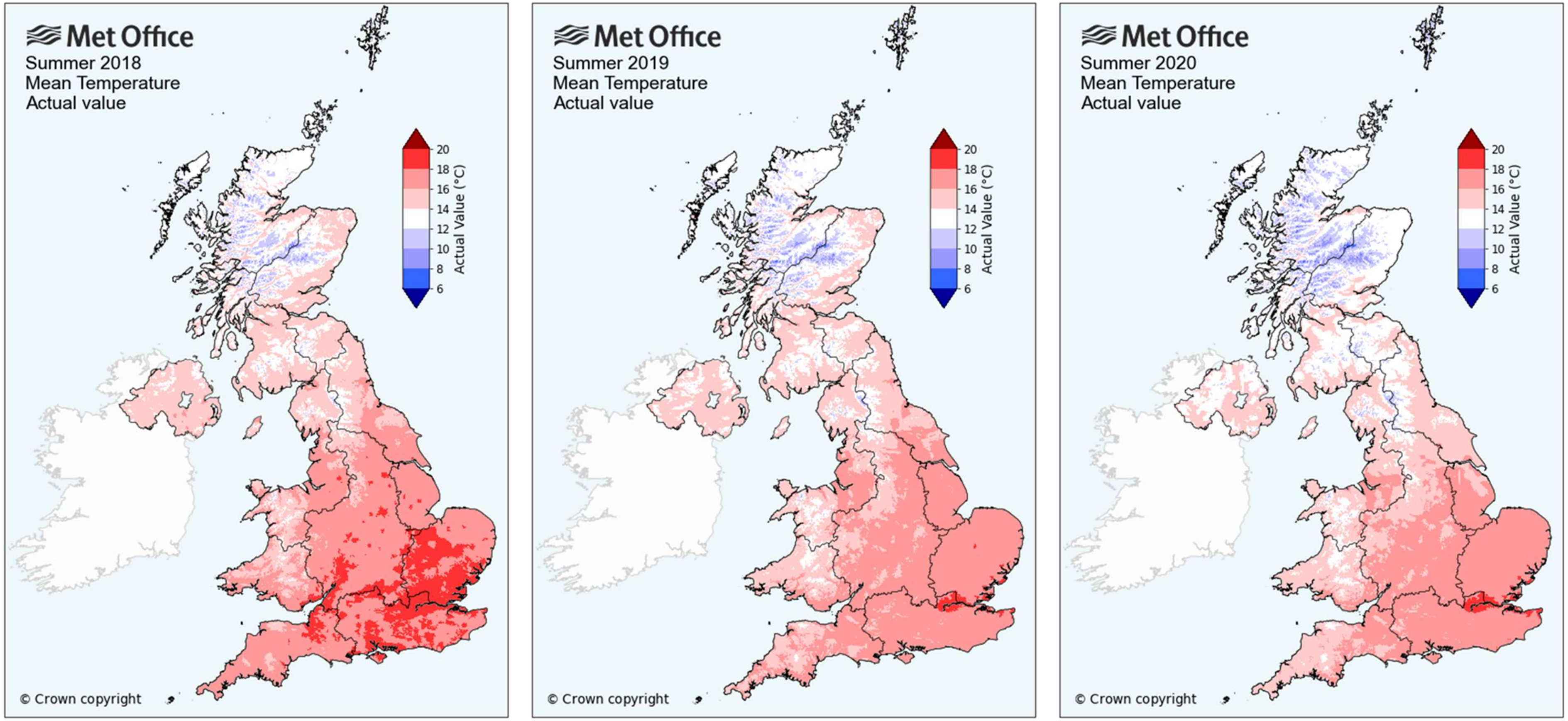

Figure 1. Met Office data showing the summer mean temperature (°C) for years 2018, 2019, 2020.
https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-actual-and-anomaly-maps

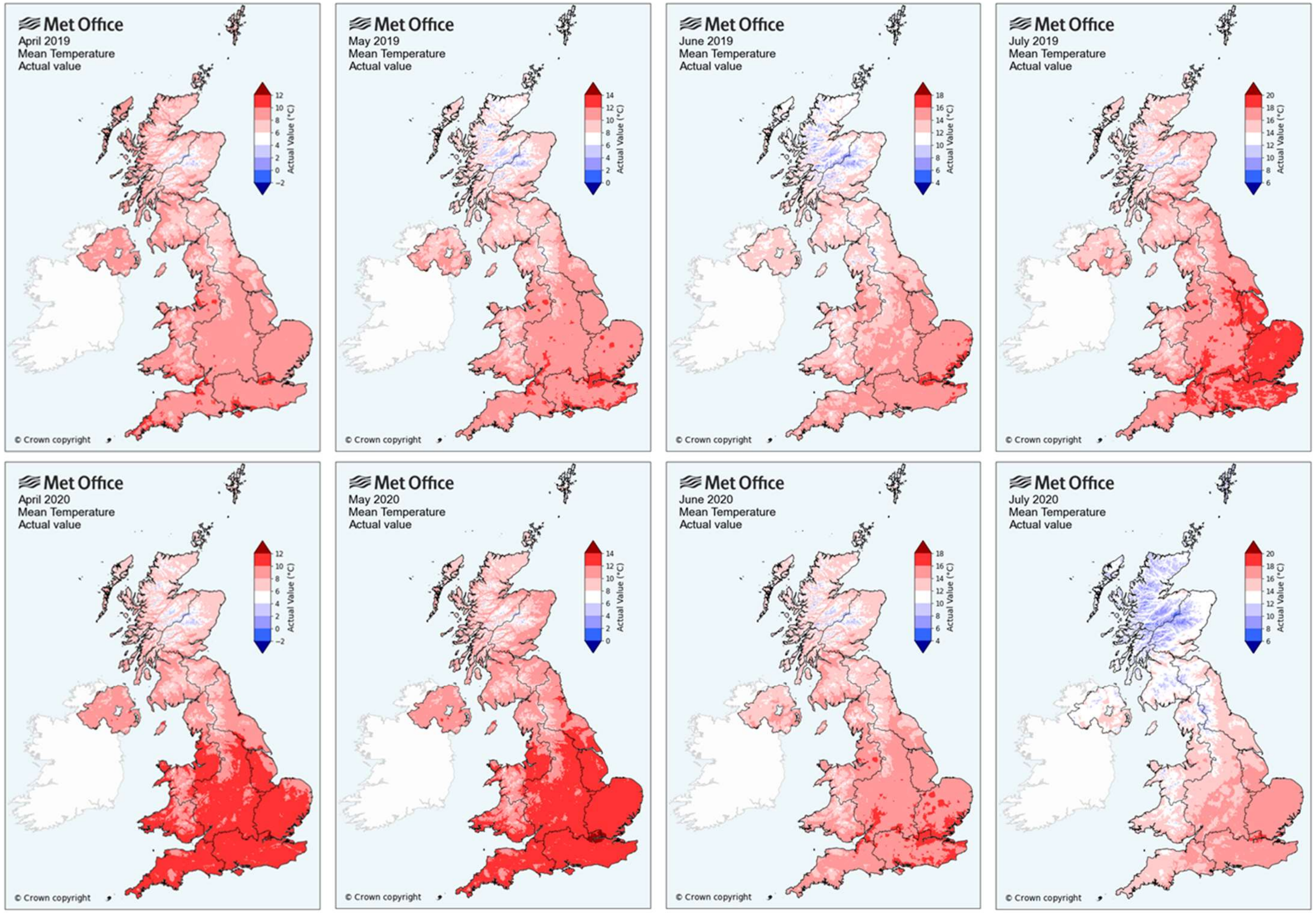

Figure 2. Met Office data showing the mean monthly temperature (°C) for the period April to July for 2019 and 2020.
https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-actual-and-anomaly-maps

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