NECD Reporting 2020 – Quantifying and mapping exceedances of ozone flux-based critical levels for vegetation in the UK in 2018

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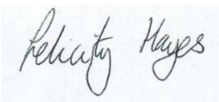
Signed 

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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*'. In order to comply with the requirements of Article 9, Member States may use the optional indicators listed in Annex V.

To meet the requirements of Annex V of the amended NECD Directive by reporting on exceedances of flux-based critical levels for ozone, we mapped the modelled exceedances for vegetation for the year 2018. 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), and 2017 (Sharps et al., 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, 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 2018 using the most recent version of 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 monthly ex-farm prices over the period 2014 - 2016) 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 2018 shows:

- Reduced UK wheat production by 5.5%, based on POD_6SPEC, amounting to a production loss of 0.78 million tonnes with an economic value of £113 million (at average farm gate prices for 2014 – 2016). The highest production losses were indicated for eastern and southern counties of England, particularly Cambridgeshire, Essex, Suffolk and Lincolnshire, and parts of Hampshire, Wiltshire and Dorset.
- Reduced UK potato yield by 6.5%, resulting in 305,000 lost tonnes of potato tubers worth £50 million, with the highest production losses in parts of North Yorkshire, Cambridgeshire, Hertfordshire and Bedfordshire.
- Reduced oilseed rape production, however, the losses were lower than for the other crops. Ozone reduced UK oilseed rape production by 1.9% in 2018, amounting to 39,000 tonnes of lost production, worth £11 million. The highest production losses were predicted for central England.
- Total economic losses for wheat, potato and oilseed rape in the UK of £173.5 million, with the majority of losses (>97%) occurring in England.
- Calculated annual biomass increment losses for the UK for managed broadleaf woodland of 7.3% (and 7.9% 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 East Anglia.
- Reduced annual biomass increment losses of coniferous trees for the UK of 1.4%. Ozone reduced annual biomass increment of coniferous trees less than broadleaf trees. The risk of potential effects across England was on average 1.5%, with some areas >1.5%, for example counties in the south-west.
- Reduced flower numbers in perennial grassland in the UK by 10%. Ozone had the potential to reduce flowering in wild plants primarily in England, with the areas at highest risk being in southern and eastern counties.
- Reduced annual total biomass increment in perennial grassland in the UK by 2.7%.

We provided maps and tables showing the exceedance of the ozone critical levels relevant for UK vegetation in 2018. In summary, we found that:

- Critical level exceedance was greatest for woodland habitats, with crops and grasslands 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 similar in England and Wales (69.2% and 68.8% of wheat growing areas respectively). There was no

exceedance for wheat in Scotland and 2.3% of the wheat growing areas in Northern Ireland showed critical level exceedance.
- Potato showed high levels of critical level exceedance in 2018, for both England (94.9%) and Wales (96.6%). Levels were lower for Scotland (4.7%) and Northern Ireland (32.6%).
- Critical level exceedance for managed broadleaf and unmanaged beech woodlands was consistently high for England, Wales and Scotland (>99%). The highest critical level exceedances tended to be in south-west England.
- Critical levels for managed coniferous forest were not exceeded in the UK in 2018.
- The percentage of the grassland areas of England where the critical level for flowering was exceeded was 74.8%.The highest critical level exceedances were in eastern and south-east England. Similarly, in Wales 62.9% of grassland areas showed exceedance of the critical level for flowering. Critical level exceedance in Scotland or Northern Ireland for this habitat was lower (4.5% and 18.2% respectively).
- The critical level for effects on the annual total biomass increment of grassland species was not exceeded in the UK.

In comparison to results on the ozone impact on UK vegetation for 2017, losses and critical level exceedance were greater in 2018 for the crops potato and oilseed rape, and for semi-natural vegetation. For trees, results for 2018 were more similar to those for 2017, 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 2018 from 2006 and 2008 data;
- Using crop price data for the period 2014 - 16;
- Combining data sources of differing spatial resolution for habitat distribution mapping.

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 2018, as part of the UK reporting requirements for the amended European Union's National Emissions Ceilings Directive (NECD; Directive (EU) 2016/2284), Art. 9.

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. 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.

Here, we use the same methodology as the previous studies (Mills et al., 2017; Sharps et al., 2019, 2020) and the most recent version of the EMEP4UK ozone model. We 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 2018.

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 2018. 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 2017 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 2015. Shipping emissions estimates from the Finnish Meteorological Institute (FMI) for the year 2015 are used in this work.

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, 2020) 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 most recent version of 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).

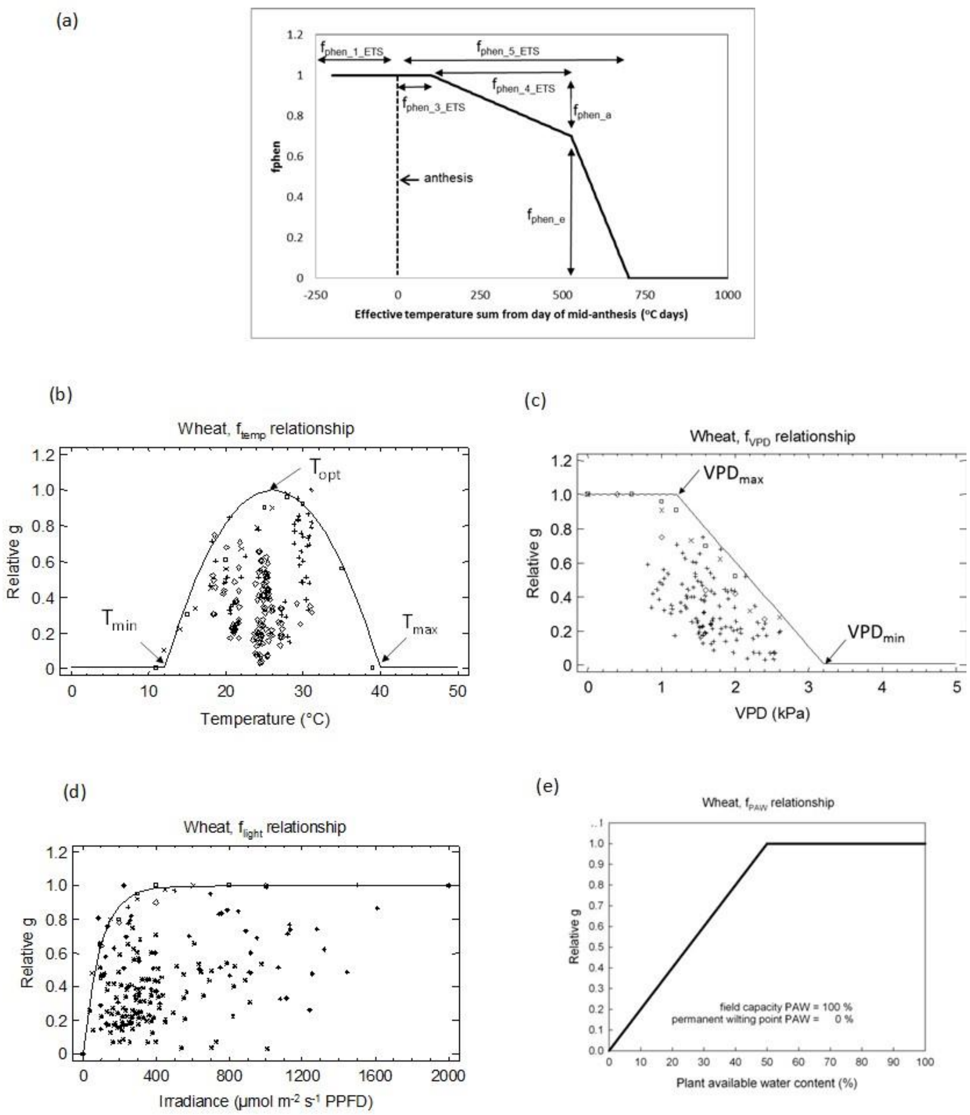

Figure 1: Illustration of the components of the DO_3SE stomatal flux model, showing for wheat how the stomatal conductance is modified by (a) phenology (growth stage), (b) temperature, (c) vapour pressure deficit - a measure of air humidity, (d), light and (e) plant available water - a measure of the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

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 (2017) 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 2018 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 2018. A conversion factor for 2018 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. '2018 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 x10km cell). For the final maps, data were aggregated to 5km x 5km resolution.

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, 2019).

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 mean values calculated over the period 2014 – 2016, to allow for the fluctuating nature of the crop prices. The average crop price (£ per tonne) was based on monthly UK ex-farm prices for wheat (£145.18); weekly UK delivered price (average across Central Scotland, Yorkshire, North West England and East Anglia/London/ Essex) for oilseed rape (£281.02); and monthly GB average prices (average of free-buy and contract purchases) for potato (£163.70).

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 2018

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 2018, 69% was grown in areas exceeding the ozone critical level of 1.3mmol m^{-2}. The average yield loss was 6.3% and the loss in production was 764,000 tonnes with an economic value of £111 million (Table 3). In Wales and N. Ireland, 69% and 2.3% of the wheat grown was in areas where the critical level was exceeded respectively, while in Scotland there were no areas where the critical level was exceeded (Table 3, Figure 2). Overall, our analysis indicated that 65% of the UK wheat production in 2018 was in areas where the critical level was exceeded. The average yield loss for the UK was 5.5% resulting in a production loss of 775,000 tonnes with an economic value of £113 million. The highest ozone fluxes in 2018 were in England, in the south and south-eastern counties of Hampshire, Dorset and West Sussex (Figure 2). However, the highest production losses were indicated for eastern and southern counties of England, particularly Cambridgeshire, Essex, Suffolk and Lincolnshire in the east, and parts of Hampshire, Wiltshire and Dorset in the south (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 and southern England

Critical level exceedance values for wheat in 2018 were similar those for 2017 (Sharps et al., 2020) in England, Scotland and N. Ireland but considerably higher for Wales (69% in 2018, 23% in 2017). Ozone fluxes have been shown to fluctuate between years (Sharps et al., 2019), and data for 2018 show increases in some areas of the UK (compared to 2017), particularly for south-west and central areas of England, and across Wales. Flux values in south-east England decreased in some areas in 2018 compared to 2017. 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 16.6 M tonnes in 2014, 14.8 M tonnes in 2017 and 13.6 M tonnes in 2018 and this will affect estimates of total production loss. In terms of production and economic losses, England, Scotland and N. Ireland showed a decrease in losses in 2018 compared to 2017. Losses in Wales increased in 2018 (as expected due to the greater area of critical level exceedance), however as wheat production in Wales is generally low, production and economic losses due to ozone remained relatively low.

Potato is classed as moderately sensitive to ozone and is thus less sensitive than wheat (Mills et al., 2007). In 2018, 95% of the potato growing areas in England and 97% of areas in Wales had ozone fluxes that exceeded the critical level of 3.8 mmol m^{-2}. Exceedance was lower in Scotland and N. Ireland with 5% and 33% respectively (Table 4, Figure 4). The average yield loss in England was 8% and the loss in production was 272,000 tonnes with an economic value of £44.6 million (Table 4). Across all of the UK potato production areas, the mean yield loss was 6.5%, resulting in 305,000 lost tonnes of potato tubers worth £49.9 million at average farm gate prices (2014 – 2016). High values for ozone flux were seen across England and Wales, with the greatest flux values in southern England, for example Hampshire, Dorset, East and West Sussex (Figure 4). However, these are areas with low potato production. Maps show pockets of high potato production and economic losses, for example in parts of North Yorkshire, Cambridgeshire, Hertfordshire and Bedfordshire (Figure 5).

In comparison to 2017 (Sharps et al., 2020), the area of critical level exceedance in 2018 was greater across the UK, particularly in England, Wales and N. Ireland. Losses for the year 2018 were the highest for all UK countries during the 5-year period of 2014 – 2018 (Sharps et al., 2019, 2020). While the highest ozone flux values were still primarily seen in southern parts of England where potato production is low (Figure 5), there was still a considerable increase in production and economic losses in England in 2018 (£44.6 M loss) compared to 2017 (£29.1 M loss). In Scotland, an economic loss of £4.2 M was estimated in 2018, compared to £1 M in 2017.

Table 3: Impacts of ozone on wheat in 2018, 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	1591466	1100581	69.2	12494	764	6.3	110.8
Wales	21882	15055	68.8	127	7.20	5.7	1.05
Scotland	92906	0	0	615	3.84	0.6	0.56
NI	5779	133	2.3	20	0.63	3.2	0.09
UK	1712033	1115769	65.2	13257	775	5.5	112.5

Table 4: Impacts of ozone on potato in 2018, 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	97337	92409	94.9	3399	272	7.97	44.6
Wales	2438	2354	96.6	36	2.69	7.46	0.4
Scotland	23145	1093	4.7	906	25.2	2.82	4.2
NI	3210	1046	32.6	94	4.08	4.23	0.7
UK	126129	96902	76.8	4435	305	6.5	49.9

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 oilseed rape is one of the top five crops in the UK and the 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 2018 (Figures 6&7).

In 2018, the average yield loss for the UK was low, estimated at 1.9%, amounting to 39,000 tonnes of lost production, worth £11.1 million (Table 5). Ozone flux values were highest in England and Wales, particularly in areas of eastern and southern England (Figure 6). The majority of oilseed rape growing areas in England had potential yield losses of 1.5–2.5%, and a few areas, for example, in Cambridgeshire, Suffolk, West and East Sussex had yield loss > 2.5% (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 2017 (Sharps et al., 2020), results for 2018 suggest higher ozone flux values for oilseed rape particularly across England and Wales, resulting in higher estimated yield losses. In turn, production losses in 2018 were also greater, 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 £5.8 M in 2017. While the location of the highest crop losses has not varied spatially (i.e. central England), oilseed rape losses for 2018 are the highest estimates over the period 2014 – 2018 (Sharps et al., 2019, 2020).

Table 5: Impacts of ozone on oilseed rape in 2018, 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	549993	NA	NA	1823	38	2.04	10.8
Wales	5155	NA	NA	7.76	0.13	1.66	0.04
Scotland	30997	NA	NA	83	0.95	1.12	0.27
NI	648	NA	NA	NA	NA	NA	NA
UK	586794	NA	NA	1914	39.38	1.9	11.07

NA: Not applicable

3.2 Impacts of ozone on broad habitats in the UK in 2018

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 2018, the ozone critical level of 5.2 mmol m^{-2} was exceeded in 99.9%, 100% and 99.5% of the area of this habitat in England, Wales and Scotland respectively (Table 6a). The overall exceeded area for the UK was 99.8%, with an average indicative biomass increment loss of 7.3%. The level of exceedance was greatest for woodland areas in south-west England (Cornwall and Devon) and patches of the eastern coast of England (Figure 8). Predicted biomass increment loss was highest in south-west England (>9%), with other small areas of high loss, for example in Norfolk (Figure 8).

In comparison to 2017 (Sharps et al., 2020), ozone flux values for managed broadleaf were generally higher across the UK, leading to larger areas of critical exceedance, particularly in Scotland. 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. However, 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 2015-2018, exceedance was greatest in the south-west of England. In 2018, % biomass increment loss increased across the UK compared to 2017, for example in England losses increased from being primarily 5-7% to >7%, while in northern Scotland, losses in 2018 were primarily between 5-7%, compared to 0-5% in 2017.

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 2018, 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 7.9%. 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 2017 (Sharps et al., 2020), exceedance of the ozone critical level and biomass increment losses were generally higher in 2018 across GB. Biomass increment losses increased in northern England and Wales from primarily 5-7% to 7-9.5%, while in southern England, values increased from 7 - 8% to 8 – 9.5%, with patches of >9.5%. As for managed broadleaf woodland however, the UK average % biomass increment loss has been broadly similar between 2014-2018, 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 2018 (Table 6c, Figure 10). Average indicative biomass increment losses were lower than for broadleaf woodland, with all estimated losses being below 2%. In 2018, the majority of grid squares in England and Wales suggested predicted losses of 1 -1.5%, with some areas with higher losses (>1.5%) particularly south-west England (Figure 10). Scotland and N. Ireland showed similar results, with the majority of estimated biomass increment losses being 1 - 1.5% (Figure10).

The critical level has not been exceeded and average biomass increment losses were similar for 2014 – 2018 (<2%). Spatial data show that biomass increment losses increased slightly in 2018 compared to 2017, particularly in northern Scotland, and also more areas with >1.5% losses were shown for England (especially in the south-west) and Wales. 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 2018, 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	555537	99.9	7.7
Wales	80621	80621	100	7.8
Scotland	108705	108208	99.5	6.4
NI	NA	NA	NA	NA
UK	745667	744366	99.8	7.3

Country	(b) Unmanaged Beech woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	58053	58053	100	8.0
Wales	5821	5821	100	7.8
Scotland	312	312	100	7.4
NI	NA	NA	NA	NA
UK	64186	64186	100	7.9

Country	(c) Managed coniferous woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	171274	0	0	1.5
Wales	105263	0	0	1.5
Scotland	511583	0	0	1.3
NI	50148	0	0	1.3
UK	838268	0	0	1.4

(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.

In 2018, the ozone critical level for flowering of ozone-sensitive grassland species (6.6 mmol m^{-2}) was exceeded for 75% (England), 63% (Wales), 5% (Scotland) and 18% (N. Ireland) of the grassland area (Table 7a, Figure 11).The indicative risk analysis suggested an average of 10% loss in flower number for the UK, with the highest losses (>15%) occurring mostly in areas of southern and south-east England (Figure 11). This could potentially affect plant species composition and/or diversity.

In comparison to 2017 (Sharps et al., 2020), ozone flux values in 2018 were higher across the UK, leading to widespread increases in critical level exceedances and flower number losses. Average flower loss for the UK has been increasing each year since 2015 (3.7%), with 10% loss estimated for 2018.

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 2018 (Table 7b; maps not presented). Hence, biomass losses were well below 10% (as defined by the critical level), with an average value of 2.7% for the UK.

Average biomass losses have fluctuated slightly over the period 2014 - 18. Estimated losses in England are at their highest in 2018 at 3.5% (1.9% in 2014; 1.4% in 2015; 1.7% in 2016, 2.2% in 2017). 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 2018, 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	603917	451856	74.8	12.8
Wales	334078	210167	62.9	10.6
Scotland	845622	38436	4.5	6.9
NI	126431	22977	18.2	9.3
UK	1910048	723437	37.9	10

Country	(b) Grassland total biomass			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	602973	0	0	3.5
Wales	334078	0	0	2.9
Scotland	843096	0	0	1.8
NI	126369	0	0	2.5
UK	1906517	0	0	2.7

3.3 Spatial and temporal variation in ozone flux

In comparison to results on the ozone impact on UK vegetation for the period 2014 - 16 (Sharps et al., 2019), and for 2017 (Sharps et al., 2020) losses and critical level exceedance were greater in 2018 for crops (particularly for potato and oilseed rape), and for semi-natural vegetation. For woodland, results for 2018 showed slight increases compared to 2017, 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 - 17 (Sharps et al., 2019, 2020) 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://emep.int/publ/common_publications.html#2019). The EMEP report for 2018 (EMEP 2020) reports a heat wave across parts of Europe from April/May to August, particularly for Northern Europe (including the UK). Hot, dry, sunny conditions can lead to increased ozone. Numerous episodes with elevated ozone levels were observed in the summer 2018 period across Europe. 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. However, ozone levels in 2018 were clearly elevated. This indicates that efficient abatement of surface ozone depends not only on the reduction of ozone precursor emissions (including NOx and VOCs) but on future climate change. While the 2018 summer heat wave led to higher levels of surface ozone, drought conditions could have resulted 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.

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 shows that temperatures were higher in the summer of 2018 than in 2017, particularly for England and Wales, and for parts of Scotland and Northern Ireland (Annex, Figure 1a & 1b).

This coincides 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. 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). Changes in air pollution emissions can be expected to have less impact than the weather as differences between years are generally small.

3.4 Ozone impacts maps for crops, trees and grasses

Wheat (POD$_6$SPEC for grain yield)

(Note: For comparison purposes, map scales have been kept the same as for the 2014-17 reports for each vegetation type however as values were higher for some vegetation types in 2018, an extra colour category has been added for some maps).

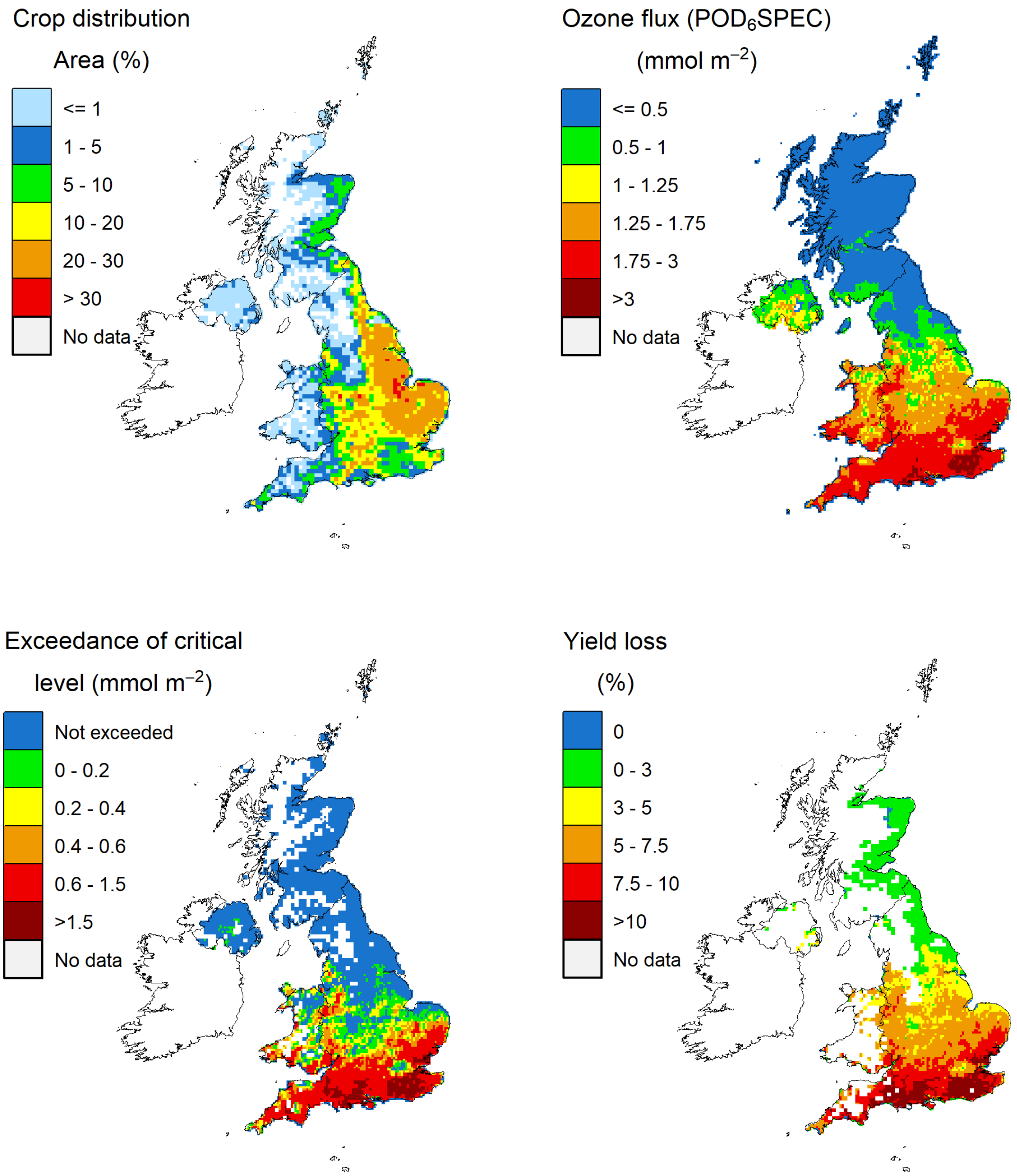

Figure 2: Impacts of ozone on wheat production in 2018 calculated using POD$_6$SPEC. (a) Distribution of wheat presented as the percentage of each 5km x 5km grid square sown with wheat; (b) POD$_6$SPEC (mmol m^{-2}) (**critical level = 1.3 mmol m^{-2}**); (c) Exceedance of the critical level; (d) Percentage yield loss.

Wheat (POD_6SPEC for grain yield)

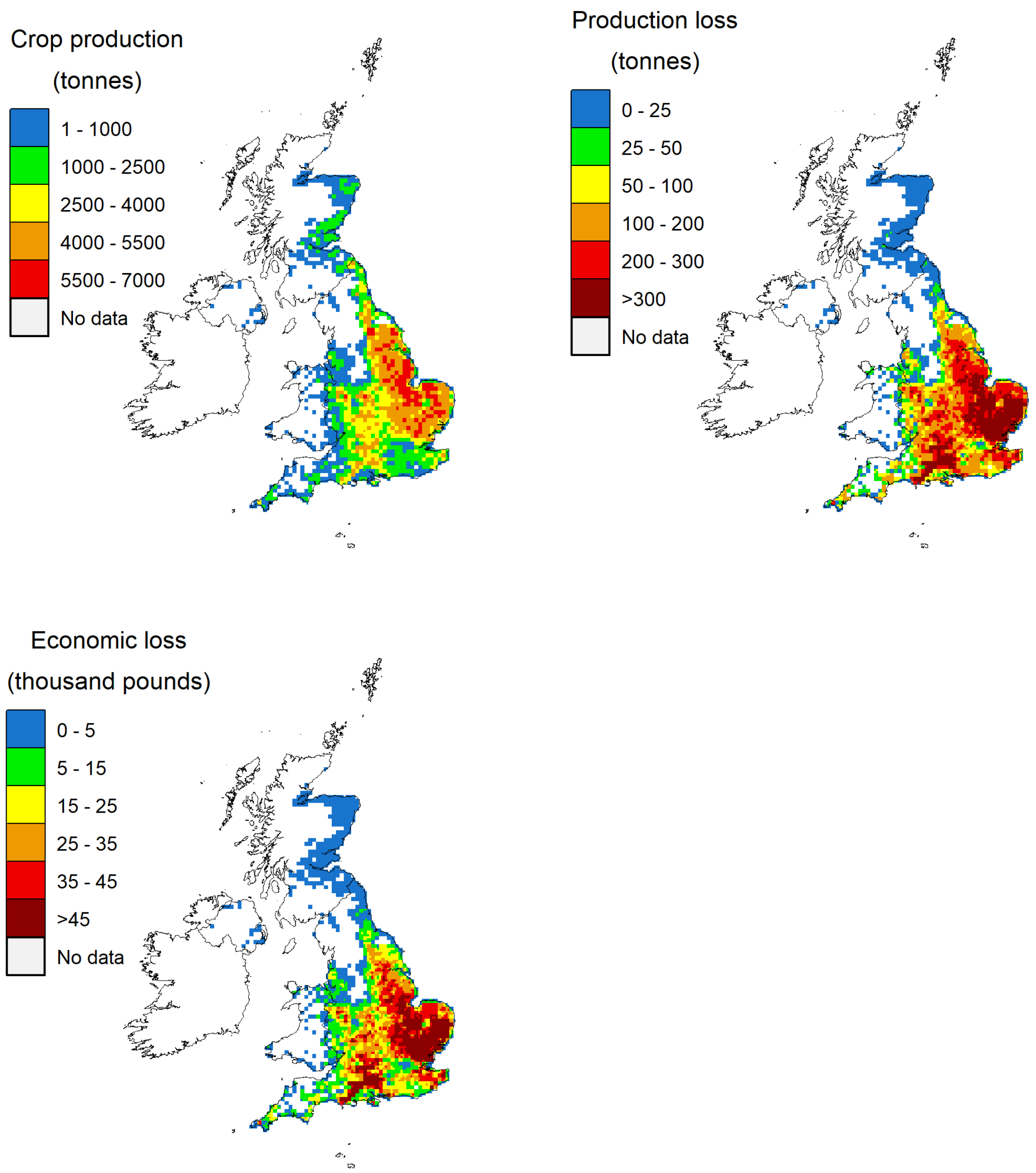

Figure 3: Impacts of ozone on wheat production in 2018 calculated using POD_6SPEC. (a) Wheat production in the UK in tonnes per 5km x 5km grid square; (b) Production loss due to ozone in tonnes per 5km x 5km grid square; and (c) Economic loss in thousand £UK per 5km x 5km grid square, based on mean price 2014-16.

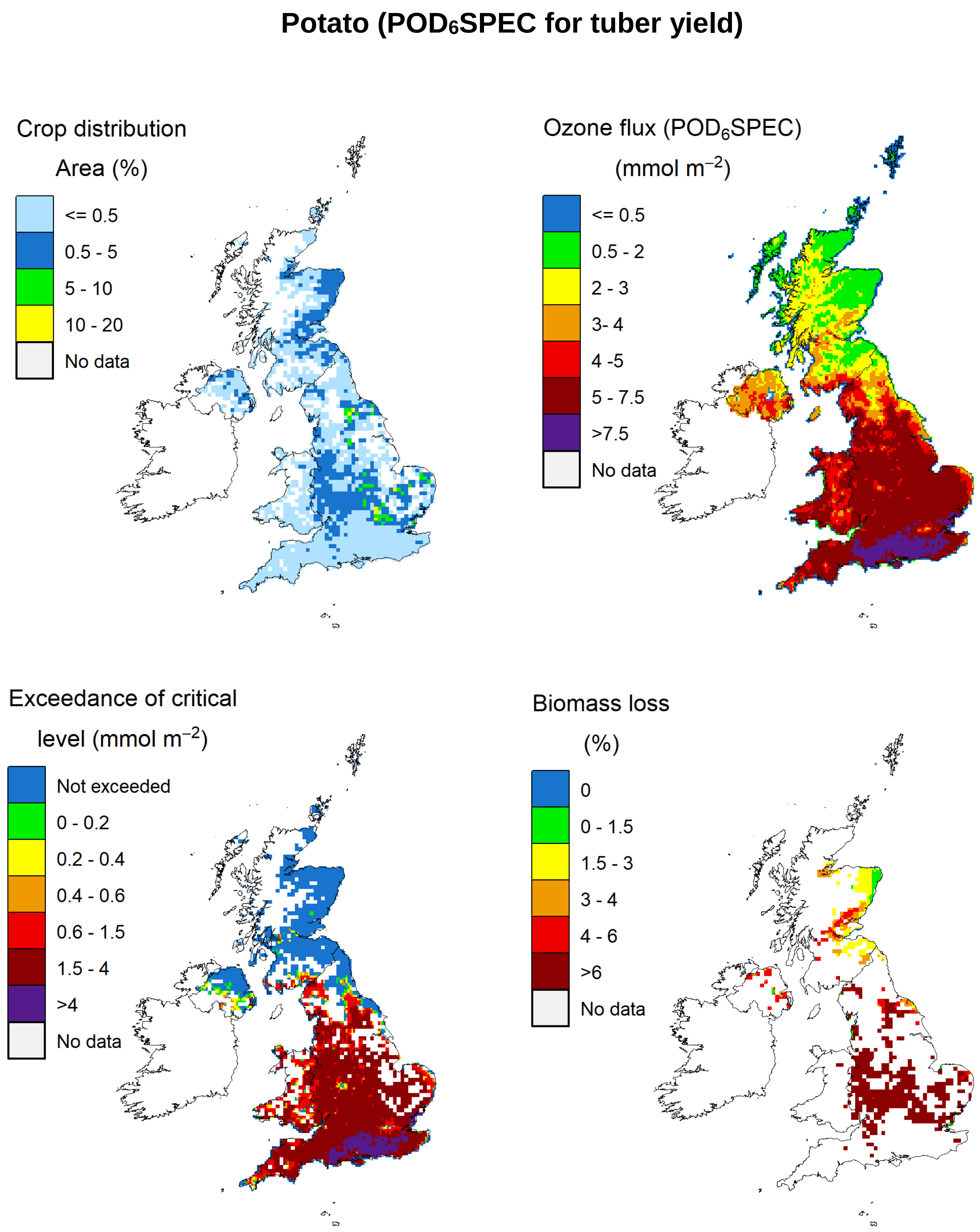

Figure 4: Impacts of ozone on potato production in 2018 calculated using POD6SPEC. (a) Distribution of potato presented as the percentage of each 5km x 5km grid square sown with potato; (b) POD6SPEC (mmol m^{-2}) (**critical level = 3.8 mmol m^{-2}**); (c) Exceedance of the critical level; (d) Percentage yield loss.

Potato (POD_6SPEC for tuber yield)

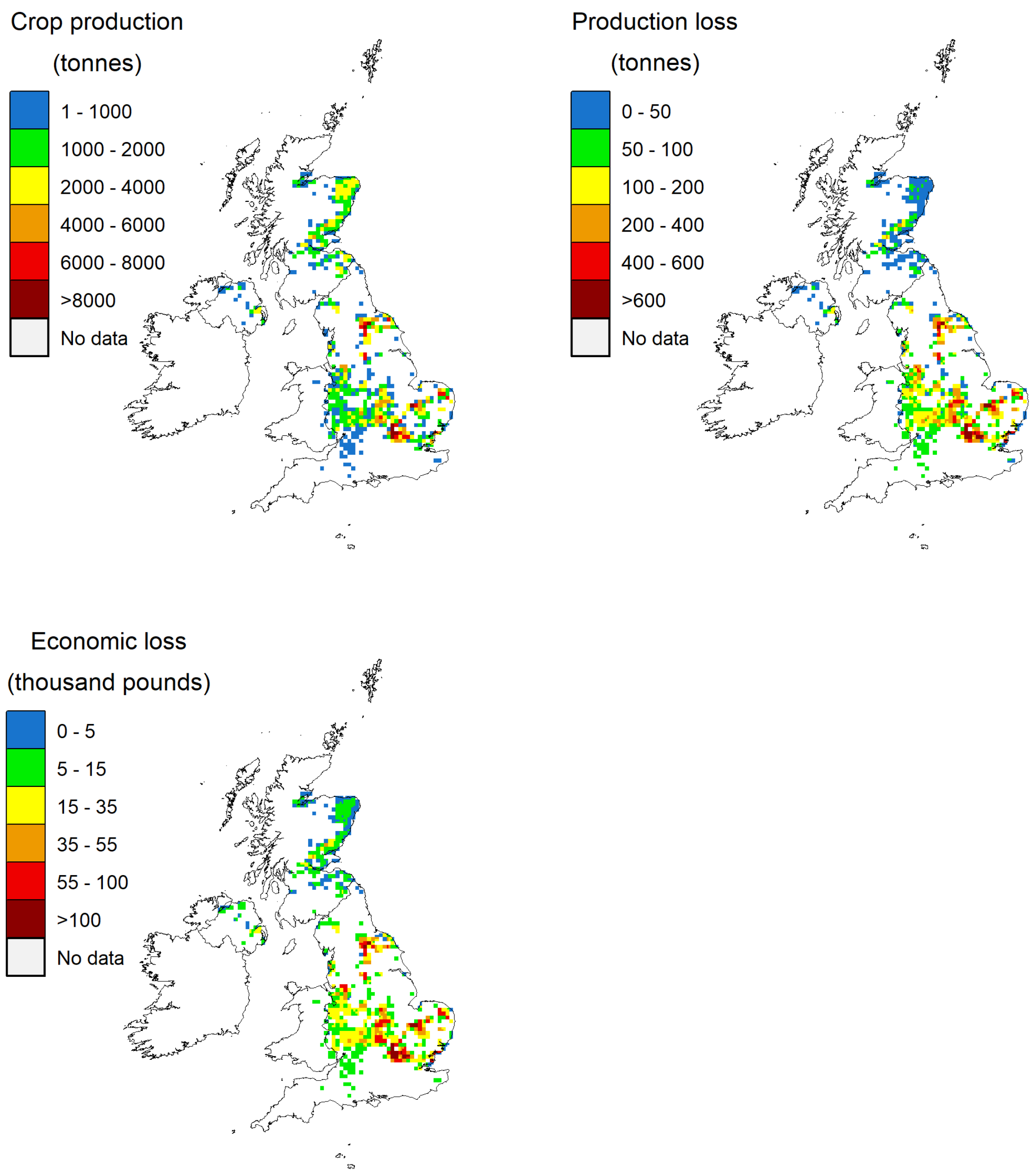

Figure 5: Impacts of ozone on potato production in 2018 calculated using POD_6SPEC. (a) Potato production in the UK in tonnes per 5km x 5km grid square; (b) Production loss due to ozone in tonnes per 5km x 5km grid square; and (c) Economic loss in thousand UK£ per 5km x 5km grid square, based on mean price 2014-16.

Oilseed rape (POD_6SPEC for grain yield)

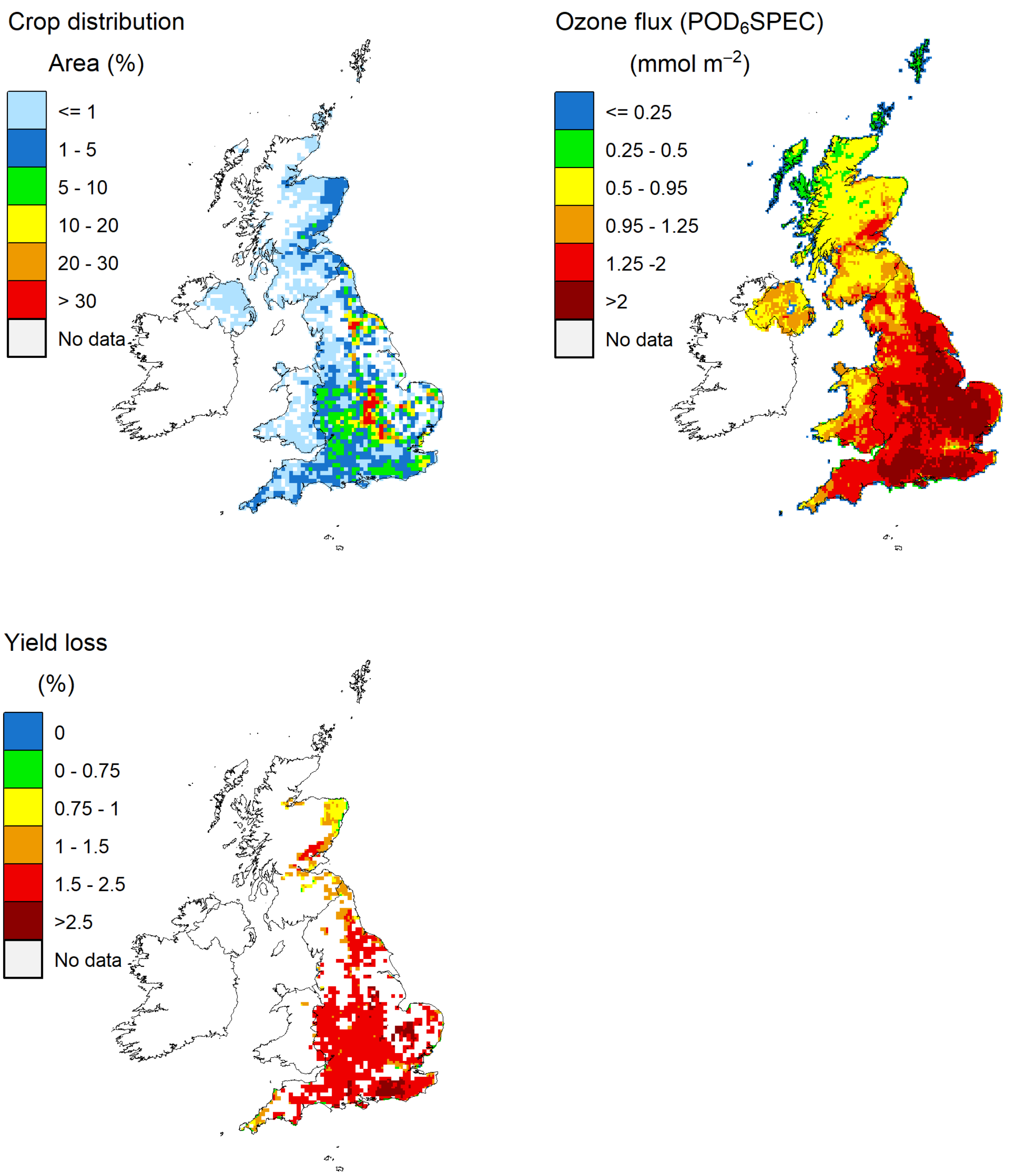

Figure 6: Impacts of ozone on oilseed rape production in 2018 calculated using POD_6SPEC. (a) Distribution of oilseed rape presented as the percentage of each 5km x 5km grid square sown with oilseed rape; (b) POD_6SPEC (mmol m^{-2}); (c) Percentage yield loss.

Oilseed rape (POD_6SPEC for grain yield)

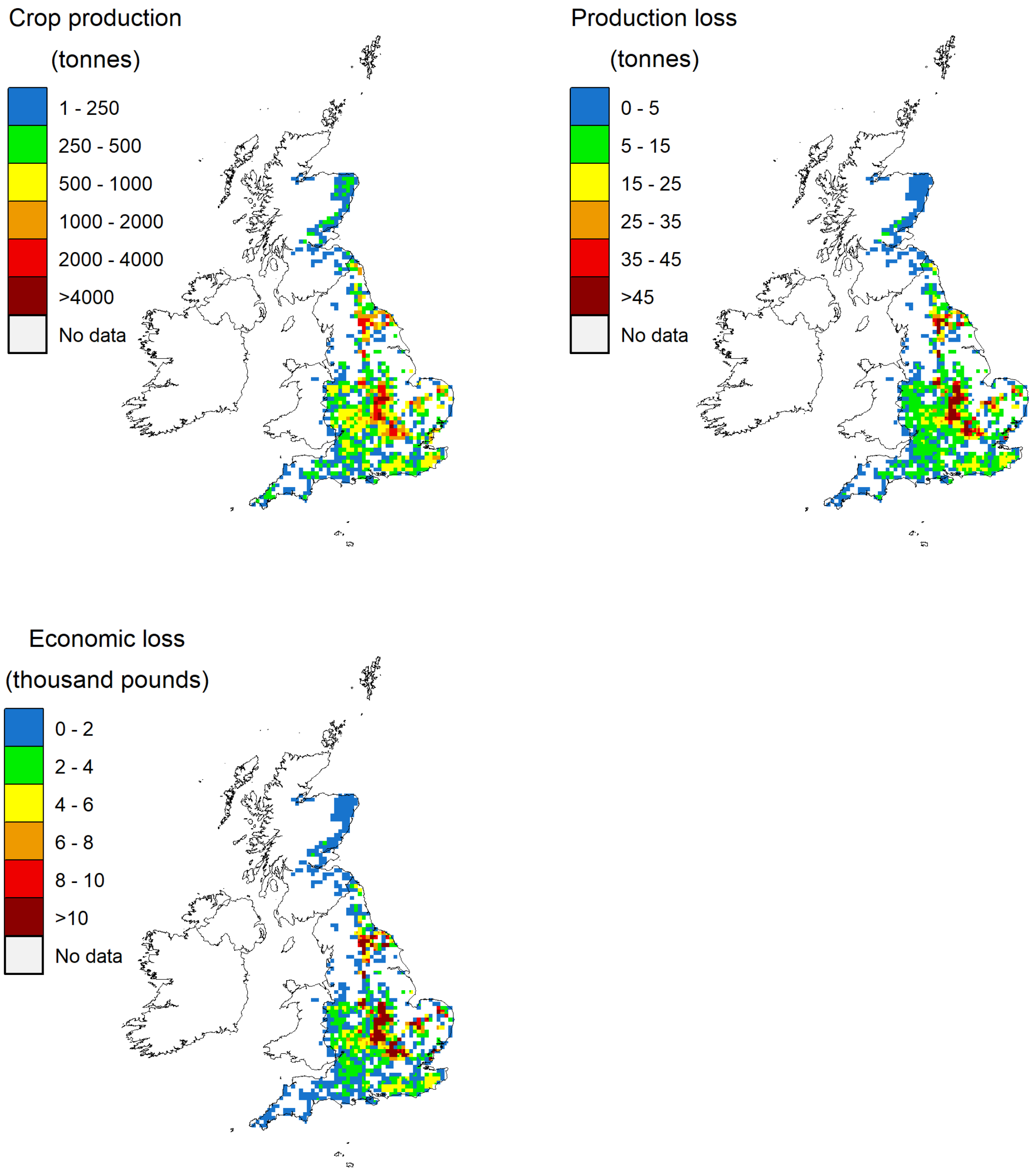

Figure 7: Impacts of ozone on oilseed rape production in 2018 calculated using POD_6SPEC. (a) Oilseed rape production in the UK in tonnes per 5km x 5km grid square; (b) Production loss due to ozone in tonnes per 5km x 5km grid square; and (c) Economic loss in thousand UK£ per 5km x 5km grid square, based on mean price 2014-16.

Managed broadleaved woodland (POD_1SPEC for biomass increment)

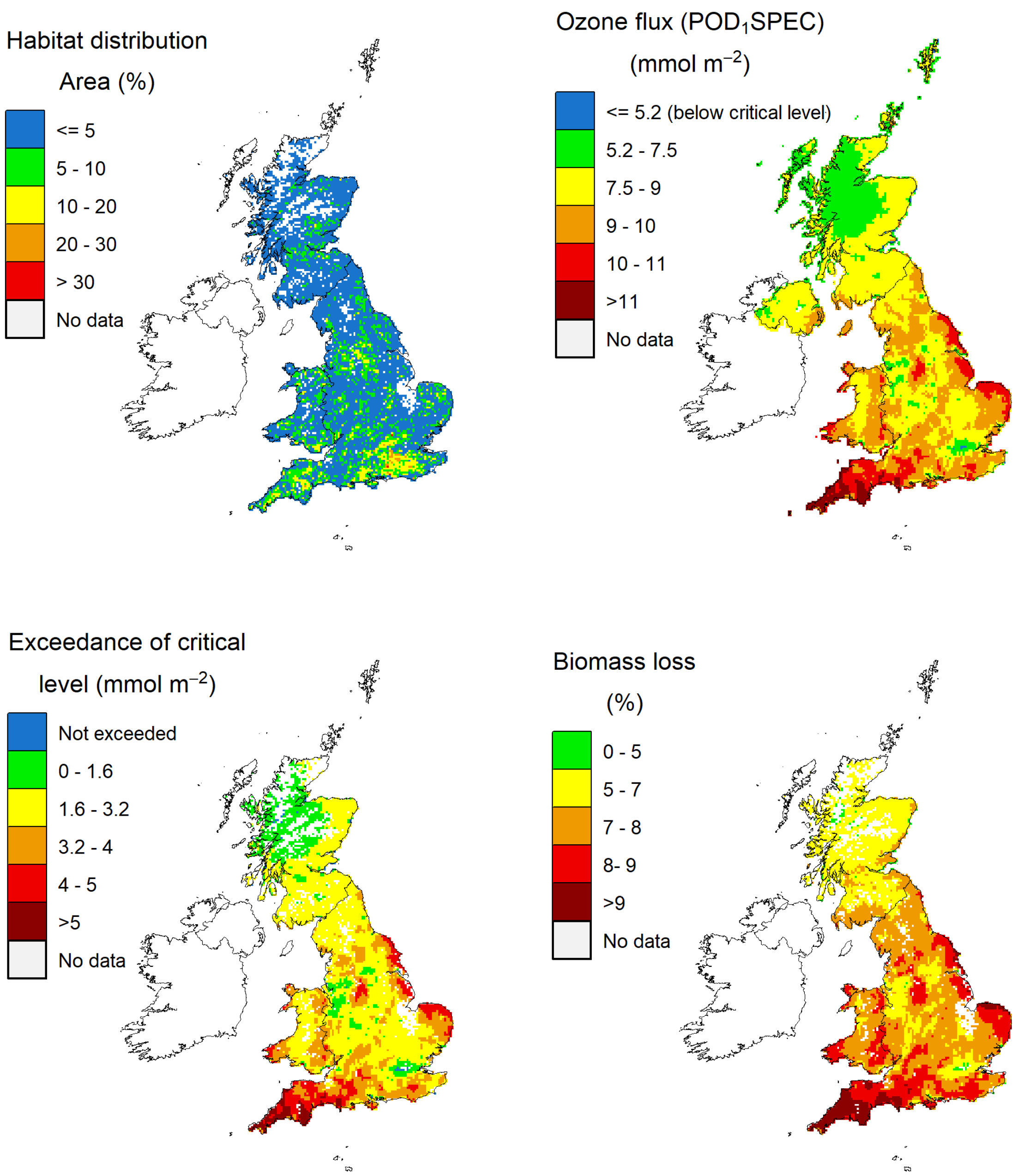

Figure 8: Impacts of ozone on managed broadleaf woodland in 2018 calculated using POD_1SPEC. (a) Distribution of managed broadleaf woodland as the percentage area of each 5km x 5km grid square; (b) POD_1SPEC (mmol m^{-2}), all squares coloured blue have POD_1SPEC values below the **critical level of 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)

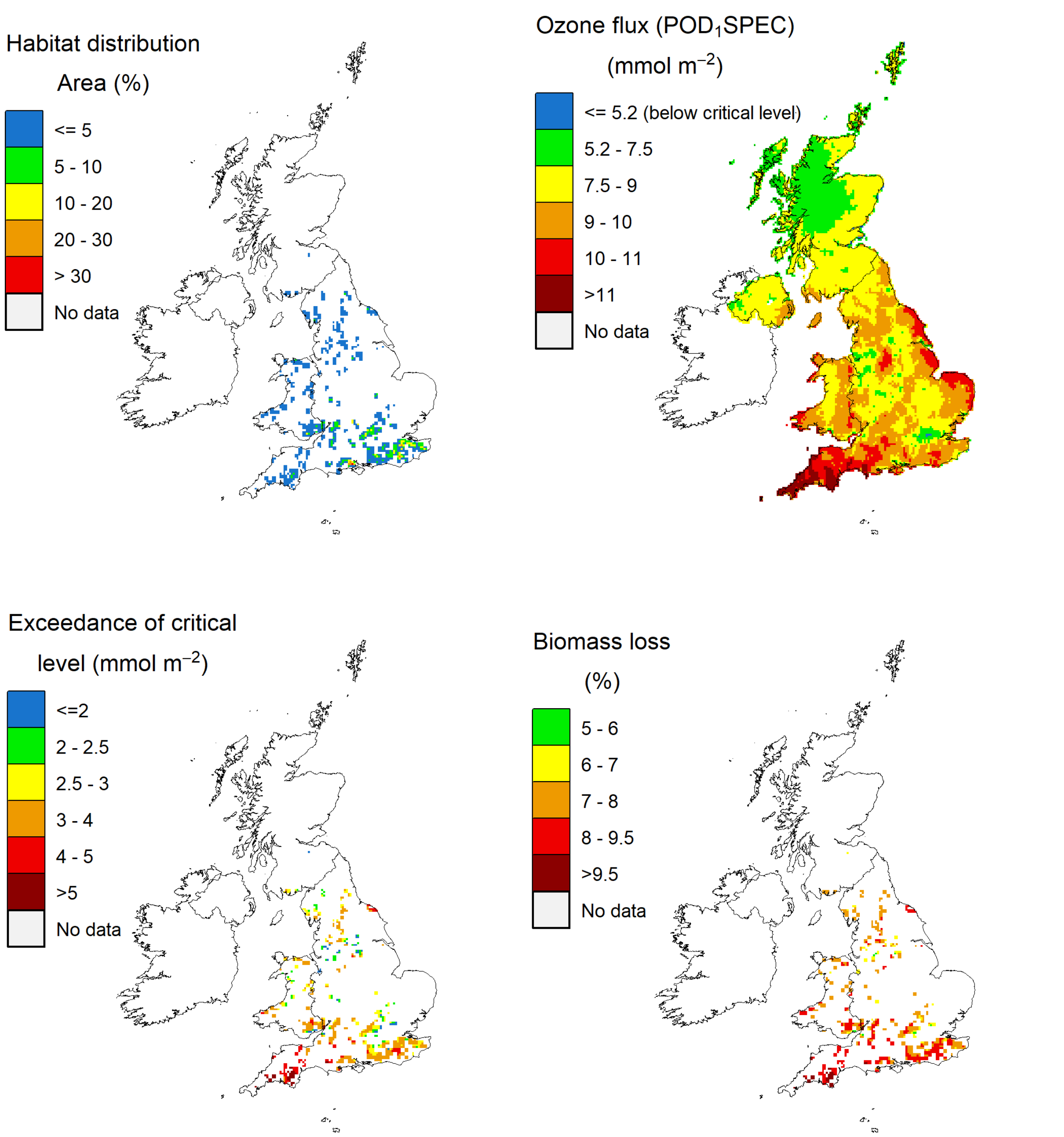

Figure 9: Impacts of ozone on unmanaged beech woodland in 2018 calculated using POD_1SPEC. (a) Distribution of unmanaged beech woodland as the percentage area of each 5km x 5km grid square; (b) POD_1SPEC (mmol m^{-2}), all squares coloured blue have POD_1SPEC values below the **critical level of 5.2 mmol m^{-2}**; (c) exceedance of the critical level; (d) Percentage biomass loss (indicative risk only).

Managed coniferous woodland (POD_1SPEC for biomass increment)

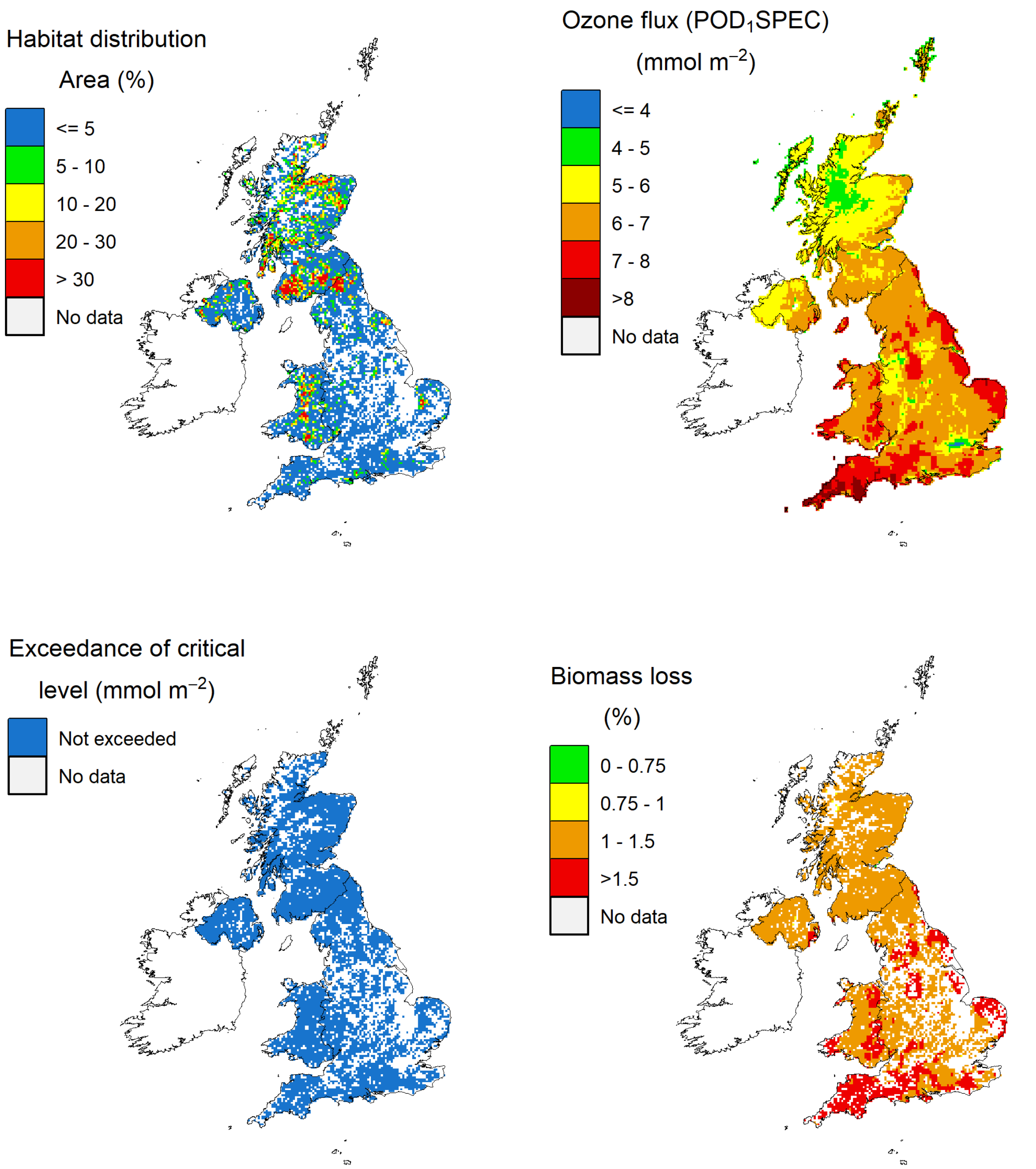

Figure 10: Impacts of ozone on managed coniferous woodland in 2018 calculated using POD_1SPEC. (a) Distribution of managed coniferous woodland as the percentage area of each 5km x 5km grid square; (b) POD_1SPEC (mmol m^{-2}) (**critical level = 9.2 mmol m^{-2}**); (c) exceedance of the critical level; (d) Percentage yield loss (indicative risk only).

Perennial grassland (POD$_1$SPEC for flower numbers)

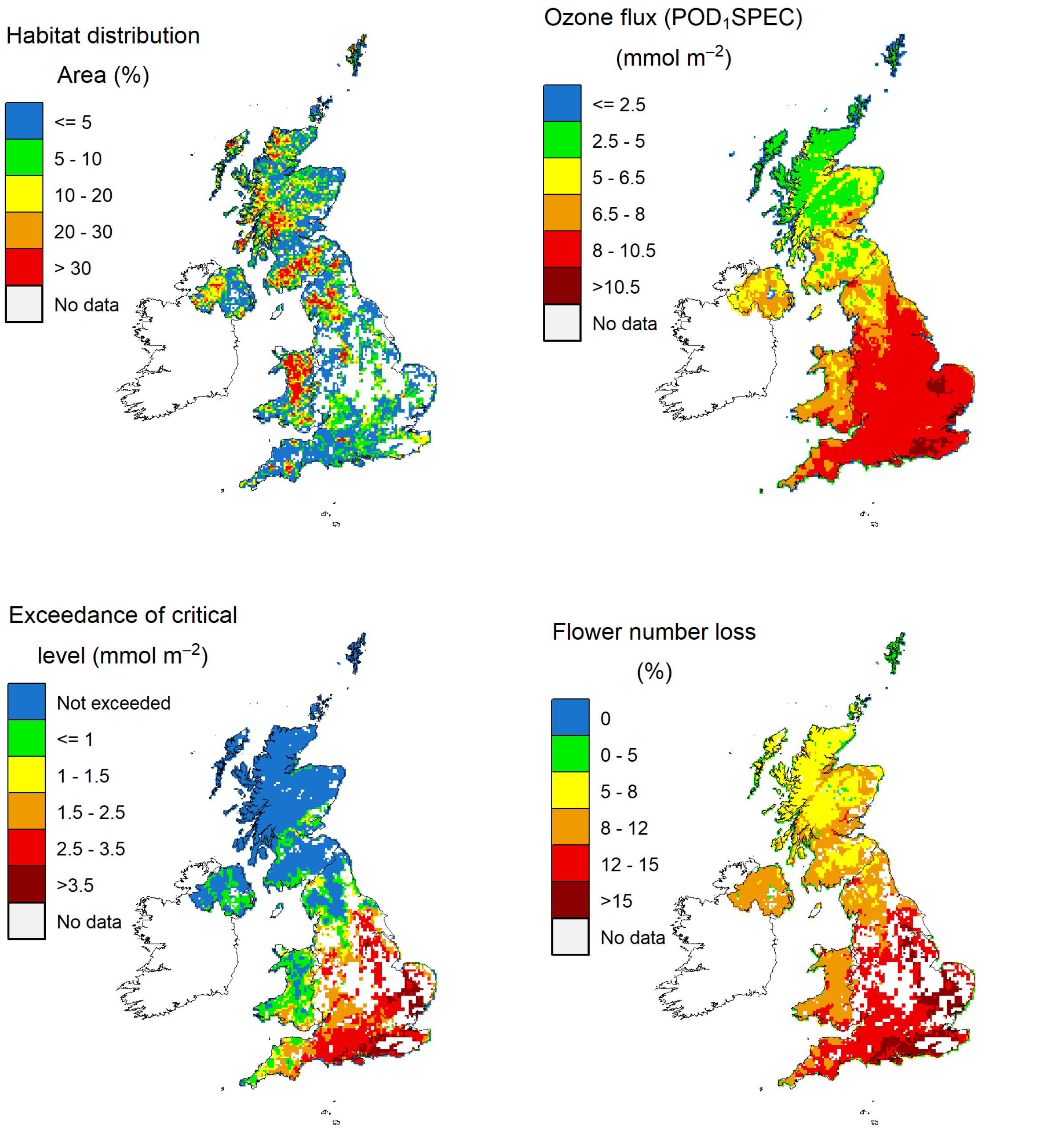

Figure 11: Impacts of ozone on perennial (semi-natural) grassland in 2018 calculated using POD$_1$SPEC. (a) Distribution of grassland as the percentage area of each 5km x 5km grid square; (b) POD$_1$SPEC (mmol m^{-2}) (**critical level = 6.6 mmol m^{-2}**); (c) Exceedance of the critical level; (d) Percentage 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

Anthropogenic emissions of NO_x, 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 2017 National Atmospheric Emission Inventory estimate (NAEI, http://naei.defra.gov.uk) These were the most up-to-date data available at the time of running the model. 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 2015. Shipping emissions estimates from the Finnish Meteorological Institute (FMI) for the year 2015 are used in this work and no annual rescaling is applied to this dataset. Moreover, the FMI shipping emissions dataset used here only include NO_x, SO_x, SO_4, CO, OC and EC. Explicitly timed volcanoes emissions and the Fire Inventory from NCAR (FINN) daily biomass burning are also included. These varying sources of data will add some uncertainty to the modelling process.

Although the WRF model has been validated against observations for other years (Vieno et al., 2010), a simple evaluation for the meteorology has 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. Also the spatial scale ~5km for EMEP4UK and 10km for EMEP MSC-W may play a role in any differences between model outputs.

4.3 Mapping crop area, production and economic losses

For crop production data, we had to scale an existing data set for 2006 – 2008 (Mills et al., 2011c) to 2018. 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 2018 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, we introduced some error 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 period 2014 - 2016. Prices were not updated to 2018 as data (at regional level) were not readily available for all three crops. In addition, this would have introduced a further source of variation into the reported results, making comparison between results for the years 2014 - 2018 more difficult. An initial investigation into crop prices for wheat and potato suggested that prices had increased (by ~16% for wheat and ~5% for potato) in 2018, therefore the final estimates of economic loss due to ozone for 2018 may be higher than reported.

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 data sets 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 most recent study for the year 2017 (Sharps et al., 2020). 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 2018.

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 2018 shows:

- Reduced UK wheat production by 5.5%, based on POD_6SPEC, amounting to a production loss of 0.78 million tonnes with an economic value of £113 million (at average farm gate prices for 2014 – 2016). The highest production losses were indicated for eastern and southern counties of England, particularly Cambridgeshire, Essex, Suffolk and Lincolnshire, and parts of Hampshire, Wiltshire and Dorset.
- Reduced UK potato yield by 6.5%, resulting in 305,000 lost tonnes of potato tubers worth £50 million, with the highest production losses in parts of North Yorkshire, Cambridgeshire, Hertfordshire and Bedfordshire.
- Reduced oilseed rape production, however, the losses were lower than for the other crops. Ozone reduced UK oilseed rape production by 1.9% in 2018, amounting to 39,000 tonnes of lost production, worth £11 million. The highest production losses were predicted for central England.
- Total economic losses for wheat, potato and oilseed rape in the UK of £173.5 million, with the majority of losses (>97%) occurring in England.
- Calculated annual biomass increment losses for the UK for managed broadleaf woodland of 7.3% (and 7.9% 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 East Anglia.
- Reduced annual biomass increment losses of coniferous trees for the UK of 1.4%. Ozone reduced annual biomass increment of coniferous trees less than broadleaf trees. The risk of potential effects across England was on average 1.5%, with some areas >1.5%, for example counties in the south-west.
- Reduced flower numbers in perennial grassland by 10%. Ozone had the potential to reduce flowering in wild plants primarily in England, with the areas at highest risk being in southern and eastern counties.
- Reduced annual total biomass increment in perennial grassland by 2.7%.

We provided maps and tables showing the exceedance of the ozone critical levels relevant for UK vegetation in 2018. In summary, we found that:

- Critical level exceedance was greatest for woodland habitats, with crops and grasslands 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 similar in England and Wales (69.2% and 68.8% of wheat growing areas respectively). There was no exceedance for wheat in Scotland and 2.3% of the wheat growing areas in Northern Ireland showed critical level exceedance.
- Potato showed high levels of critical level exceedance in 2018, for both England (94.9%) and Wales (96.6%). Levels were lower for Scotland (4.7%) and Northern Ireland (32.6%).
- Critical level exceedance for managed broadleaf and unmanaged beech woodlands was consistently high for England and Wales (>99%). The highest critical level exceedances tended to be in south-west England.
- Critical levels for managed coniferous forest were not exceeded in the UK in 2018.
- The percentage of the grassland areas of England where the critical level for flowering was exceeded was 74.8%.The highest critical level exceedance was in eastern and south-east England. Similarly, in Wales 62.9% of grassland areas showed exceedance of the critical level. Critical level exceedance in Scotland or Northern Ireland for this habitat was lower (4.5% and 18.2% respectively).
- The critical level for effects on the annual total biomass increment of grassland species was not exceeded in the UK.

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6 References

Bergmann, E., Bender, J., Weigel, H.-J. 2015. Assessment of the impacts of ozone on biodiversity in terrestrial ecosystems: Literature review and analysis of methods and uncertainties in current risk assessment approaches. Part II: Literature review of the current state of knowledge on the impact of ozone on biodiversity in terrestrial ecosystems. Umwelt Bundesamt TEXTE 71/2015, Dessau-Roßlau, Germany. ISSN 1862-4804.

Braun, S., Schindler, C., Leuzinger, S. 2010. Use of sap flow measurements to validate stomatal functions for mature beech (*Fagus* sylvatica) in view of ozone uptake calculations. Environmental Pollution 158: 2954-2963.

Braun, S., Schindler, C., Rihm, B. 2014. Growth losses in Swiss forests caused by ozone: Epidemiological data analysis of stem increment of *Fagus sylvatica* L. and *Picea abies* Karst. Environmental Pollution 192: 129–138.

Büker, P., Feng, Z., Uddling, J., Briolat, A., Alonso, R., Braun, S., Elvira, S., Gerosa, G., Karlsson, P.E., Le Thiec, D., Marzuoli, R., Mills, G., Oksanen, E., Wieser, G., Wilkinson, M., Emberson, L.D. 2015. New flux based dose–response relationships for ozone for European forest tree species. Environmental Pollution 206: 163–174.

De Bock, M., Op de Beeck, M., De Temmerman, L., Guisez, Y., Ceulemans, R., Vandermeiren, K. 2011. Ozone dose-response relationships for spring oilseed rape and broccoli. Atmospheric Environment 45: 1759-1765.

EMEP, 2020. Status Report, 1/2020. Transboundary particulate matter, photo-oxidants, acidifying and eutrophying components. ISSN 1504-6192 (on-line).

https://emep.int/publ/reports/2020/EMEP_Status_Report_1_2020.pdf

Fuller, R.M., Smith, G.M., Sanderson, J.M., Hill, R.A., Thomson, A.G. 2002. The UK Land Cover Map 2000: construction of a parcel based vector map from satellite images. Cartographic Journal 39: 115-25.

Hall, J., Curtis, C., Dore, T., Smith, R. 2015. Methods for the calculation of critical loads and their exceedances in the UK. Report to Defra under contract AQ0826. Centre for Ecology & Hydrology. http://www.cldm.ceh.ac.uk/content/methods-calculation-critical-loads-and-their-exceedances-uk

Hayes, F., Jones, M.L.M., Mills, G., Ashmore, M. 2007. Meta-analysis of the relative sensitivity of semi-natural vegetation species to ozone. Environmental Pollution 146: 754-76.

Grünhage, L., Pleijel, H., Mills, G., Bender, J., Danielsson, H., Lehmann, Y., Castell, J.-F., Bethenod, O. 2012. Updated stomatal flux and flux-effect models for wheat for quantifying effects of ozone on grain yield, grain mass and protein yield. Environmental Pollution 165 : 147-157.

LRTAP Convention, 2017. Mapping Critical Levels for Vegetation, Chapter III of Manual on methodologies and criteria for modelling and mapping critical loads and levels and air pollution effects, risks and trends. UNECE Convention on Long-range Transboundary Air Pollution. https://icpvegetation.ceh.ac.uk/get-involved/manuals/mapping-manual and https://www.umweltbundesamt.de/en/cce-tf-mm

Mills, G., Hayes, F., Simpson, D., Emberson, L., Norris, D., Harmens, H., Büker, P. 2011a. Evidence of widespread effects of ozone on crops and (semi-)natural vegetation in Europe (1990 – 2006) in relation to AOT40 – and flux-based risk maps. Global Change Biology 17: 592-613.

Mills, G., Pleijel, H., Braun, S., Büker, P., Bermejo, V., Danielsson, H., Emberson, L., Grünhage, L., González Fernández, I., Harmens, H., Hayes, F., Karlsson, P.-E., Simpson, D. 2011b. New stomatal flux-based critical levels for ozone effects on vegetation. Atmospheric Environment 45: 5064 – 5068.

Mills G., Hayes, F., Norris, D., Hall, J., Coyle, M., Cambridge, H., Cinderby, S., Abbott. J., Cooke, S., Murrells, T. 2011c. Impacts of Ozone Pollution on Food Security in the UK: A Case Study for Two Contrasting years, 2006 and 2008. Report for Defra contract AQ08610, available at http://icpvegetation.ceh.ac.uk/ and http://uk-air.defra.gov.uk/library/

Mills, G., Vienno, M., Sharps, K., Hall, J., Harmens, H., Hayes, F. 2017. Scoping study for NECD reporting for effects of ozone on vegetation in the UK. Centre for Ecology & Hydrology, Bangor, UK. Contract AQ0833 (Work package 7), ICP Vegetation.

Morice, C.P., Kennedy, J.J., Rayner, N.A. and Jones, P.D., 2012. Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. Journal of Geophysical Research: Atmospheres 117: (D8).

National Centers for Environmental Prediction, N. W. S. N. U. S. D. o. C.: Ncep gdas/fnl 0.25 degree global tropospheric analyses and forecast grids, in, Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory, Boulder, CO, 2015.

Pleijel, H., Danielsson, H., Emberson, L., Ashmore, M., Mills, G. 2007. Ozone risk assessment for agricultural crops in Europe: Further development of stomatal flux and flux–response relationships for European wheat and potato. Atmospheric Environment 4: 3022-3040.

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: https://www.R-project.org/.

Sharps, K., Harmens, H., Sawicka, K., Vieno, M., Steadman, C. & Hayes, F. (2019) NECD Reporting 2019 – Quantifying and mapping exceedances of ozone-flux based critical levels for vegetation in the UK (2014-16). Centre for Ecology & Hydrology, Bangor, UK. Contract AQ0846 (Work package 6), ICP Vegetation.

Sharps, K., Harmens, H., Vieno, M., Beck, R., Sawicka, K. & Hayes, F. (2020) NECD Reporting 2020 – Quantifying and mapping exceedances of ozone-flux based critical levels for vegetation in the UK in 2017. Centre for Ecology & Hydrology, Bangor, UK. Contract AQ0846 (Work package 6), ICP Vegetation.

Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L. D., Fagerli, H., Flechard, C. R., Hayman, G. D., Gauss, M., Jonson, J. E., Jenkin, M. E., Nyíri, A., Richter, C., Semeena, V. S., Tsyro, S., Tuovinen, J. P., Valdebenito, Á., Wind, P. 2012. The EMEP MSC-W chemical transport model - technical description. Atmospheric Chemistry and Physics 12: 7825-7865.

Vieno, M., Dore, A. J., Stevenson, D. S., Doherty, R., Heal, M. R., Reis, S., Hallsworth, S., Tarrason, L., Wind, P., Fowler, D., Simpson, D., Sutton, M. A. 2010. Modelling surface ozone during the 2003 heat-wave in the UK. Atmospheric Chemistry and Physics 10: 7963-7978.

Vieno, M., Heal, M. R., Williams, M. L., Carnell, E. J., Nemitz, E., Stedman, J. R., Reis, S. 2016. The sensitivities of emissions reductions for the mitigation of UK PM2.5. Atmospheric Chemistry and Physics 16: 265-276.

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

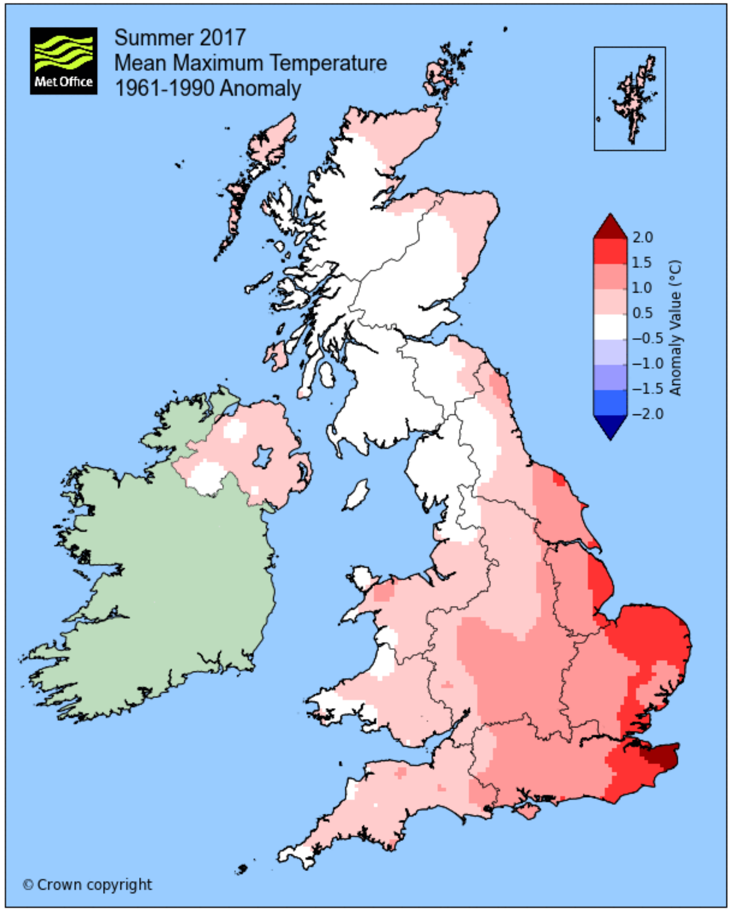
User notes for Annex, Table 1

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

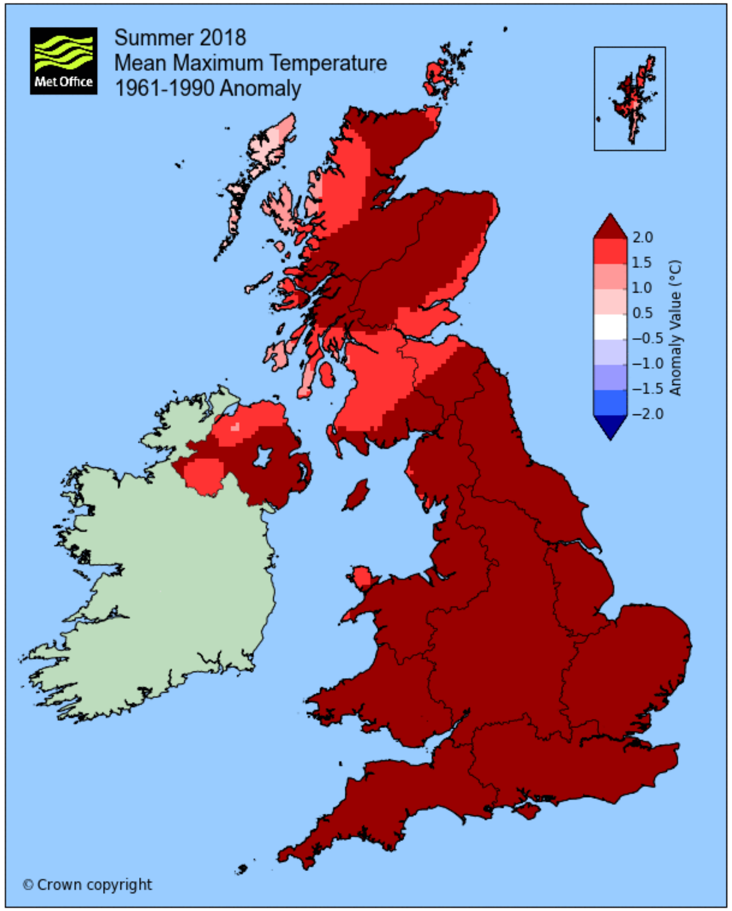
*(Simpson, D., Winiwarter, W., Börjesson, G., Cinderby, S., Ferreiro, A., Guenther, A., Hewitt, C.N., Janson, R., Khalil, M.A.K., Owen, S. and Pierce, T.E., 1999. Inventorying emissions from nature in Europe. *Journal of Geophysical Research: Atmospheres*, *104*(D7), pp.8113-8152.)

Table 2: Input parameterisation for DO_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	#	#	#	#	#	#	#	#	#	#	#	#	#



1. a)



1. b)

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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