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NECD Reporting 2022 – Quantifying and mapping exceedances of ozone flux-based critical levels for vegetation in the UK in 2019

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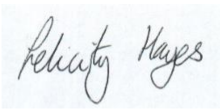

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Executive Summary

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*'. In order 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 year 2019. 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 for the years 2014-16 (Sharps et al., 2019), 2017 (Sharps et al., 2020a) and 2018 (Sharps et al., 2020b). 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, broad-leaf 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 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 shows:

- Reduced UK wheat production by 1.9%, based on POD_6SPEC, amounting to a production loss of 390,000 tonnes with an economic value of £62 million (at average weekly prices for 2019). The highest production losses were indicated for eastern counties of England, particularly Norfolk, Suffolk and Essex.
- Reduced UK potato yield by 2.6%, resulting in 130,000 lost tonnes of potato tubers worth £24 million, with the highest production losses in Norfolk, Cambridgeshire and Bedfordshire.
- Reduced oilseed rape production, however, the losses were lower than for the other crops. Ozone reduced UK oilseed rape production by 1.3% in 2019, amounting to 24,000 tonnes of lost production, worth £8 million. The highest production losses were predicted for central England.
- Total economic losses for wheat, potato and oilseed rape in the UK of £93.89 million, with the majority of losses (>96%) occurring in England.
- Calculated annual biomass increment losses for the UK for managed broadleaf woodland of 6.9% (and 7.6% 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 increment losses of coniferous trees for the UK of 1.3%. Ozone reduced annual biomass increment of coniferous trees less than broadleaf trees. The risk of potential effects across England was on average 1.4%, with some areas >1.5%, for example counties in the south-west.
- Reduced flower numbers in perennial grassland in the UK by 6.3%. 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 1.5%.

We provided maps and tables showing the exceedance of the ozone critical levels relevant for UK vegetation in 2019. In summary, we found that:

- Critical level exceedance was greatest for woodland habitats, with grasslands having intermediate exceedance and crops having low 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 (1.1% of wheat growing area). There was no exceedance for wheat in Wales, Scotland or Northern Ireland.

- Similarly, for potato, only England showed exceedance of the critical level (2.5% of potato growing area), with no exceedance for Wales, Scotland or Northern Ireland.
- Critical level exceedance for managed broadleaf woodlands was high for England and Wales (100% and 99.7% respectively), with the highest critical level exceedances in the south-west of England. Levels for Scotland were lower at 78.8%.
- 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 not exceeded in the UK in 2019.
- The percentage of the grassland areas of England where the critical level for flowering was exceeded was 31.6%.The highest critical level exceedances were in eastern and south-east England. Critical levels for this habitat were not exceeded in 2019 in Wales, 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.

In comparison to results on the ozone impact on UK vegetation for 2018, losses and critical level exceedance were lower in 2019 for the crops wheat, potato and oilseed rape, and for semi-natural vegetation. 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.

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 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 $POD_Y SPEC$ for the UK would be beneficial too.

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*'. In order 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.

In 2017, 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.

In 2019, 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.

In early 2020, 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.

In late 2020, the study was carried out using data for the year 2018. 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.

Here, we use the same methodology as the previous studies (Mills et al., 2017; Sharps et al., 2019, 2020a, 2020b), reporting results from the EMEP4UK ozone model for the year 2019. 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 version rv4.17 (Vieno et al., 2016) is based on the official EMEP MSC-W model (Simpson et al., 2012) and called here EMEP4UK. 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 version 3.7.1 is used to calculate hourly 3D meteorological data used to drive the EMEP4UK model for the year 2019. 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).

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 version of EMEP4UK used for the current report is the same as that used for the previous reports investigating ozone impacts on vegetation in the UK (Sharps et al., 2019, 2020a & b) therefore results can be compared between reports. This is in contrast to the Mills et al., (2017) report, which used EMEP4UK rv4.10. Model outputs for the two model versions did show some differences, with ozone flux values from rv4.17 being lower than outputs from rv4.10. This is thought to be for a number of reasons, including an update of the radiation equation used in the model, the resolution of a bug that was discovered in the official EMEP model, and many changes in the atmospheric chemistry of the model that have been included in the newer model version.

The EMEP4UK model (rv4.17) was parameterised for this study using ozone critical level parameterisations (see Annex 1 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 1, Table 1).

This year, a new EMEP4UK and WRF model domain (3km x 3km resolution, using polar stereo projection) has replaced the previous ~5km x 5km domain. The modelled PODySPEC data was 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.

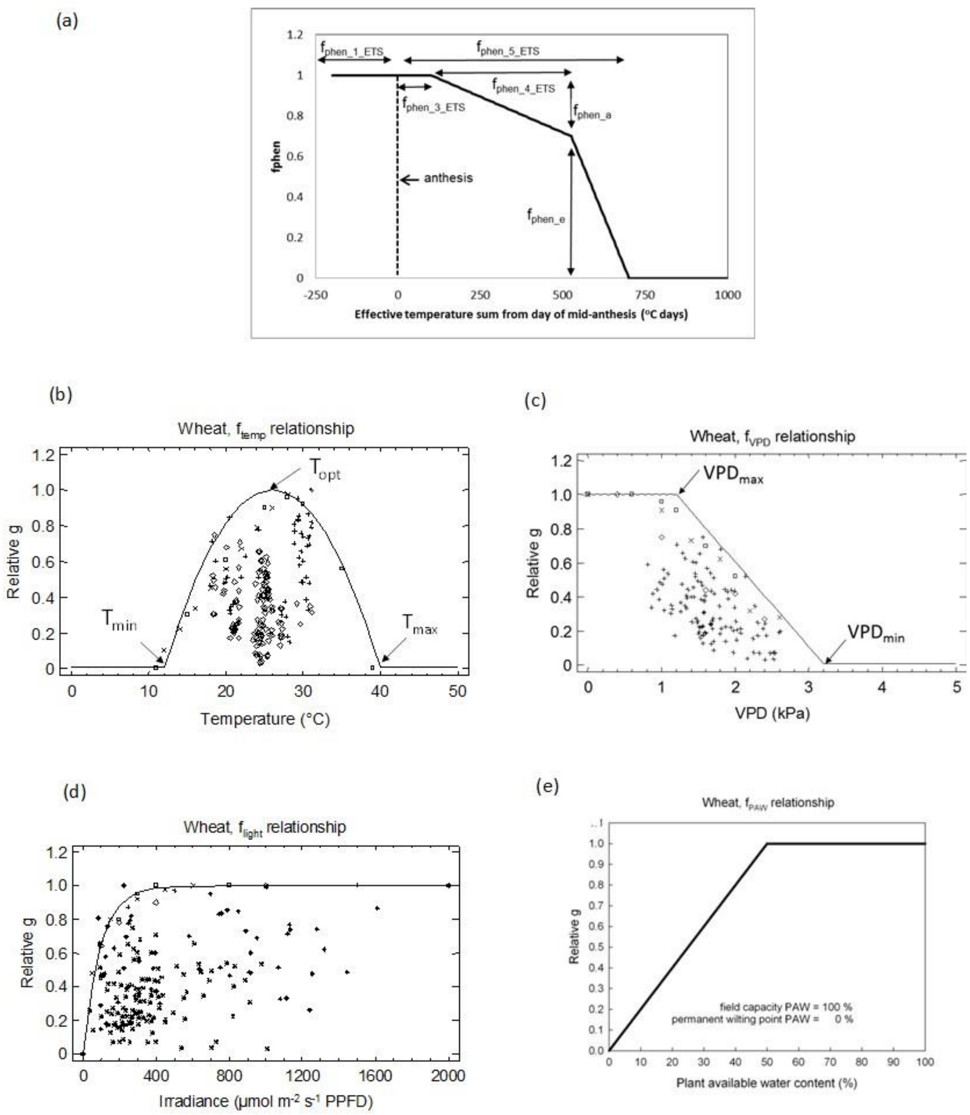

Figure 1: Illustration of the components of the DO_3SE stomatal flux model, showing for wheat how the stomatal conductance is modified by (a) phenology (growth stage), (b) temperature, (c) vapour pressure deficit - a measure of air humidity, (d), light and (e) plant available water - a measure of the soil water content.

2.2 Critical levels for ozone

The critical levels used in this study have been derived from exposure response relationships from experimental studies. Data included in the response functions was 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).

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$_6$SPEC [ii]**
Wheat	Grain yield	POD$_6$SPEC	5%	1.3	0.0	3.85
Potato	Tuber yield	POD$_6$SPEC	5%	3.8	0.0	1.34
Oilseed Rape	Seed yield	POD$_6$SPEC	NA	NA	NA	1.10
Beech and birch	Whole tree biomass [iii]	POD$_1$SPEC	4%	5.2	0.9	0.93
Norway spruce	Whole tree biomass [iii]	POD$_1$SPEC	2%	9.2	0.1	0.22
Temperate perennial grassland	Total biomass [iii,iv]	POD$_1$SPEC	10%	16.2	0.1	0.62
Temperate perennial grassland	Flower number[v]	POD$_1$SPEC	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$_6$SPEC – Ref10 POD$_6$SPEC) 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).

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). Oilseed rape has been included in the analysis however 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.

Note, due to data availability, in 2019, 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.

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 v. 2.7.14 and maps were created using R (R Core Team, 2021).

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 CEH 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) was 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). For potatoes, price data 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 - 11) 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

Three major UK crops with a combined area of ~2.5 million hectares were considered in this study: wheat, potato and oilseed rape.

Wheat is grown most extensively in England. In 2019, only 1% was grown in areas exceeding the ozone critical level of 1.3mmol m^{-2}. The average yield loss was 2.3% and the loss in production was 382,000 tonnes with an economic value of £60.96 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 0.98% of the UK wheat production in 2019 was in areas where the critical level was exceeded. The average yield loss for the UK was 1.9% resulting in a production loss of 389,000 tonnes with an economic value of £62.07 million. The highest ozone fluxes in 2019 were in England, in the eastern counties of Norfolk, Suffolk and Essex, and there were patches of higher values in the southern counties of Kent and Sussex (Figure 2). The highest production losses were indicated for eastern counties of England, particularly Norfolk, Suffolk and Essex (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

Critical level exceedance values for wheat in 2019 were considerably lower than values for 2018 (Sharps et al., 2020b) for England and Wales. Ozone fluxes have been shown to fluctuate between years (Sharps et al., 2019), and data for 2019 show more similar patterns to those seen in 2015. Average yield loss for the UK has also fluctuated across the years, at 3.7% (2014), 2.2% (2015), 3.6% (2016), 5.7% (2017) and 5.5% in 2018. Wheat production does vary slightly between years, for example, the UK total was 14.8 M tonnes in 2017, 13.6 M tonnes in 2018 and 14.8 M tonnes in 2019 and this will affect estimates of total production loss. In terms of economic losses, the total loss for the UK was considerably lower for 2019 (£62.07 million) compared to 2018 (£112.5 million).

Potato is classed as moderately sensitive to ozone and is thus less sensitive than wheat (Mills et al., 2007). In 2019, 2.5% of the potato growing areas in England had ozone fluxes that exceeded the critical level of 3.8 mmol m^{-2}. There was no critical level exceedance for potato in Wales, Scotland and N. Ireland (Table 4, Figure 4). The average yield loss in England was 3.3% and the loss in production was 119,000 tonnes with an economic value of £21.99 million (Table 4). Across all of the UK potato production areas, the mean yield loss was 2.6%, resulting in 130,000 lost tonnes of potato tubers worth £24.04 million. The highest values for ozone flux were seen in eastern England, with moderate values across eastern and southern England, and in patches of south-east Wales (Figure 4). 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 and Bedfordshire (Figure 5).

In comparison to 2018 (Sharps et al., 2020b), the area of critical level exceedance in 2019 was considerably smaller across the UK, particularly for England and Wales. Losses in 2019 were more similar to those seen in the years 2014-2016 (Sharps et al., 2019). Economic losses in England in 2019 (£21.99 million loss) were lower than for 2018 (£44.6 million), and 2017 (£29.1 million loss). In Scotland, the economic loss of £1.7 million in 2019 was considerably lower than the estimate of £4.2 million in 2018 (Sharps et al., 2020b), being more similar to the estimate of £1 million in 2017 (Sharps et al., 2020a).

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	1656125	17610	1.1	14831	382	2.3	60.96
Wales	23256	0	0	162	1.19	0.7	0.19
Scotland	103147	0	0	851	5.68	0.5	0.91
NI	7147	0	0	32	0.07	0.2	0.01
UK	1789675	17610	0.98	15876	389	1.9	62.07

Table 4: 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	2482	2.5	3542	119	3.3	21.99
Wales	1936	0	0	31	0.93	2.9	0.17
Scotland	25058	0	0	960	9.23	0.9	1.70
NI	3415	0	0	107	0.97	0.9	0.18
UK	128350	2482	1.93	4640	130	2.6	24.04

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 (Figures 6&7).

In 2019, the average yield loss for the UK was low, estimated at 1.3%, amounting to 24,000 tonnes of lost production, worth £7.78 million (Table 5). Ozone flux values were highest in England (Figure 6). Oilseed rape growing in northern, central, eastern and south-eastern areas of England had potential yield losses of >1.5% (Figure 6). The highest production and economic losses (>45 tonnes and >£10,000 per 5km x 5km square respectively) were predicted for central England (and parts of North Yorkshire), where moderate ozone fluxes coincided with areas of high oilseed rape production per 5km x 5km square (Figure 7).

In comparison to 2018 (Sharps et al., 2020b), results for 2019 suggest a slightly reduced level of yield losses due to ozone for oilseed rape. In turn, production losses in 2019 were also reduced, particularly for England (where the majority of GB production occurs). Economic losses due to ozone were estimated at £10.8 M for England in 2018, compared to £7.51 M in 2019. Despite slight fluctuations between years, the location of the highest crop losses has not varied much spatially (i.e. central England) (Sharps et al., 2019, 2020a).

Table 5: 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	23.14	1.4	7.51
Wales	5458	NA	NA	8	0.09	1.1	0.03
Scotland	30412	NA	NA	82	0.73	0.9	0.24
NI	663	NA	NA	NA	NA	NA	NA
UK	535938	NA	NA	1657	23.96	1.3	7.78

NA: Not applicable

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

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 8).

In 2019, the ozone critical level of 5.2 mmol m^{-2} was exceeded in 100%, 99.7% and 78.8% of the area of this habitat in England, Wales and Scotland respectively (Table 6a). The overall exceeded area for the UK was 96.9%, with an average indicative biomass increment loss of 6.9%. The level of exceedance was greatest for woodland areas in south-west England (Cornwall and Devon) and patches of the south-west coast of Wales (Figure 8). Predicted biomass increment loss was highest in south-west England (>9%), with other patches of high loss, for example in south-west Wales and south-east England (Figure 8).

In comparison to 2018 (Sharps et al., 2020b), ozone flux values for managed broadleaf were generally similar in 2019 in England and Wales. In Scotland, however, values had reduced back to the levels seen in 2014 – 2017 (Sharps et al., 2019, 2020a). Between 2014 – 2018, average UK % biomass increment loss has been broadly similar between years, ranging from 5.9% in 2015 to 7.3% in 2018. The value for 2019 (6.9%) continues this pattern. Examination of the maps for each year shows some spatial variation in the areas with the greatest critical level exceedance. For example in 2014, the greatest exceedance was seen in the south-east of England while in 2015-2019, exceedance was greatest in the south-west of England. In 2019, % biomass increment loss decreased in many parts of England compared to 2018, for example, there were less areas of 8-9% losses in central England in 2019 compared to 2018, while in northern Scotland, losses in 2019 were primarily between 0-5%, compared to 5-7% in 2018.

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 9). In 2019, the ozone critical level was exceeded in 100% of the area of this habitat in England, Wales and Scotland (Table 6b). For the UK overall, the average indicative biomass increment loss was 7.6%. The level of exceedance was greatest in the south-west of England, where in some areas biomass increment losses of >9.5% were predicted (Figure 9).

In comparison to 2018 (Sharps et al., 2020b), biomass increment losses were generally slightly lower in 2019 across GB. Biomass increment losses decreased in northern England from primarily 7-9.5% in 2018 to more areas of 6-7% in 2019, while in southern England, values reduced from 8-9.5% to more areas of 7-8%. As for managed broadleaf woodland however, the UK average % biomass increment loss has been broadly similar between 2014-2019, ranging from 6.6% (2015, 2016) to 7.9% in 2018.

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}. The critical level was not exceeded in any of the areas in the UK where this habitat is found in 2019 (Table 6c, Figure 10). Average indicative biomass increment losses were lower than for broadleaf woodland, with all estimated losses being below 1.5%. In 2019, the majority of grid squares in England, Wales and N. Ireland suggested predicted losses of 1 -1.5%, with some areas with higher losses (>1.5%) particularly south-west England (Figure 10). In the south of Scotland the majority of estimated biomass increment losses were between 1 - 1.5%, while in the north of the country, there were more areas of loss between 0 – 1% (Figure10).

The critical level has not been exceeded and average biomass increment losses were similar for 2014 – 2019 (<2%). Spatial data show that biomass increment losses decreased slightly in 2019 compared to 2018, particularly in northern Scotland, and also there were less areas with >1.5% losses for England and Wales, with higher values seen mostly in the south-west and south-east of each country. However, the maximum annual biomass increment loss for this vegetation type remains relatively low.

Table 6: 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	556218	100	7.4
Wales	80621	80361	99.7	7.5
Scotland	108705	85667	78.8	5.7
NI	NA	NA	NA	NA
UK	745667	722246	96.9	6.9

Country	(b) Unmanaged Beech woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	58053	58053	100	7.7
Wales	5821	5821	100	7.6
Scotland	312	312	100	7.2
NI	NA	NA	NA	NA
UK	64186	64186	100	7.6

Country	(c) Managed coniferous woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	171274	0	0	1.4
Wales	105263	0	0	1.4
Scotland	511583	0	0	1.1
NI	50148	0	0	1.1
UK	838268	0	0	1.3

(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.

In 2019, the ozone critical level for flowering of ozone-sensitive grassland species (6.6 mmol m^{-2}) was exceeded in England (31.6%) but not Wales, Scotland or N. Ireland (Table 7a, Figure 11).The indicative risk analysis suggested an average of 6.3% loss in flower number for the UK, with the highest losses (>11%) occurring mostly in areas of eastern and south-east England (Figure 11). This could potentially affect plant species composition and/or diversity.

In comparison to 2018 (Sharps et al., 2020b), ozone flux values in 2019 were lower for this vegetation type across the UK, leading to lower levels of critical level exceedance and flower number losses. For example, in 2018, the critical level was exceeded for ~63% of this habitat in Wales while in 2019 there were no areas of exceedance. In addition, in 2018 the majority of areas in England showed estimated flower number losses of 12 - 15%, and >15%, while in 2019, there were many more areas with estimated losses of 8 -11%. Average flower loss for the UK had been increasing between 2015 (3.7%) and 2018 (10%), but the value has decreased for 2019 (6.3%).

The critical level for effects of ozone on grassland annual increment of total biomass is higher at 16.2 mmol m^{-2} and was not exceeded anywhere for this habitat in the UK in 2019 (Table 7b; maps not presented). Hence, biomass losses were well below 10% (as defined by the critical level), with an average value of 1.5% for the UK.

Average biomass losses have fluctuated slightly over the period 2014 - 19. Estimated losses in England were at their highest in 2018 at 3.5% (1.9% in 2014; 1.4% in 2015; 1.7% in 2016, 2.2% in 2017, 2.1% in 2019). However, the critical level has not been exceeded over the 5-year period.

Table 7: 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	190589	31.6	8.9
Wales	334078	0	0	6.4
Scotland	846649	0	0	3.7
NI	126405	0	0	4.9
UK	1911016	190589	9.97	6.3

Country	(b) Grassland total biomass			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	603884	0	0	2.1
Wales	334078	0	0	1.5
Scotland	846649	0	0	0.8
NI	126405	0	0	1.0
UK	1911016	0	0	1.5

3.3 Spatial and temporal variation in ozone flux

In 2018, ozone fluxes and critical level exceedance were greater than previous years, particularly for the crops potato and oilseed rape, and for semi-natural vegetation (Sharps et al., 2020b). In 2019, levels reduced again and were more similar to values for the period 2014-2017.

For woodland, results for 2019 showed slight decreases compared to 2018, however were generally similar to those for the period 2014 -17, with some spatial variation in ozone fluxes, losses and critical level exceedance between years.

The previous reports spanning the period 2014 – 18 (Sharps et al., 2019, 2020a, 2020b) showed spatial and temporal variation in ozone flux values for the UK, with examination of model inputs suggesting that these patterns were 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.

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.

Met Office data allows a closer examination of UK temperature changes between years, relative to a 1961-1990 reference period (for background information on the methodology, see Morice et al., 2012). A comparison between annual temperature anomalies across the UK for the years 2017-2019 shows that temperatures were higher in the summer of 2018 than in both 2017 and 2019, particularly for England and Wales, and for parts of Scotland and Northern Ireland (Annex, Figure 1a, b &c).

The previous reports spanning the period 2014 – 18 (Sharps et al., 2019, 2020a, 2020b) show that the vegetation types studied can respond differently in a particular year (for example high losses estimated for potato but not for wheat). 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. 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 temperatures shown in the Met Office figures (Annex, Fig. 1) coincide with the growing season for all vegetation types included in this report. 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. In 2018, potatoes showed the largest increase in critical level exceedance and yield loss compared to previous years. This crop has a longer accumulation period (used to calculate ozone flux) and a higher g_{max} than wheat (Annex, Tables 1 & 2). Similarly, while the g_{max} of oilseed rape is more similar to that for wheat, the ozone flux accumulation period is considerably longer (Annex, Tables 1 & 2). For the woodland habitat types, ozone impacts have not varied greatly between years, with critical levels exceeded in many areas for broadleaved woodland across the period 2014-2019, particularly in England and Wales. In 2018 however, ozone flux values were higher across Scotland too, leading to a higher level of critical level exceedance for this habitat for this extreme year. In contrast, for managed coniferous woodland, critical levels have not been exceeded at all for the UK over the period 2014-19, with this vegetation type having lower ozone sensitivity, a higher critical level and relatively low value for g_{max}.

3.4 Ozone impacts maps for crops, trees and grasses

Wheat (POD_6SPEC for grain yield)

(Note: For comparison purposes, map scales have been kept the same as for the 2014-18 reports for each vegetation type).

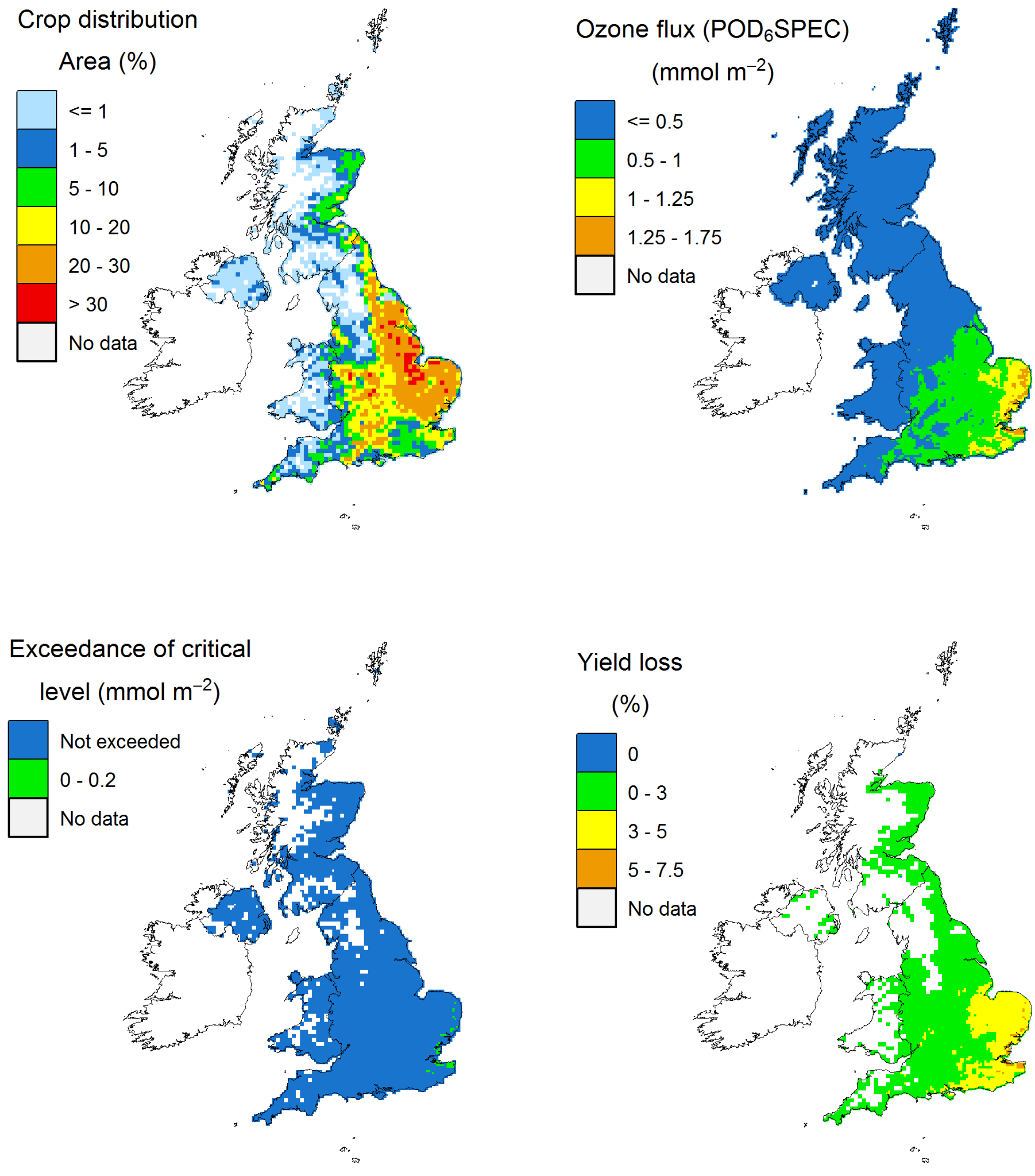

Figure 2: Impacts of ozone on wheat production in 2019 calculated using POD_6SPEC. (a) Distribution of wheat presented as the percentage of each 5km x 5km grid square sown with wheat; (b) POD_6SPEC (mmol m^{-2}) (**critical level = 1.3 mmol m^{-2}**); (c) Exceedance of the critical level; (d) Percentage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

Wheat (POD_6SPEC for grain yield)

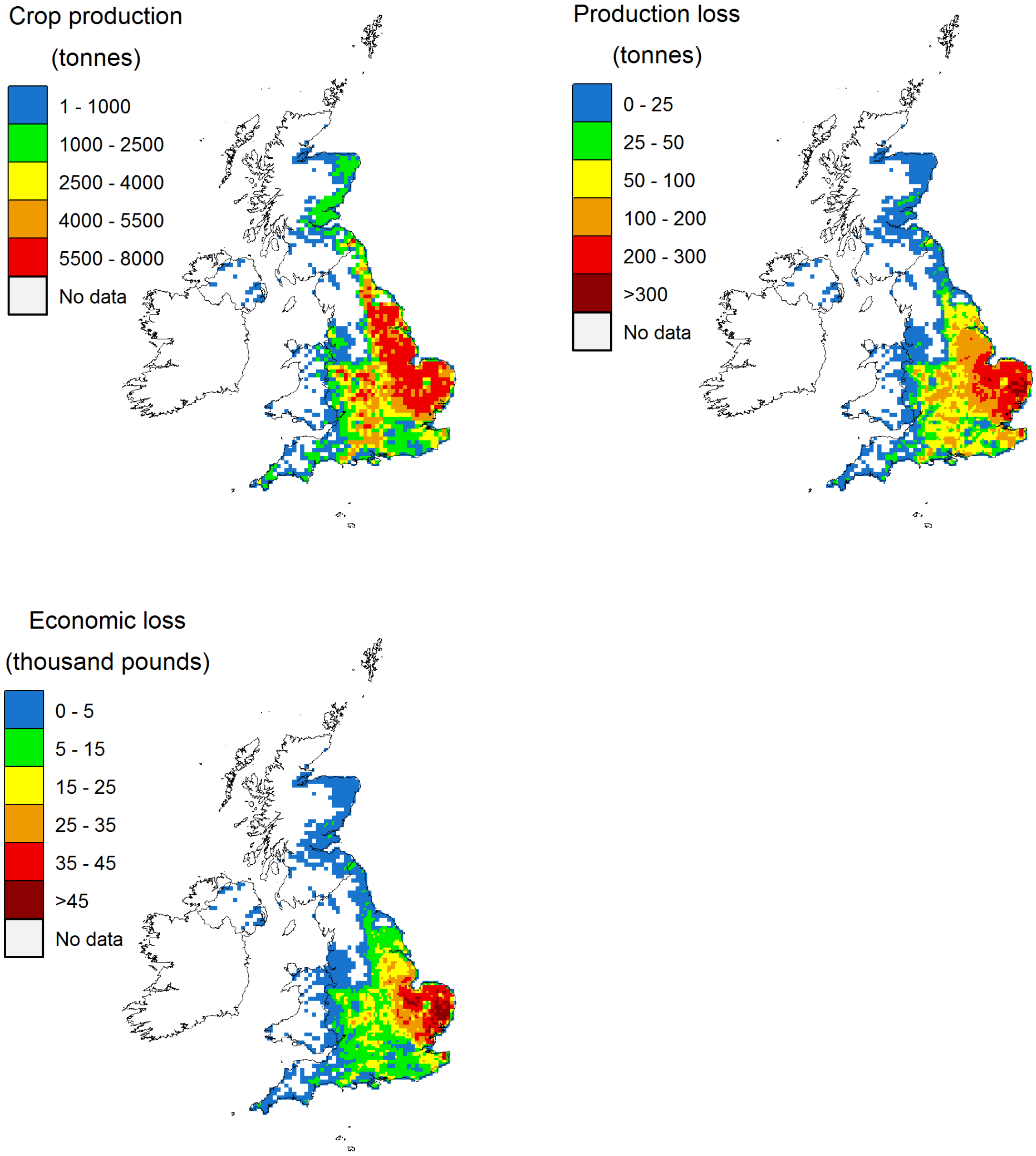

Figure 3: Impacts of ozone on wheat production in 2019 calculated using POD_6SPEC. (a) Wheat production in the UK in tonnes per 5km x 5km grid square; (b) Production loss due to ozone in tonnes per 5km x 5km grid square; and (c) Economic loss in thousand £UK per 5km x 5km grid square, based on mean price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

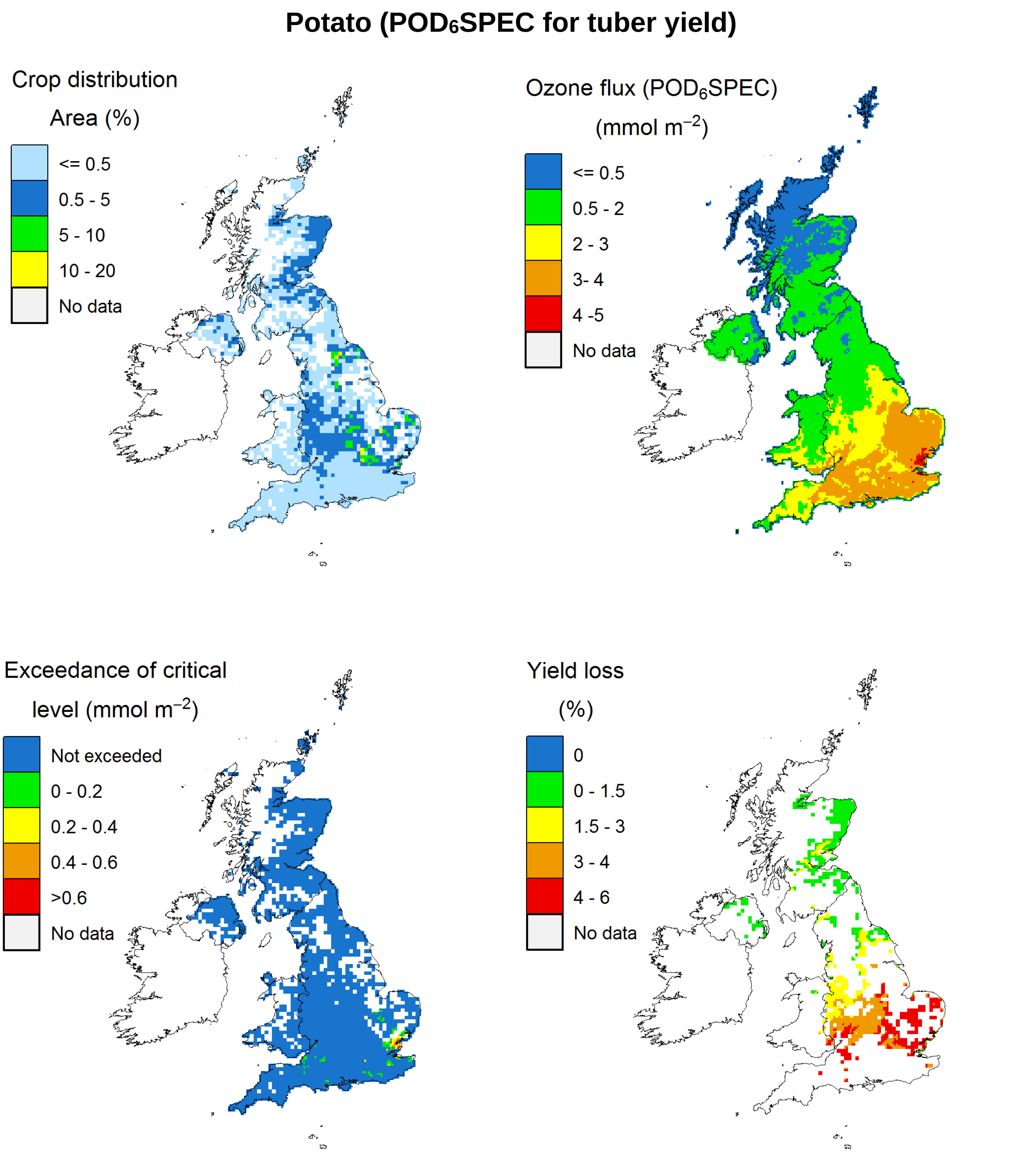

Figure 4: Impacts of ozone on potato production in 2019 calculated using POD6SPEC. (a) Distribution of potato presented as the percentage of each 5km x 5km grid square sown with potato; (b) POD6SPEC (mmol m^{-2}) (**critical level = 3.8 mmol m^{-2}**); (c) Exceedance of the critical level; (d) Percentage yield loss.

Potato (POD_6SPEC for tuber yield)

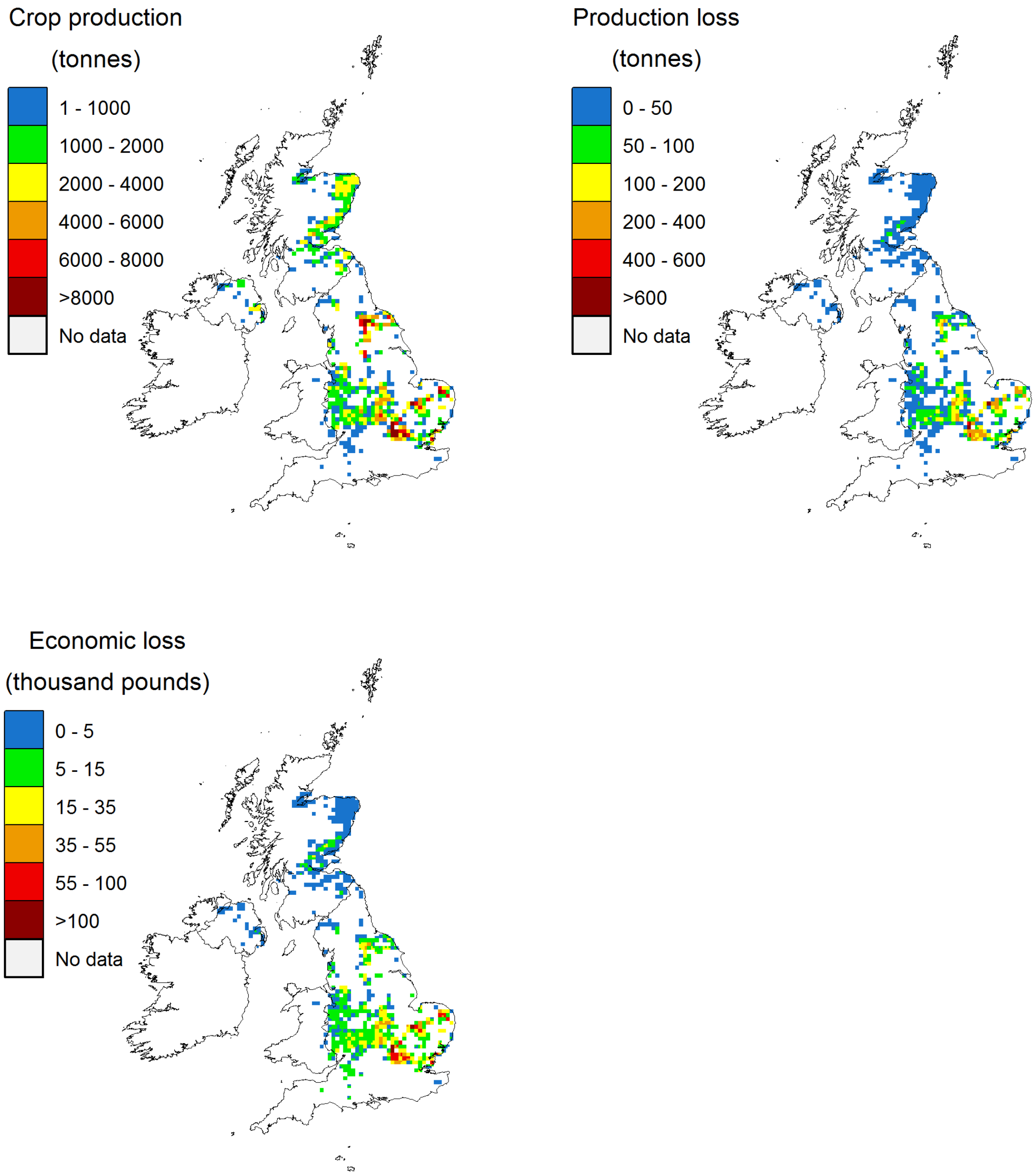

Figure 5: Impacts of ozone on potato production in 2019 calculated using POD_6SPEC. (a) Potato production in the UK in tonnes per 5km x 5km grid square; (b) Production loss due to ozone in tonnes per 5km x 5km grid square; and (c) Economic loss in thousand UK£ per 5km x 5km grid square, based on mean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

Oilseed rape (POD_6SPEC for grain yield)

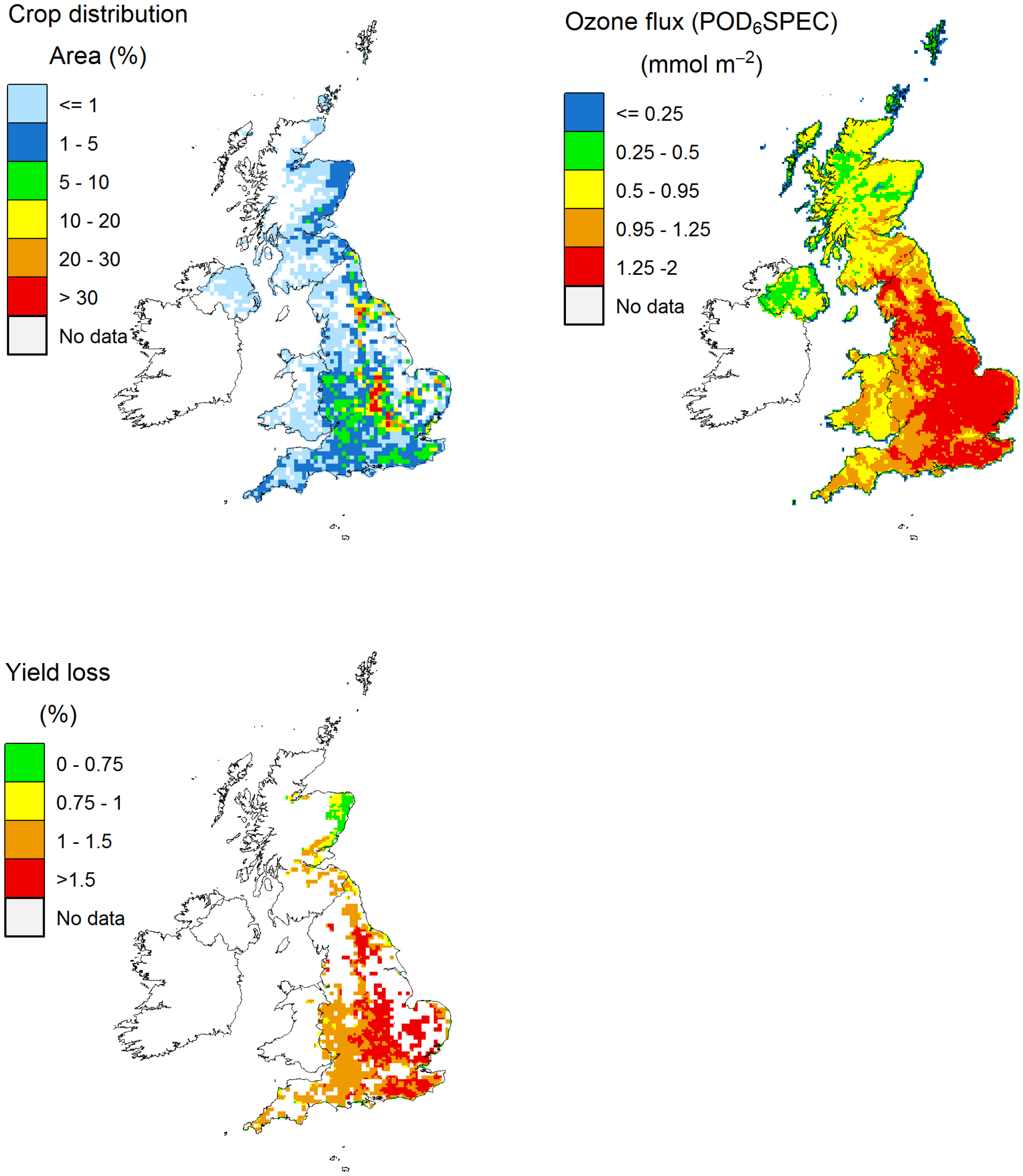

Figure 6: Impacts of ozone on oilseed rape production in 2019 calculated using POD_6SPEC. (a) Distribution of oilseed rape presented as the percentage of each 5km x 5km grid square sown with oilseed rape; (b) POD_6SPEC (mmol m^{-2}); (c) Percentage yield loss.

Oilseed rape (POD$_6$SPEC for grain yield)

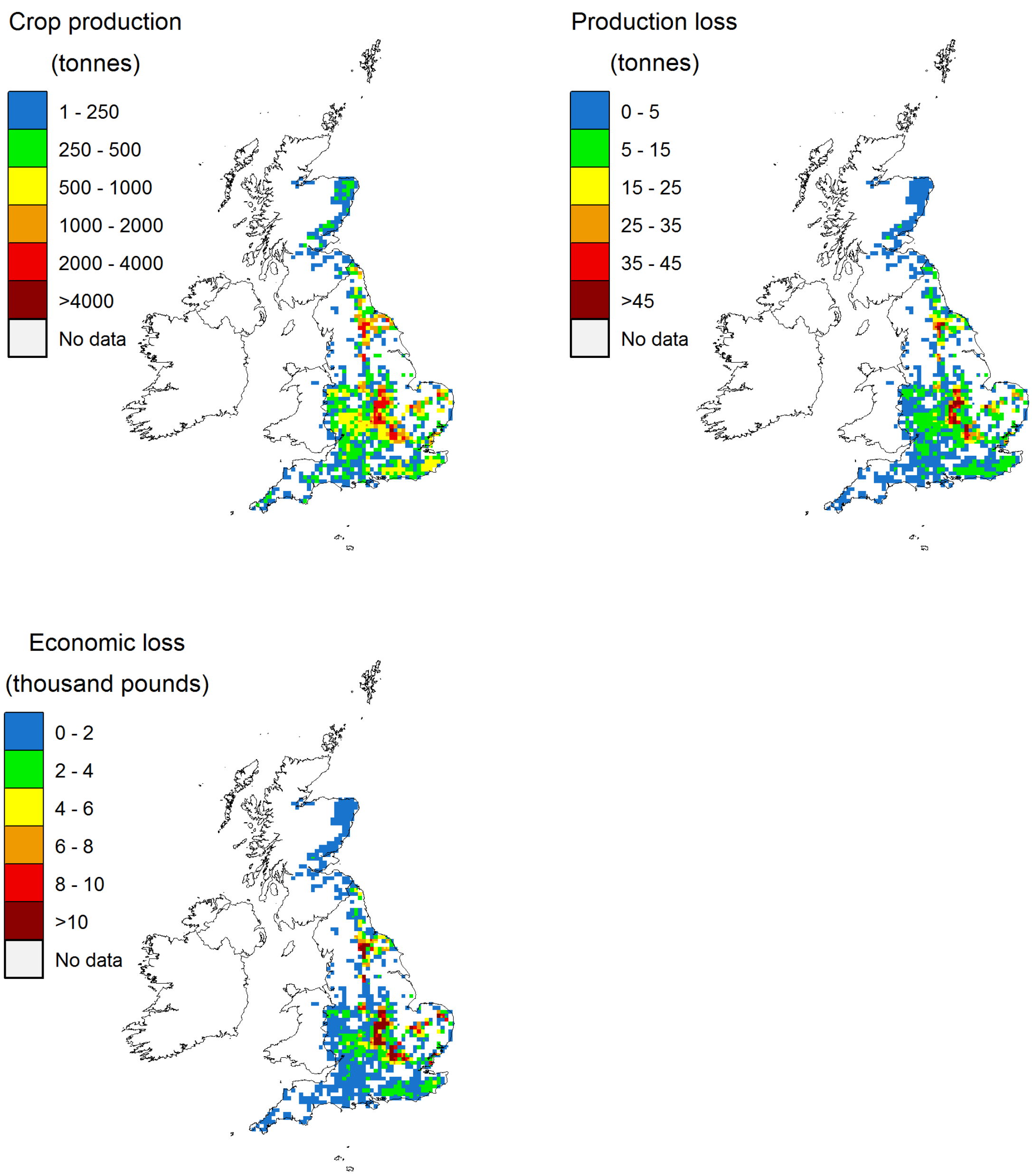

Figure 7: Impacts of ozone on oilseed rape production in 2019 calculated using POD$_6$SPEC. (a) Oilseed rape production in the UK in tonnes per 5km x 5km grid square; (b) Production loss due to ozone in tonnes per 5km x 5km grid square; and (c) Economic loss in thousand UK£ per 5km x 5km grid square, based on mean price in 2019.

Managed broadleaved woodland (POD_1SPEC for biomass increment)

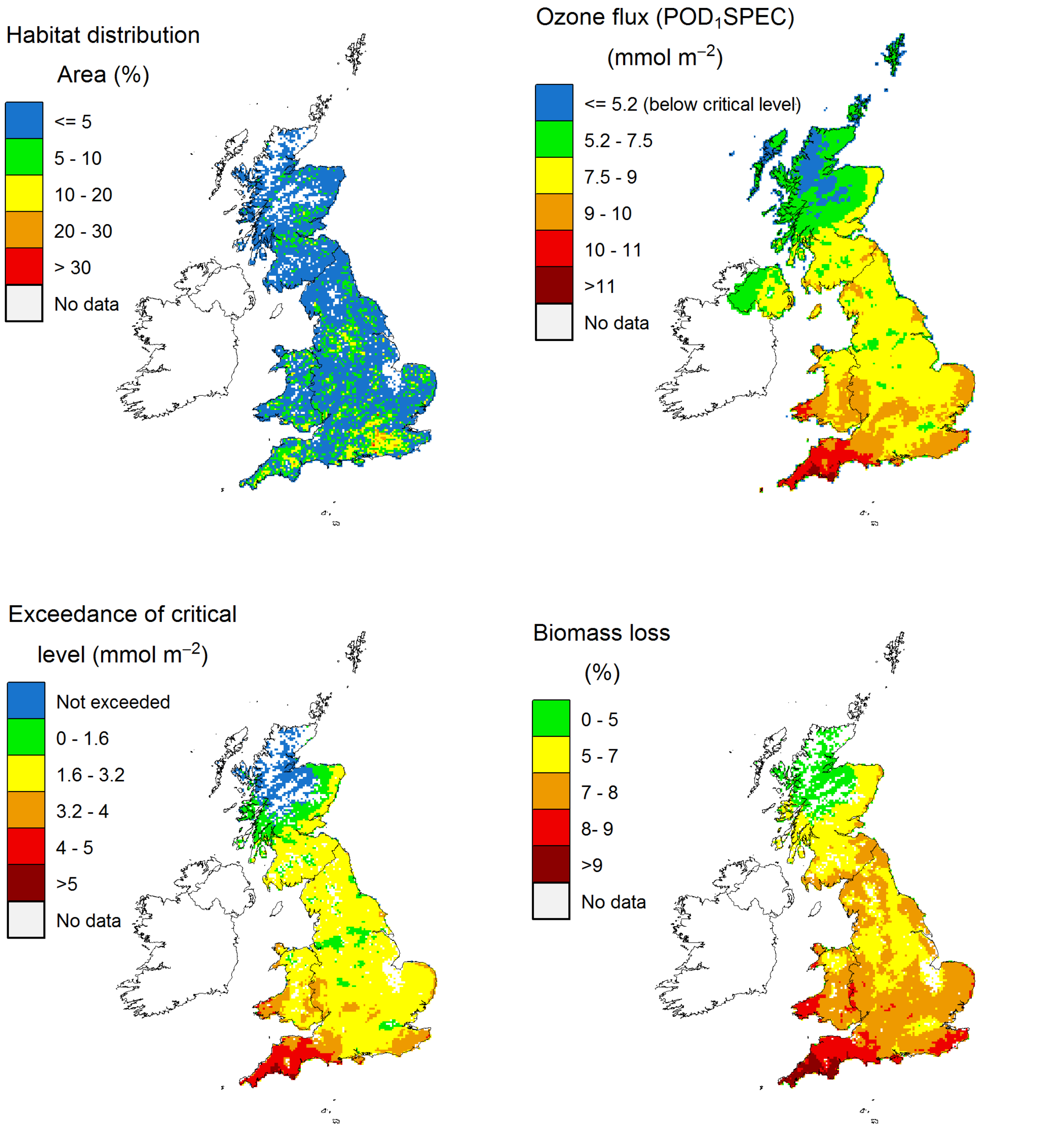

Figure 8: Impacts of ozone on managed broadleaf woodland in 2019 calculated using POD_1SPEC. (a) Distribution of managed broadleaf woodland as the percentage area of each 5km x 5km grid square; (b) POD_1SPEC (mmol m^{-2}), all squares coloured blue have POD_1SPEC values below the **critical level of 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)

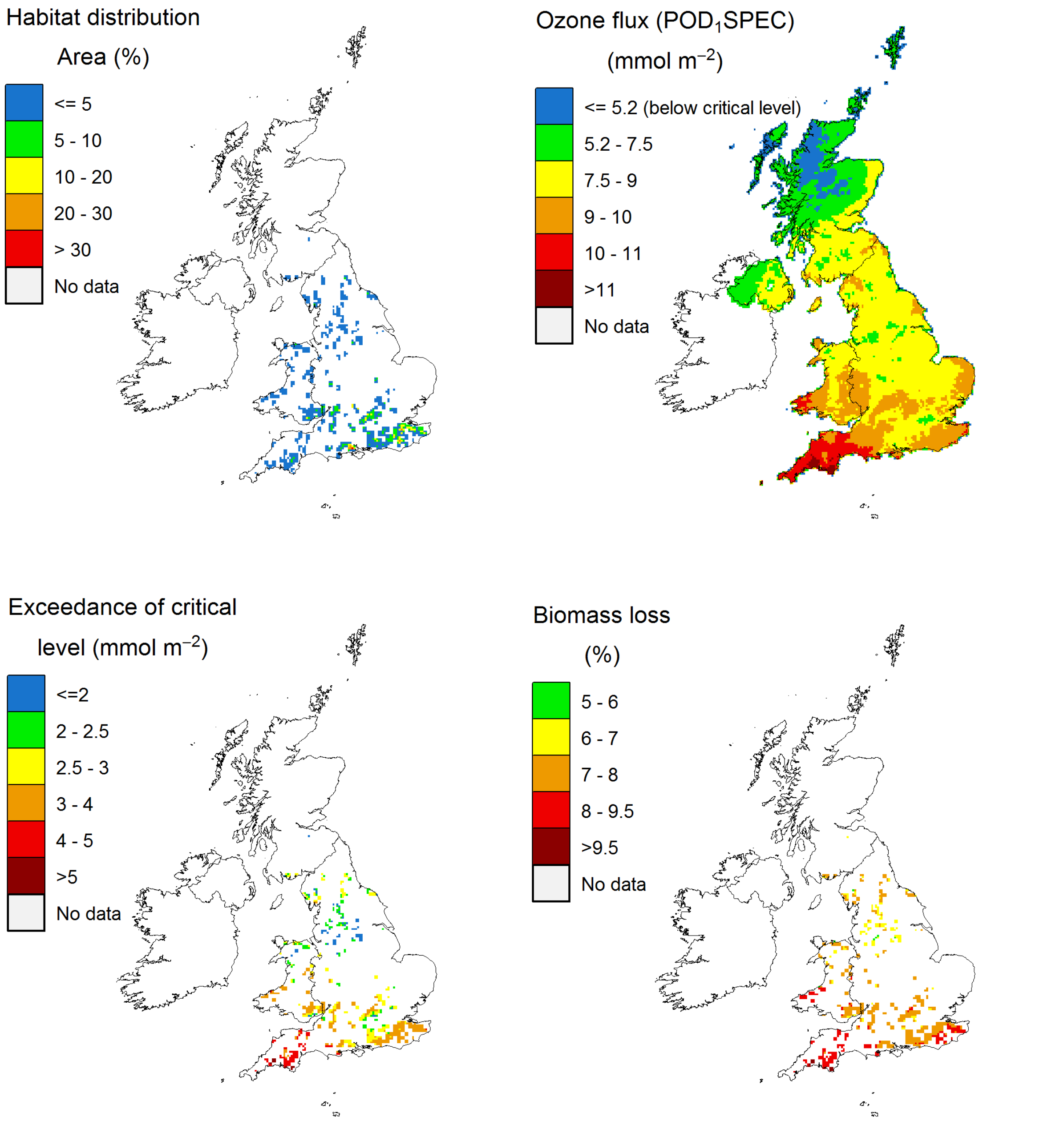

Figure 9: Impacts of ozone on unmanaged beech woodland in 2019 calculated using POD_1SPEC. (a) Distribution of unmanaged beech woodland as the percentage area of each 5km x 5km grid square; (b) POD_1SPEC (mmol m^{-2}), all squares coloured blue have POD_1SPEC values below the **critical level of 5.2 mmol m^{-2}**; (c) exceedance of the critical level; (d) Percentage biomass loss (indicative risk only).

Managed coniferous woodland (POD_1SPEC for biomass increment)

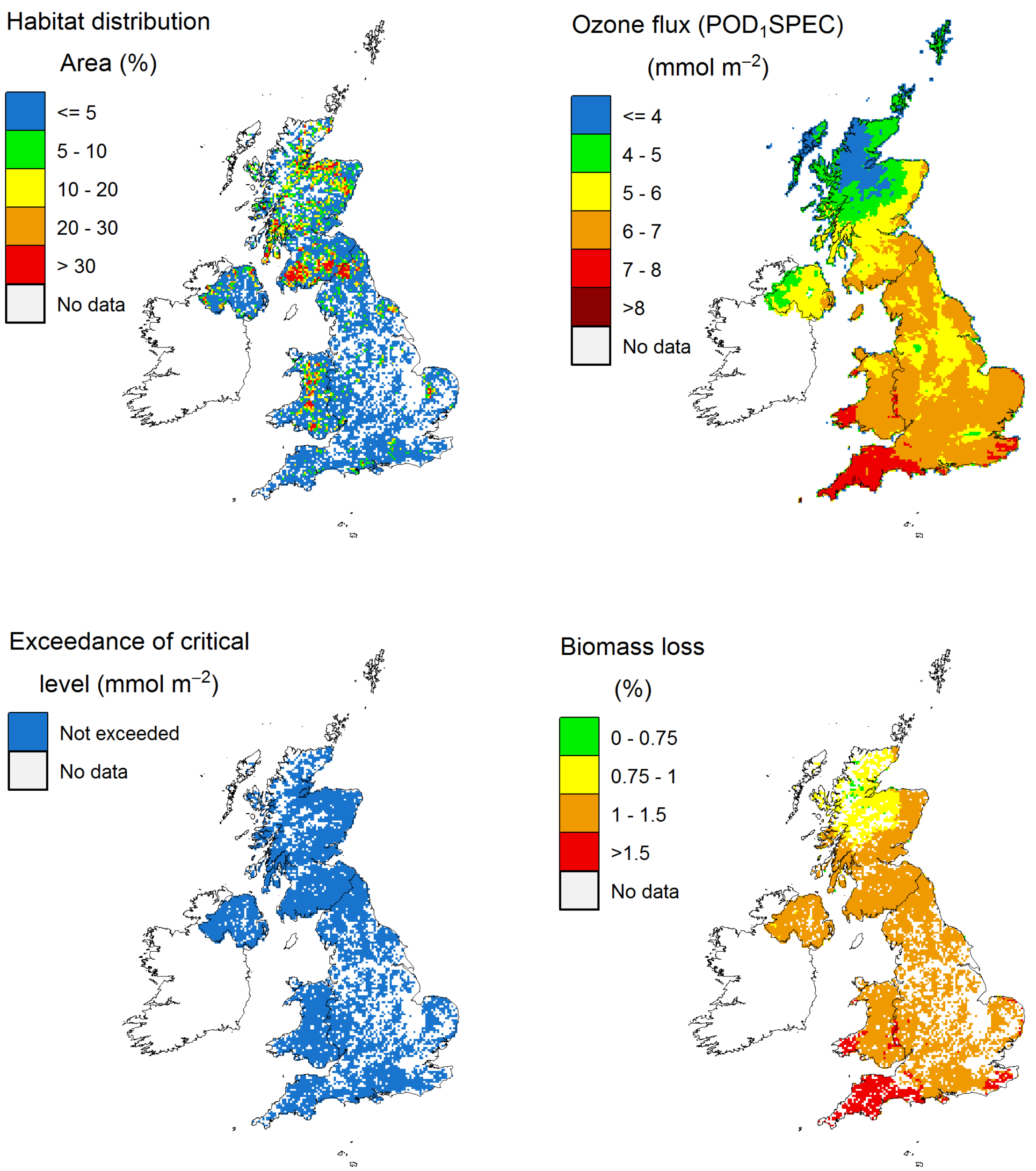

Figure 10: Impacts of ozone on managed coniferous woodland in 2019 calculated using POD_1SPEC. (a) Distribution of managed coniferous woodland as the percentage area of each 5km x 5km grid square; (b) POD_1SPEC (mmol m^{-2}) (**critical level = 9.2 mmol m^{-2}**); (c) exceedance of the critical level; (d) Percentage yield loss (indicative risk only).

Perennial grassland (POD_1SPEC for flower numbers)

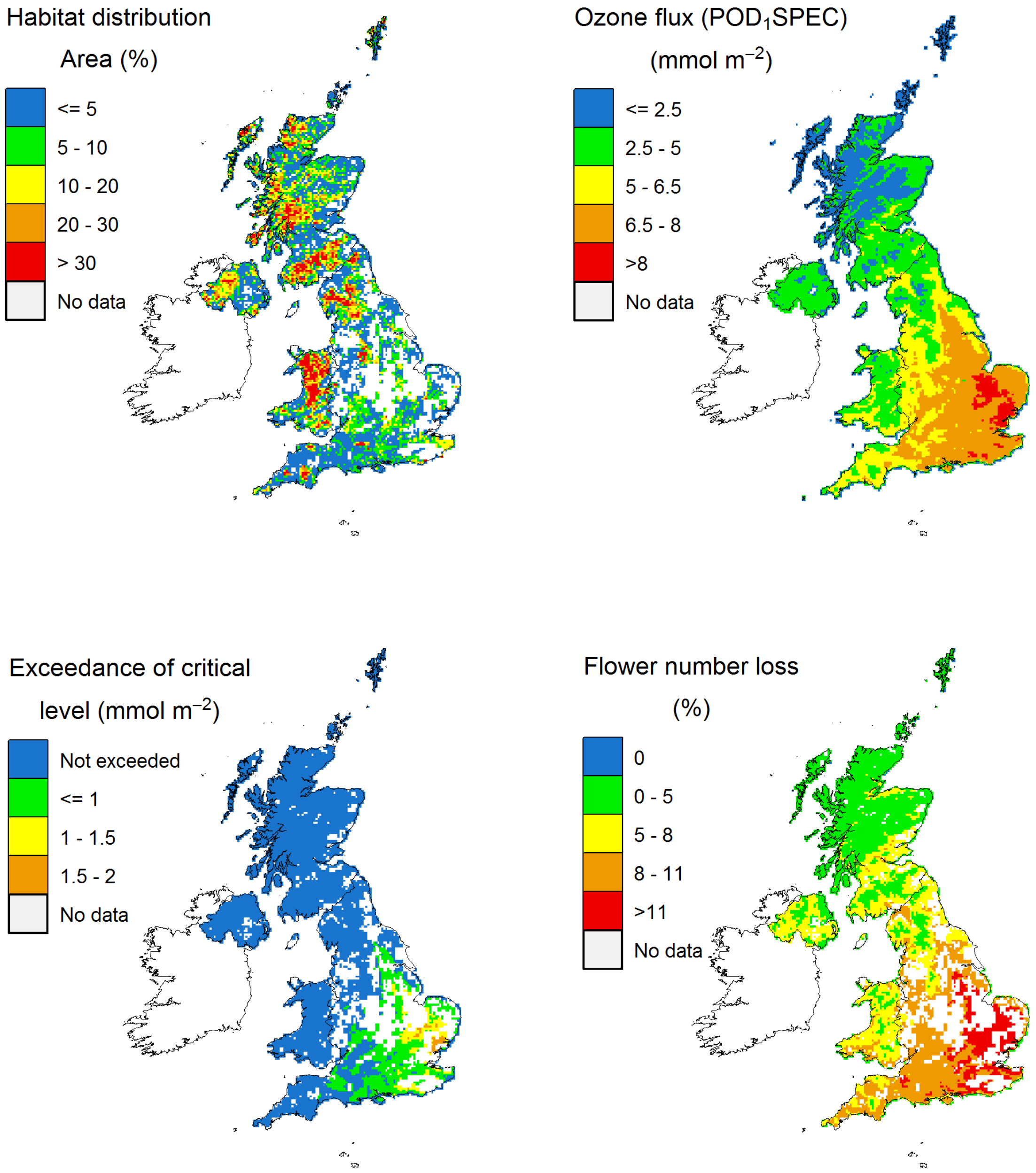

Figure 11: Impacts of ozone on perennial (semi-natural) grassland in 2019 calculated using POD_1SPEC. (a) Distribution of grassland as the percentage area of each 5km x 5km grid square; (b) POD_1SPEC (mmol m^{-2}) (**critical level = 6.6 mmol m^{-2}**); (c) Exceedance of the critical level; (d) Percentage flower number loss (indicative risk only).

4 Sources of uncertainty in 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.

4.1 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. 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 several more stages are required to analyse effects on timber production or carbon sequestration in trees.

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 UK CEH 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.

4.2 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.

This year, a new EMEP and WRF model domain (3km x 3km resolution, using polar stereo projection) has been 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 Mapping crop 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. 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 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.

Economic losses are provided as an indicative cost based on the mean price over the year 2019. Previous reports (Sharps et al., 2019, 2020a, 2020b) used mean crop prices for the period 2014-2016 as updated price data were not readily available at the time of writing. The crop prices for 2019 show an increase for all the crops studied. An investigation into crop prices for wheat and potato suggested that prices had also increased in 2018, therefore the reported economic losses due to ozone for 2018 may have been slightly underestimated.

The habitat distribution maps 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).There are plans to update the habitat distribution data for the UK (currently based on land cover data for the year 2000) by UK CEH colleagues working with critical loads data (including nitrogen, acidity (sulphur + nitrogen) and ammonia). These data will also be useful for future mapping of ozone critical level exceedance.

5 Conclusions

This study was undertaken to build on the scoping study to investigate the ozone impact on UK vegetation in 2015 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) and 2018 (Sharps et al., 2020b). The study provides information relevant to Article 9 and Annex V of the amended NECD (Directive (EU) 2016/2284), 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 year 2019.

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 risk of ozone impacts on crops, trees and grassland in 2019 shows:

- Reduced UK wheat production by 1.9%, based on POD_6SPEC, amounting to a production loss of 390,000 tonnes with an economic value of £62 million (at average weekly prices for 2019). The highest production losses were indicated for eastern counties of England, particularly Norfolk, Suffolk and Essex.
- Reduced UK potato yield by 2.6%, resulting in 130,000 lost tonnes of potato tubers worth £24 million, with the highest production losses in Norfolk, Cambridgeshire and Bedfordshire.
- Reduced oilseed rape production, however, the losses were lower than for the other crops. Ozone reduced UK oilseed rape production by 1.3% in 2019, amounting to 24,000 tonnes of lost production, worth £8 million. The highest production losses were predicted for central England.
- Total economic losses for wheat, potato and oilseed rape in the UK of £93.89 million, with the majority of losses (>96%) occurring in England.
- Calculated annual biomass increment losses for the UK for managed broadleaf woodland of 6.9% (and 7.6% 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 increment losses of coniferous trees for the UK of 1.3%. Ozone reduced annual biomass increment of coniferous trees less than broadleaf trees. The risk of potential effects across England was on average 1.4%, with some areas >1.5%, for example counties in the south-west.
- Reduced flower numbers in perennial grassland in the UK by 6.3%. 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 1.3%.

We provided maps and tables showing the exceedance of the ozone critical levels relevant for UK vegetation in 2019. In summary, we found that:

- Critical level exceedance was greatest for woodland habitats, with grasslands having intermediate exceedance and crops having low 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 (1.1% of wheat growing area). There was no exceedance for wheat in Wales, Scotland or Northern Ireland.
- Similarly, for potato, only England showed exceedance of the critical level (2.5% of potato growing area), with no exceedance for Wales, Scotland or Northern Ireland.
- Critical level exceedance for managed broadleaf woodlands was high for England and Wales (100% and 99.7% respectively), with the highest critical level exceedances in the south-west of England. Levels for Scotland were lower at 78.8%.
- 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 not exceeded in the UK in 2019.
- The percentage of the grassland areas of England where the critical level for flowering was exceeded was 31.6%.The highest critical level exceedances were in eastern and south-east England. Critical levels for this habitat were not exceeded in 2019 in Wales, 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.

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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_SPR	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_CF	IAM_CR	ECR	NOLPJ	1	20	1	123	2.57	213	2.57	0	3.5	70	22	700	0

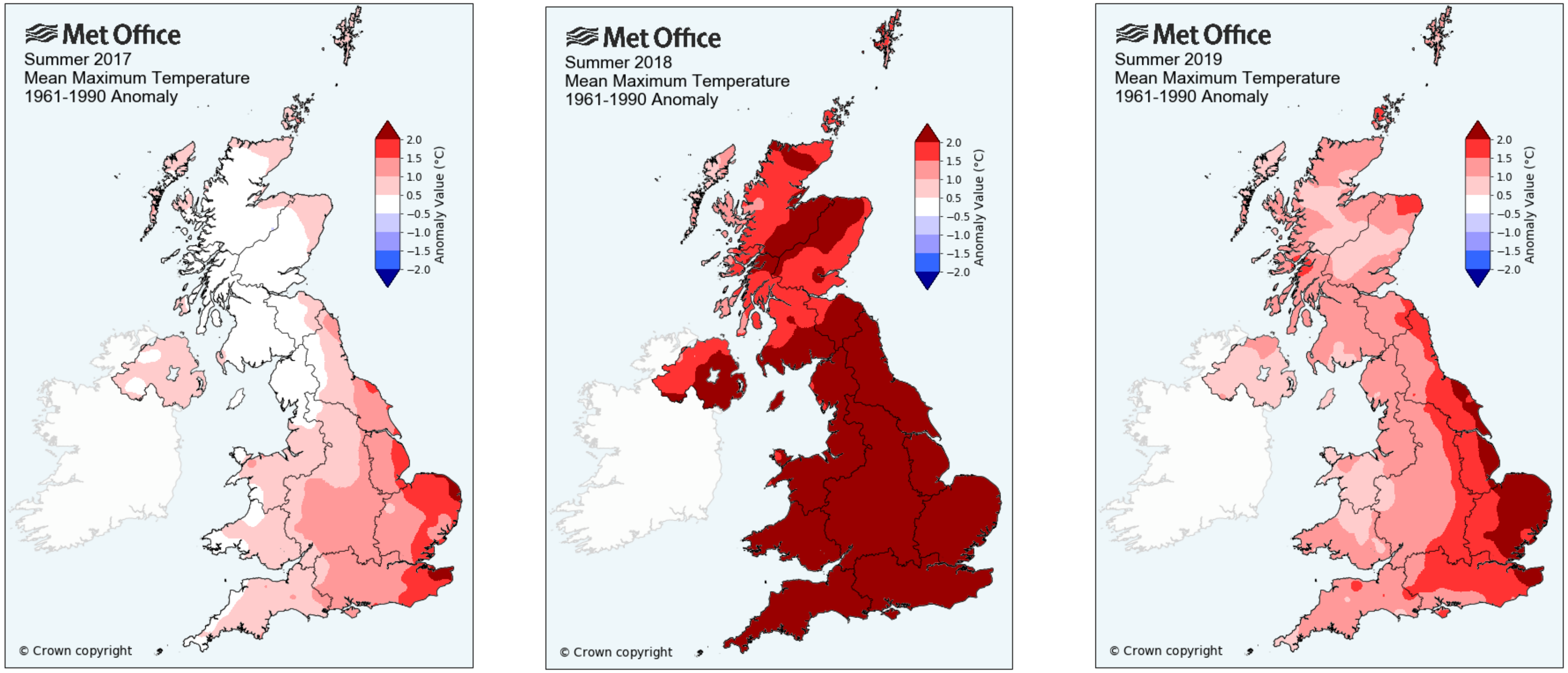
User notes for Annex, Table 1

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$_3$SE 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	#	#	#	#	#	#	#	#	#	#	#	#	#



1. a) 1. b) 1. c)

Figure 1. Met Office data showing the difference (°C) in mean maximum temperature for the summer of a) 2017 and b) 2018 compared to the average temperature for the period 1961 – 1990.

https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-actual-and-anomaly-maps

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