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NECD Reporting 2020 – Quantifying and mapping exceedances of ozone flux-based critical levels for vegetation in the UK in 2017

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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 2017. We followed the same approach as previously used in an initial scoping study for the year 2015 (Mills et al., 2017), and then the subsequent study investigating annual variation in ozone impacts for the years 2014-16 (Sharps et al., 2019). 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 2017 using the most recent version of the EMEP4UK atmospheric chemistry transport model. Spatial data was collated at 5x5 km 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 2017 shows:

- Reduced UK wheat production by 5.7%, based on POD_6SPEC, amounting to a production loss of 0.93 million tonnes with an economic value of £135 million (at average farm gate prices for 2014 – 2016).The highest production losses were indicated for eastern counties, particularly Cambridgeshire, Essex, Suffolk and Norfolk.
- Reduced UK potato yield by 2.9%, resulting in 187,000 lost tonnes of potato tubers worth £31 million, with the highest production losses in parts of Hertfordshire and Bedfordshire.
- Reduced oil seed rape production, however, the losses were lower than for the other crops. Ozone reduced UK oil seed rape production by 0.99% in 2017, amounting to 21,000 tonnes of lost production, worth £5.9 million. The highest production losses were predicted for central England.
- Total economic losses for wheat, potato and oil-seed rape in the UK of £171.9 million, with the majority of losses (>97%) occurring in England.
- Calculated annual biomass increment losses for the UK for managed broadleaf woodland of 6%. Impacts on managed and unmanaged broadleaf woodland tended to be greatest in the southern half of England, with additional areas of high biomass loss in north Wales for managed broadleaf.
- Reduced annual biomass increment losses of coniferous trees for the UK of 1.1%. Ozone reduced annual biomass increment of coniferous trees less than broadleaf trees. The risk of potential effects across England was uniform (between 1-1.5%).
- Reduced flower numbers in perennial grassland by 6.4%. Ozone had the potential to reduce flowering in wild plants primarily in the southern half of England, with the areas at highest risk being in southern and eastern counties.
- Reduced annual total biomass increment in perennial grassland by 1.5%.

We provided maps and tables showing the exceedance of the ozone critical levels relevant for UK vegetation. 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 greatest in England (71% of wheat growing areas). In Wales, exceedance was 22.7%. There was no exceedance for wheat in Scotland or Northern Ireland.
- Potato showed less critical level exceedance than wheat, with the only exceedances occurring in English potato growing areas (31.9% of growing area).
- Critical level exceedance for managed broadleaf and unmanaged beech woodlands was consistently high for England and Wales (>95%). While all of the unmanaged beech growing in Scotland was growing in areas exceeding the

ozone critical level, exceedance for managed broadleaf was lower at 67.5%. The highest critical level exceedances tended to be in southern England.
- Critical levels for managed coniferous forest were not exceeded in the UK in 2017.
- The percentage of the grassland areas of England where the critical level for flowering was exceeded was 31.3%.The highest critical level exceedance was in central-south and south-east England. In Wales, only very small areas showed exceedance of the critical level (0.3% of habitat area).There was no critical level exceedance in Scotland or Northern Ireland for this habitat.
- 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 the period 2014-16, losses and critical level exceedance were greater in 2017 for crops (particularly for wheat and potato), and also 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.

Sources of uncertainty

The analysis presented 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 in this analysis, 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 2017 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_YSPEC 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 2017, 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 to reduce 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 biodiversity and vegetation growth, 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 values varied with year. Critical level exceedances also varied with year, particularly for crops and perennial grasslands.

Here, we use the same methodology as the previous studies (Mills et al., 2017; Sharps et al., 2019) 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 2017.

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 stage 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 model and the EMEP4UK 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 the EMEP4UK use 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 2017. 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 2016 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 Sharps et al., 2019 report investigating ozone impacts for the period 2014-16 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).

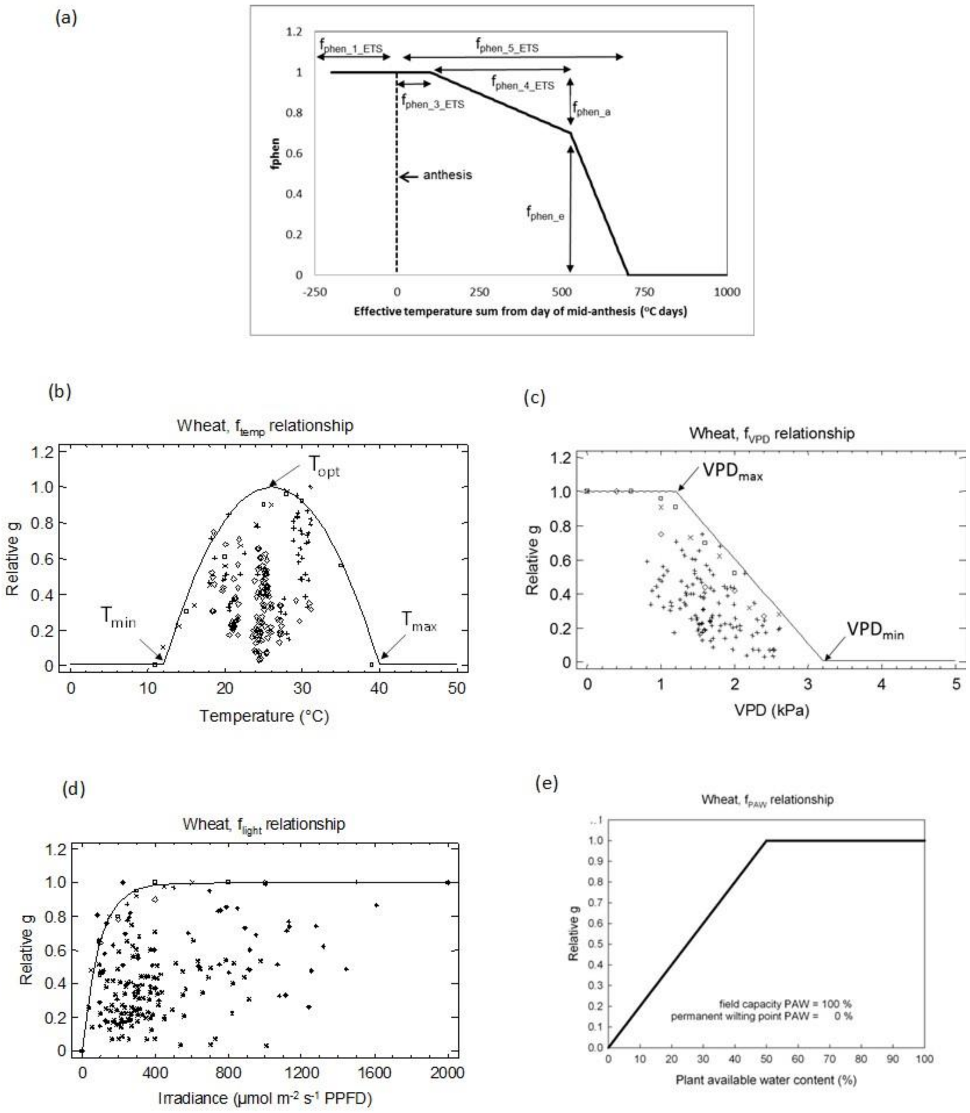

Figure 1: Illustration of the components of the DO_3SE stomatal flux model, showing for wheat how the stomatal conductance is modified by (a) phenology (growth stage), (b) temperature, (c) vapour pressure deficit - a measure of air humidity, (d), light and (e) plant available water - a measure of the 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 from the list of critical levels available, those most suited to the UK for application in this study (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_6SPEC** [ii]
Wheat	Grain yield	POD_6SPEC	5%	1.3	0.0	3.85
Potato	Tuber yield	POD_6SPEC	5%	3.8	0.0	1.34
Beech and birch	Whole tree biomass [iii]	POD_1SPEC	4%	5.2	0.9	0.93
Norway spruce	Whole tree biomass [iii]	POD_1SPEC	2%	9.2	0.1	0.22
Temperate perennial grassland	Total biomass [iii,iv]	POD_1SPEC	10%	16.2	0.1	0.62
Temperate perennial grassland	Flower number[v]	POD_1SPEC	10%	6.6	0.1	1.54

[i] Ref10 POD_6 is the flux of ozone at a pre-industrial ozone concentration of 10 ppb;

[ii] The % reduction for a given PODy is calculated using the following formula:
(POD_6SPEC – Ref10 POD_6SPEC) x potential maximum rate of reduction;

[iii] Annual increment of whole tree or total grassland biomass;

[iv] Based on a combined function for the species: *Campanula rotundifolia* (harebell), *Dactylis glomerata* (cock's foot grass), *Leontodon hispidus* (rough hawkbit), *Ranunculus acris* (meadow buttercup);

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

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), 10x10 km 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 2017 ozone 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) (potatoes) and Northern Ireland's DAERA (Department of Agriculture, Environment and Rural Affairs) (potatoes) for 2006, 2008 and 2017. A conversion factor for 2017 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 1x1 km scale, i.e. : '2017 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 1x1 km cells within each 10x10 km cell). For the final maps, data were aggregated to 5x5 km resolution.

All maps include only cells where the crop area was >1ha within each 1x1 km cell (for wheat and oilseed rape) and >0.5ha within each 1x1 km cell (potato). For Northern Ireland, there were no oilseed rape areas >1ha within any of the 1x1 km cells.

Data processing was done using Python v. 2.7.8 and maps were created using R (R Core Team, 2018).

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 1x1 km resolution and for this study, the area data were aggregated to 5x5 km 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 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 5x5 km 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 1x1 km scale, then production loss values (tonnes) were summed for each 5x5 km cell, therefore maps are at 5x5 km resolution.

Data on the economic value of crops in the UK was 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 2017

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 2017, 71% was grown in areas exceeding the ozone critical level of 1.3mmol m^{-2}. The average yield loss was 6.6% and the loss in production was 912,000 tonnes with an economic value of £132.5 million (Table 3). In Wales, 23% of the wheat grown was in areas where the critical level was exceeded and none of the wheat grown in N. Ireland or Scotland was in areas where the critical level was exceeded (Table 3, Figure 2). Overall, our analysis indicated that 66% of the UK wheat production in 2017 was in areas where the critical level was exceeded. The average yield loss for the UK was 5.7% resulting in a production loss of 931,000 tonnes with an economic value of £135 million. The highest ozone fluxes in 2017 were in the south-eastern counties of Kent and West and East Sussex (Figure 2). However, the highest production losses were indicated for eastern and north-eastern counties of England, particularly Cambridgeshire, Essex, Suffolk and Norfolk in the east, and slightly further north in Lincolnshire, where ozone flux values above the critical level were predicted for areas with a production of over 5500 tonnes per 5km x 5km grid square (Figure 3). Economic losses were therefore also predicted to be highest in eastern and north-eastern England. There was a small area of high production and economic losses predicted for central-southern England, covering parts of the counties of Hampshire/Berkshire/Oxfordshire.

In comparison to results for the period 2014 - 16 (Sharps et al., 2019), critical level exceedance for wheat in 2017 was considerably greater, for example in 2016, only 32% and 3% of the wheat area showed exceedance of the critical level for ozone in England and Wales respectively. Ozone fluxes have been shown to fluctuate between years (Sharps et al., 2019), and data for 2017 show increases compared to 2014, 15 and 16, particularly for eastern and southern England. Average yield loss for the UK has also fluctuated across the years, at 3.7% (2014), 2.2% (2015), and 3.6% (2016), and is again highest in 2017 at 5.7%. The greatest production and economic losses for 2014 - 2016 were estimated for 2014, with 683,000 tonnes of production loss and 97.5 million pounds of economic loss.

Potato is classed as moderately sensitive to ozone and is thus less sensitive than wheat (Mills et al., 2007). In 2017, 31.9% of the potato growing areas in England had ozone fluxes that exceeded the critical level of 3.8 mmol m^{-2}, with zero exceedance in Wales, Scotland and N. Ireland (Table 4, Figure 4). The average yield loss in England was 3.9% and the loss in production was 178,000 tonnes with an economic value of £29.1 million (Table 4). Across all of the UK potato production areas, the mean yield loss was 2.9%, resulting in 187,000 lost tonnes of potato tubers worth £31million at average farm gate prices (2014 – 2016). The area with the highest ozone flux and exceedance of the critical level was primarily in south-east England, where very low amounts of the crop are grown (Figure 4). Maps show pockets of high production and economic losses, for example in parts of Hertfordshire and Bedfordshire (Figure 5).

In comparison to 2014 - 16 (Sharps et al., 2019), the area of critical exceedance in England was considerably greater (31.9% compared with ~2%), however as the increased flux values were primarily seen in the south-east of England where potato production is low, the average yield loss, production and economic losses due to ozone were not greatly increased in 2017.

Table 3: Impacts of ozone on wheat in 2017, 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	1624278	1153198	71.0	13530	912	6.6	132.5
Wales	21019	4765	22.7	131	4.8	3.5	0.7
Scotland	103255	0	0	808	13.2	1.5	1.9
NI	7370	0	0	40	0.65	1.6	0.1
UK	1755922	1157963	65.9	14509	931	5.7	135

Table 4: Impacts of ozone on potato in 2017, 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	98850	31498	31.9	4387	178	3.9	29.1
Wales	2453	0	0	50	1.4	2.7	0.2
Scotland	23514	0	0	968	6.1	0.6	1.00
NI	2937	0	0	129	0.86	0.7	0.1
UK	127754	31498	24.7	5535	187	2.9	31

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 2017 (Figures 6&7).

In 2017, the average yield loss for the UK is predicted to be low at 0.99%, amounting to 21,000 tonnes of lost production, worth £5.9 million (Table 5). The majority of oilseed rape areas in England have potential yield losses of 1–1.5%, and a few areas in Hampshire and West Sussex have yield loss > 1.5% (Figure 6). The highest production and economic losses (> 45 tonnes and > £10,000 per 5km x 5km square respectively) are predicted for central England where moderate ozone fluxes coincide with areas of high oilseed rape production per 5km x 5km grid square (Figure 7).

In comparison to 2014 - 16 (Sharps et al., 2019), results for 2017 suggest slightly higher production and economic losses due to ozone than in 2015 and 2016 (not in 2014), but overall results are similar, with the greatest losses predicted for central England in all years.

Table 5: Impacts of ozone on oilseed rape in 2017, 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	524234	NA	NA	1939	21	1.1	5.8
Wales	4764	NA	NA	7.9	0.08	1.02	0.02
Scotland	32358	NA	NA	96	0.4	0.5	0.1
NI	636	NA	NA	NA	NA	NA	NA
UK	561992	NA	NA	2043	21	0.99	5.9

NA: Not applicable

3.2 Impacts of ozone on broad habitats in the UK in 2017

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 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 2017, the ozone critical level of 5.2 mmol m^{-2} was exceeded in 99.8%, 99.9% and 67.5% of the area of this habitat in England, Wales and Scotland respectively (Table 6a). The overall exceeded area for the UK was 94.3%, with an average indicative biomass increment loss of 6%. The level of exceedance was greatest for woodland areas in south-west England (Cornwall and Devon) (Figure 8). The largest area showing no exceedance of the critical level was in northern Scotland. Predicted biomass increment loss was highest in south-west England (<8%), with other small areas of high loss, for example in north Wales and along the south coast of England (Figure 8).

In comparison to 2014 - 2016 (Sharps et al., 2019), the overall exceeded area and average % biomass increment loss have been broadly similar between years, 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 2015-2017, exceedance was greatest in the south-west of England. Looking regionally, compared to 2016, critical level exceedance in 2017 has decreased in some areas of northern, central and eastern England. Also, while average biomass increment loss is similar between years, examination of the mapped results suggests that biomass loss due to ozone has decreased in some areas of England in 2017, for example in East Anglia but increased in other areas, for example along the southern coast of England, including parts of Dorset, Hampshire and West Sussex.

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 2017, the ozone critical level was exceeded in 99.9%, 100% and 100% of the area of this habitat in England, Wales and Scotland respectively (Table 6b). For the UK overall, the average indicative biomass increment loss was 6.6%. The level of exceedance was greatest on the south coast of England, including areas of Devon, Cornwall and Dorset, where in some areas biomass increment losses of >8% were predicted (Figure 9).

In comparison to 2014 - 16 (Sharps et al., 2019), exceedance of the ozone critical level and biomass increment losses were similar in 2017 both in terms of average values, and in terms of spatial distribution. Maps for 2016 and 2017 show similar patterns of biomass increment loss, except for slightly higher losses in counties on the southern coast of England, including Dorset, Hampshire and West Sussex.

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 2017 (Table 6c, Figure 10). Indicative biomass increment losses were lower than for broadleaf woodland, with all predicted losses being below 2%. In 2017, the majority of grid squares in England suggested predicted losses of 1 -1.5%, with some very small pockets with higher losses (>1.5%) along the coast of southern England (Figure 10). Lower values for predicted biomass increment losses were found for large parts of Scotland (0 - 0.75%) (Figure10).

The critical level has not been exceeded and average biomass increment losses were similar for2014 – 2017. Spatial data show that biomass increment losses have been decreasing slightly with year on the southern coast of England while losses in Scotland have fluctuated, but the maximum annual biomass increment loss for this vegetation type is only 1.5%.

Table 6: Impacts of ozone on woodland habitats in the UK in 2017, 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	549396	98.8	6.3
Wales	80621	80555	99.9	6.6
Scotland	108705	73337	67.5	5.0
NI	NA	NA	NA	NA
UK	745667	703288	94.3	6.0

Country	(b) Unmanaged Beech woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	58053	57999	99.9	6.6
Wales	5821	5821	100	6.7
Scotland	312	312	100	6.6
NI	NA	NA	NA	NA
UK	64186	64132	99.9	6.6

Country	(c) Managed coniferous woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	171274	0	0	1.2
Wales	105263	0	0	1.2
Scotland	511583	0	0	1
NI	50148	0	0	1.2
UK	838268	0	0	1.1

(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 5.1) and lower effect values are not currently justified.

In 2017, the ozone critical level for flowering of ozone-sensitive grassland species of 6.6 mmol m^{-2} was exceeded for 31.3% of the area of this grassland type in England and 0.3% in Wales (Table 7a). The critical level was not exceeded for Scotland or N. Ireland (Figure 11).The indicative risk analysis suggested an average of 10% loss in flower number for the UK, with the highest losses (>11%) occurring in areas of central-southern and south-east England (Figure 11). This could potentially affect plant species composition and/or diversity.

In comparison to 2014 - 2016 (Sharps et al., 2019), the exceeded area in England was considerably higher in 2017, particularly compared to 2015 and 2016 (138,171ha in 2014; 1894ha in 2015 and 3356ha in 2015). Ozone flux in 2017 was higher in England than in 2015-16, showing a similar pattern to ozone flux in 2014 (highest values in south-east England).Average flower loss for the UK has fluctuated and in 2017 was similar to the average value in 2016 (6.1%). In the south of England, flower loss has been increasing, with values of >11% estimated in the south-east and spreading westwards (compared to 2014 - 16).

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 2017 (Table 7b; maps not presented). Hence, biomass losses were well below 10% (as defined by the critical level) and did not exceed 1.5% on average in the UK.

Average biomass losses have fluctuated slightly over the period 2014 - 17. Estimated losses in England are at their highest in 2017 at 2.2% (1.9% in 2014; 1.4% in 2015; 1.7% in 2016). However, the critical level has not been exceeded over the 4-year period.

Table 7: Impacts of ozone on (a) flowering and (b) total biomass of grassland habitats in the UK in 2017, 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	603823	188975	31.3	8.8
Wales	334078	1105	0.3	7.3
Scotland	841595	0	0	3.7
NI	126426	0	0	6.3
UK	1905922	190080	10.0	6.4

Country	(b) Grassland total biomass			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	602338	0	0	2.2
Wales	334078	0	0	1.7
Scotland	840513	0	0	0.8
NI	126426	0	0	1.4
UK	1903355	0	0	1.5

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), losses and critical level exceedance were greater in 2017 for crops (particularly for wheat and potato), and also for semi-natural vegetation. For trees, results for 2017 were similar to those for 2014 -16, with some spatial variation in ozone fluxes, losses and critical level exceedance between years.

The previous report for 2014 - 16 (Sharps et al., 2019) showed spatial and temporal variation in ozone flux values for the UK, with examination of model inputs suggesting these patterns were due to changes in meteorology. Also, the EMEP-WRF model calculates the POD 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 model outputs for ozone (https://emep.int/publ/common_publications.html#2019). Results show that differences in ozone levels between years are primarily due to changes in weather. For example summer temperatures in the UK were slightly higher than normal in 2017 (EMEP 2019), whereas in 2015, summer ozone levels in the UK were generally low with few peaks and ozone episodes (EMEP 2017). In 2017, there were a number of ozone episodes during the summer in the UK, with high daily maximum values in Southern England in June. This coincides with the growing season for all vegetation types included in this report. However, 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. Changes in air pollution emissions can be expected to have less impact than the weather as differences between years are generally small.

Wheat (POD_6SPEC for grain yield)

(Note: For comparison purposes, map scales have been kept the same as for the 2014-16 report for each vegetation type however as values for wheat and potato were higher in 2017, in some maps, an extra red and/or dark red category has been added).

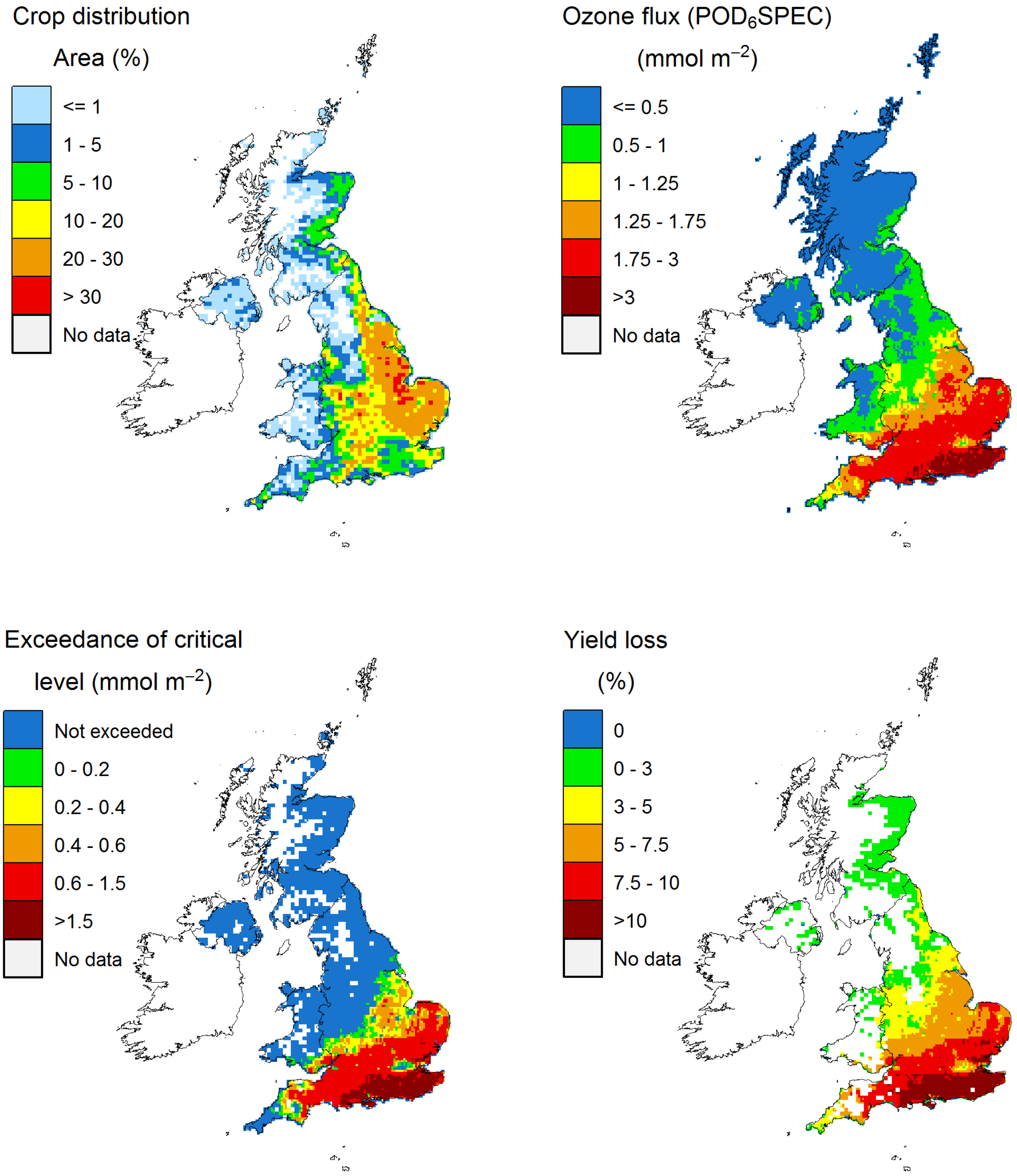

Figure 2: Impacts of ozone on wheat production in 2017 calculated using POD_6SPEC. (a) Distribution of wheat presented as the percentage of each 5km x 5km grid square sown with wheat; (b) POD_6SPEC (mmol m^{-2}) (**critical level = 1.3 mmol m^{-2}**); (c) Exceedance of the critical level; (d) Percentage yield loss.

Wheat (POD$_6$SPEC for grain yield)

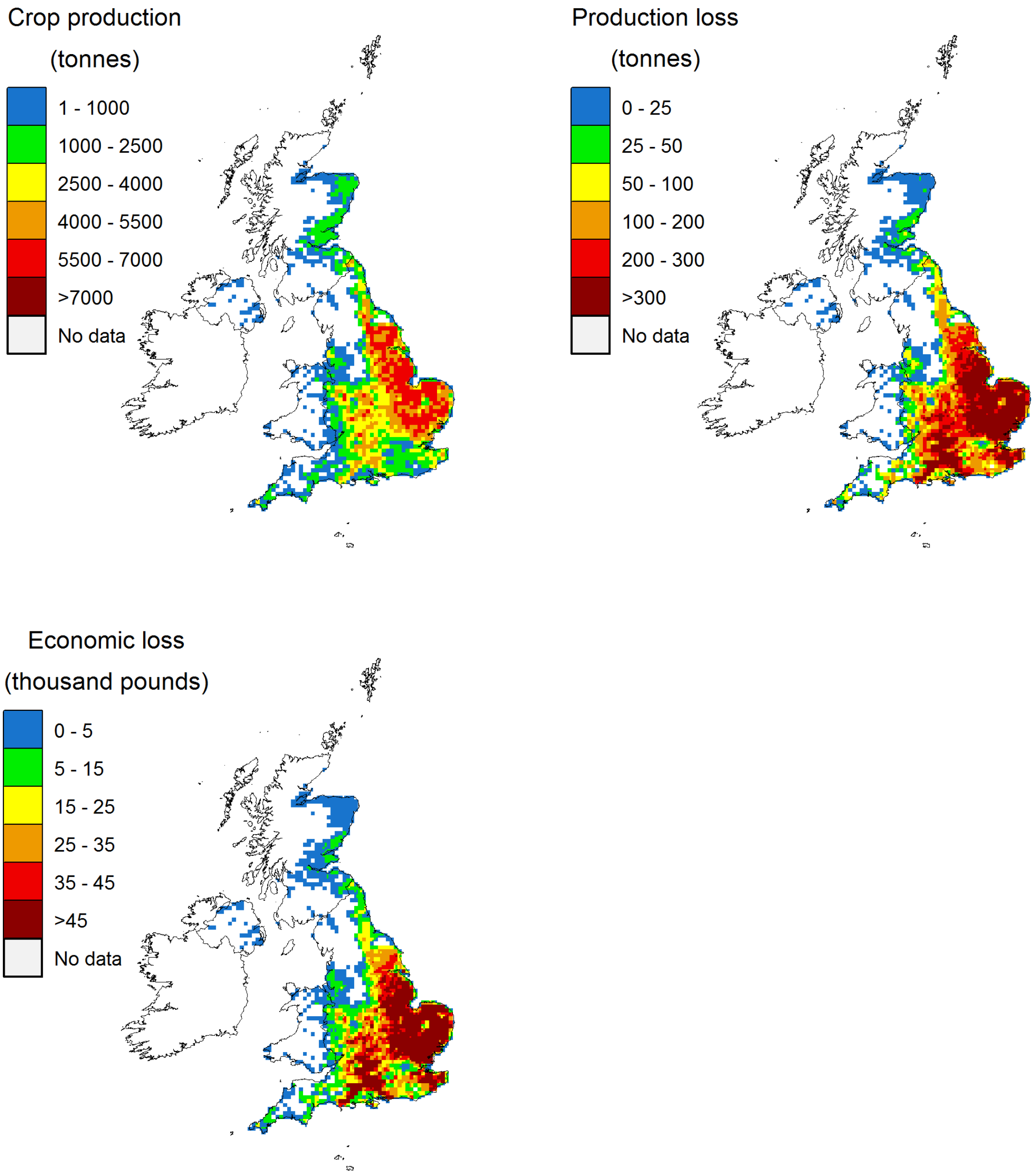

Figure 3: Impacts of ozone on wheat production in 2017 calculated using POD$_6$SPEC. (a) Wheat production in the UK in tonnes per 5km x5km grid square; (b) Production loss due to ozone in tonnes per 5km x5km grid square; and (c) Economic loss in thousand £UK per 5km x 5km grid square, based on mean price 2014-16.

Potato (POD$_6$SPEC for tuber yield)

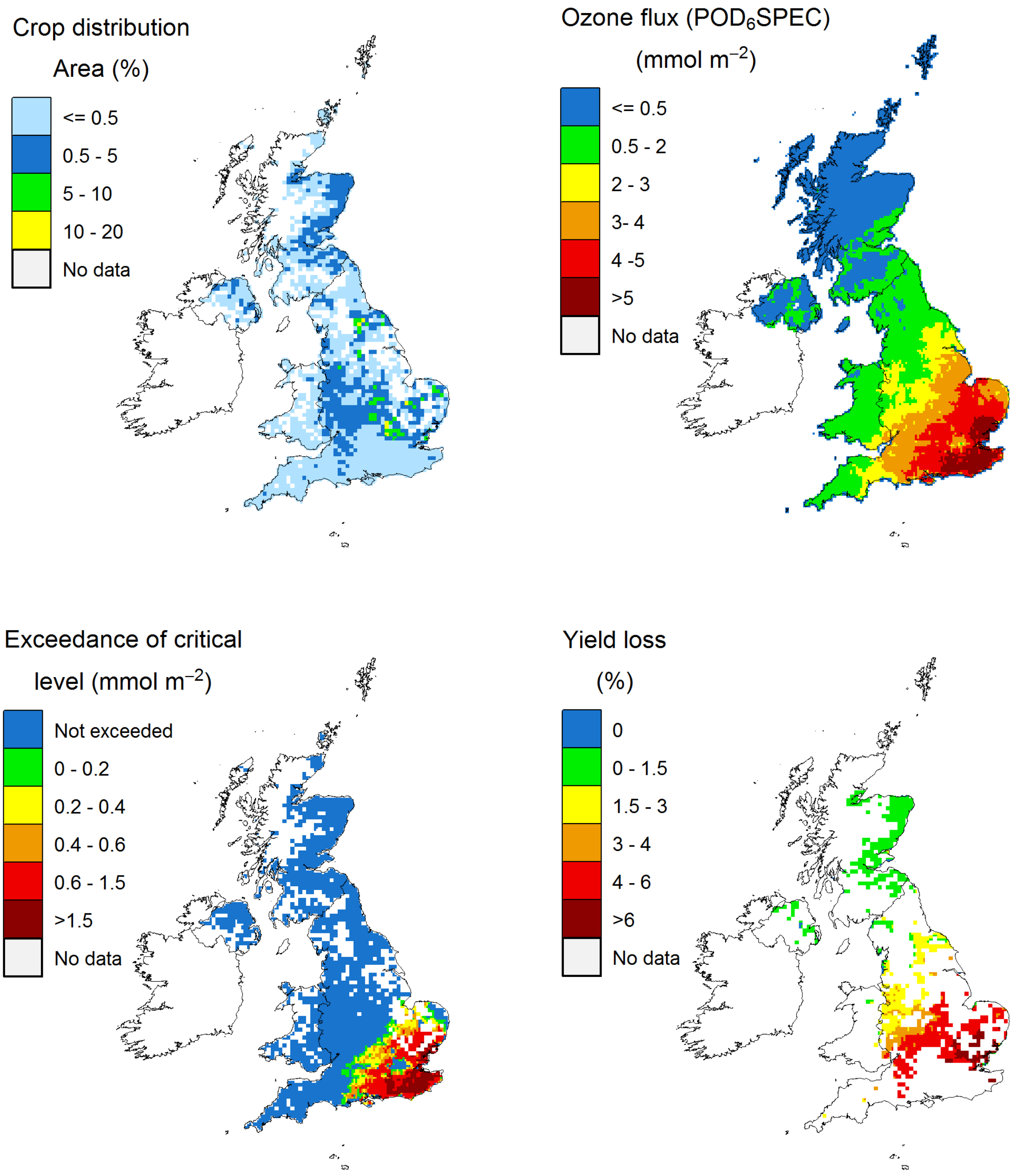

Figure 4: Impacts of ozone on potato production in 2017 calculated using POD$_6$SPEC. (a) Distribution of potato presented as the percentage of each 5x5 km grid square sown with potato; (b) POD$_6$SPEC (mmol m^{-2}) (**critical level = 3.8 mmol m^{-2}**); (c) Exceedance of the critical level; (d) Percentage yield loss.

Potato (POD_6SPEC for tuber yield)

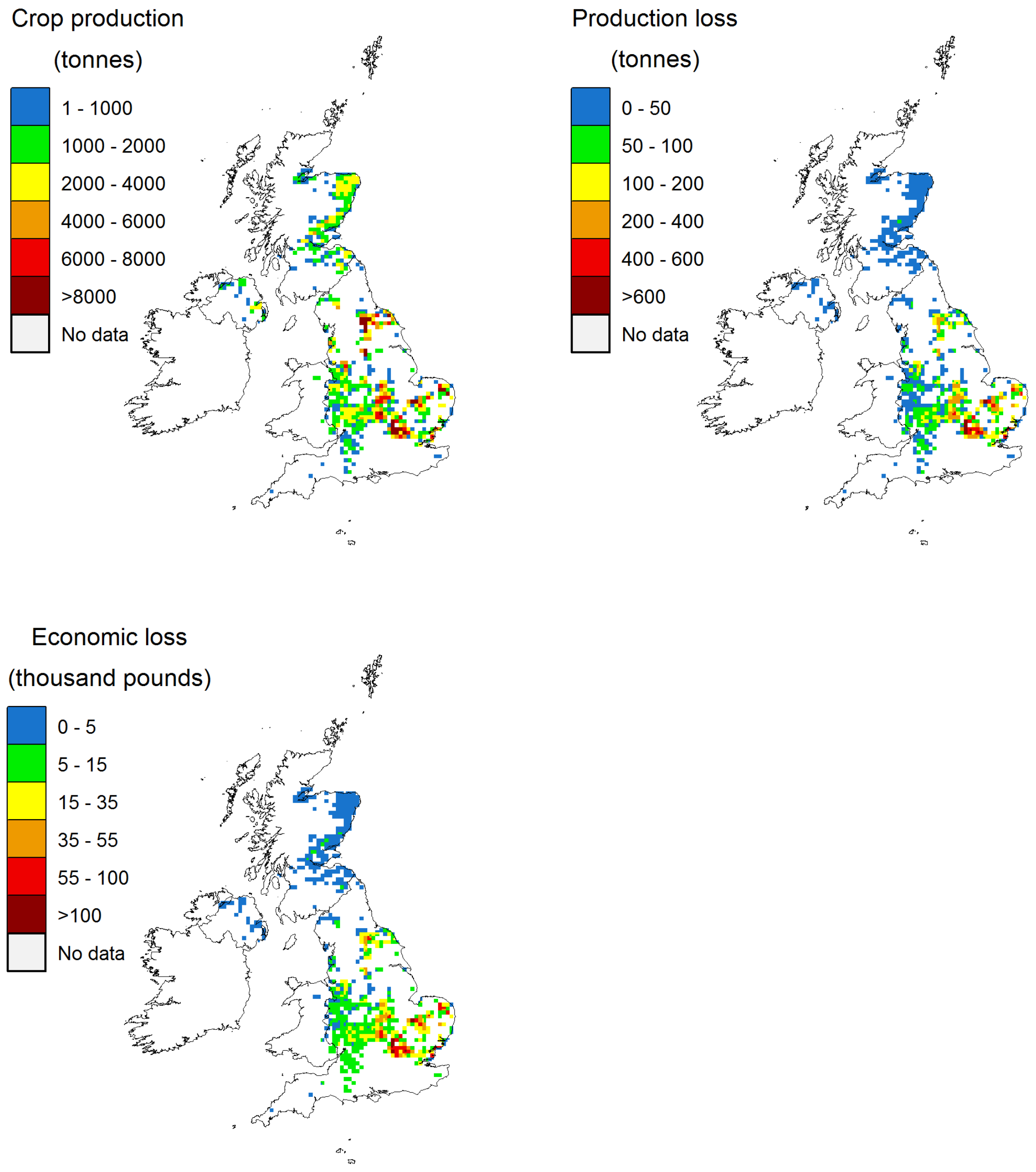

Figure 5: Impacts of ozone on potato production in 2017 calculated using POD_6SPEC. (a) Potato production in the UK in tonnes per 5km x5km grid square; (b) Production loss due to ozone in tonnes per 5km x5km grid square; and (c) Economic loss in thousand UK£ per 5km x5km grid square, based on mean price 2014-16.

Oilseed rape (POD_6SPEC for grain yield)

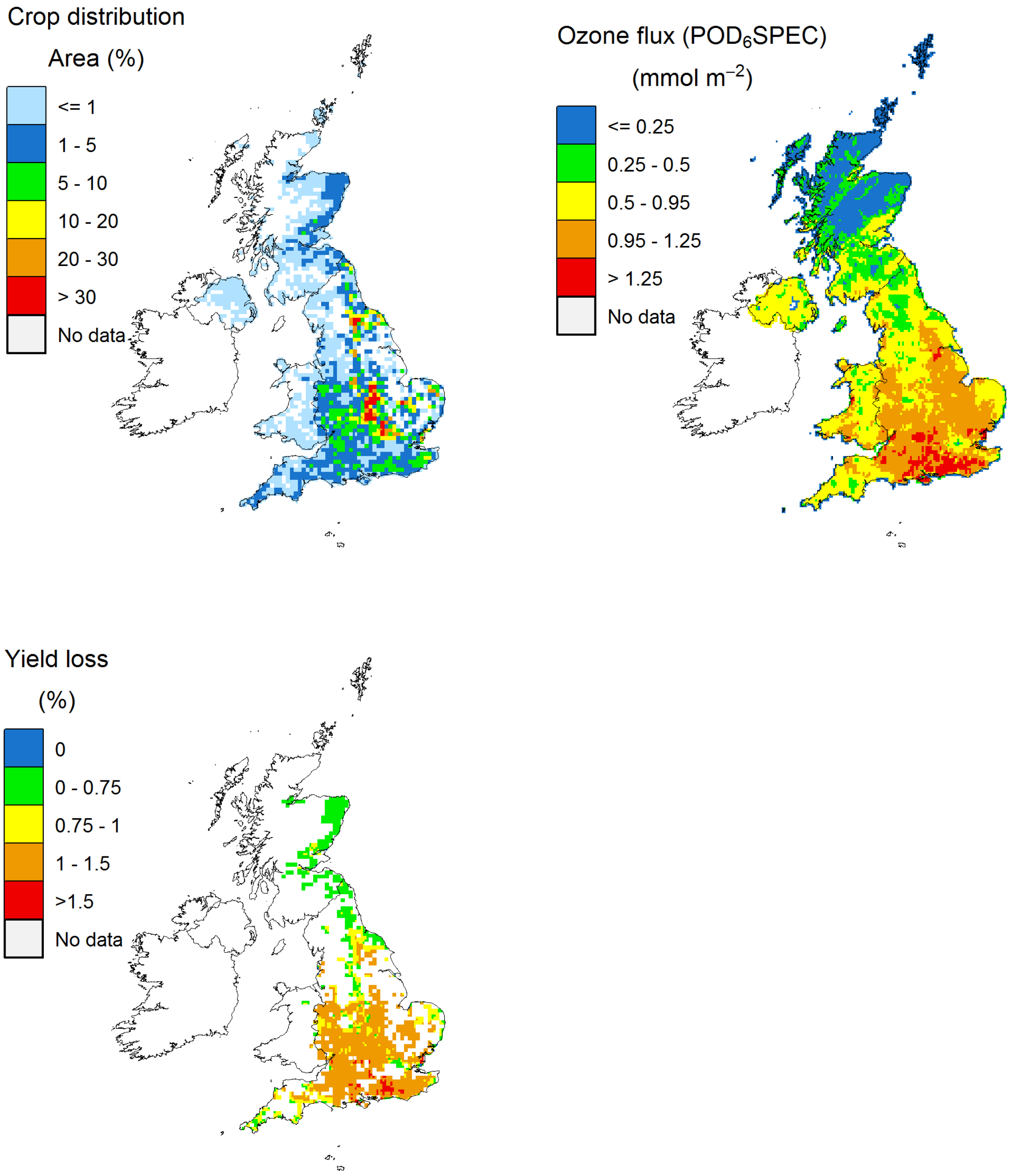

Figure 6: Impacts of ozone on oilseed rape production in 2017 calculated using POD_6SPEC. (a) Distribution of oilseed rape presented as the percentage of each 5km x5km grid square sown with oilseed rape; (b) POD_6SPEC ($mmol\ m^{-2}$); (c) Percentage yield loss.

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

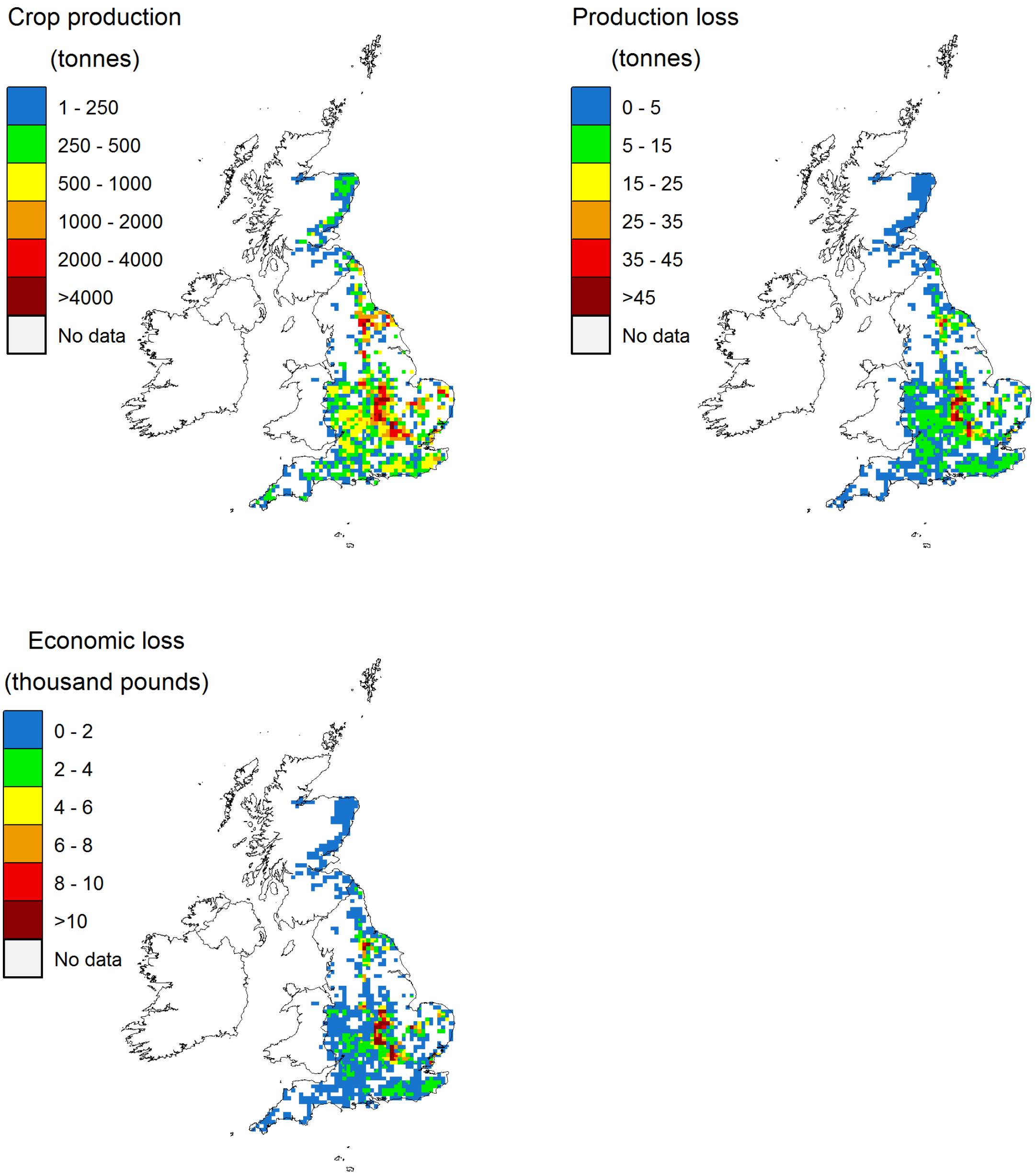

Figure 7: Impacts of ozone on oilseed rape production in 2017 calculated using POD$_6$SPEC. (a) Oilseed rape production in the UK in tonnes per 5km x5km grid square; (b) Production loss due to ozone in tonnes per 5km x5km grid square; and (c) Economic loss in thousand UK£ per 5km x5km grid square, based on mean price 2014-16.

Managed broadleaved woodland (POD_1SPEC for biomass increment)

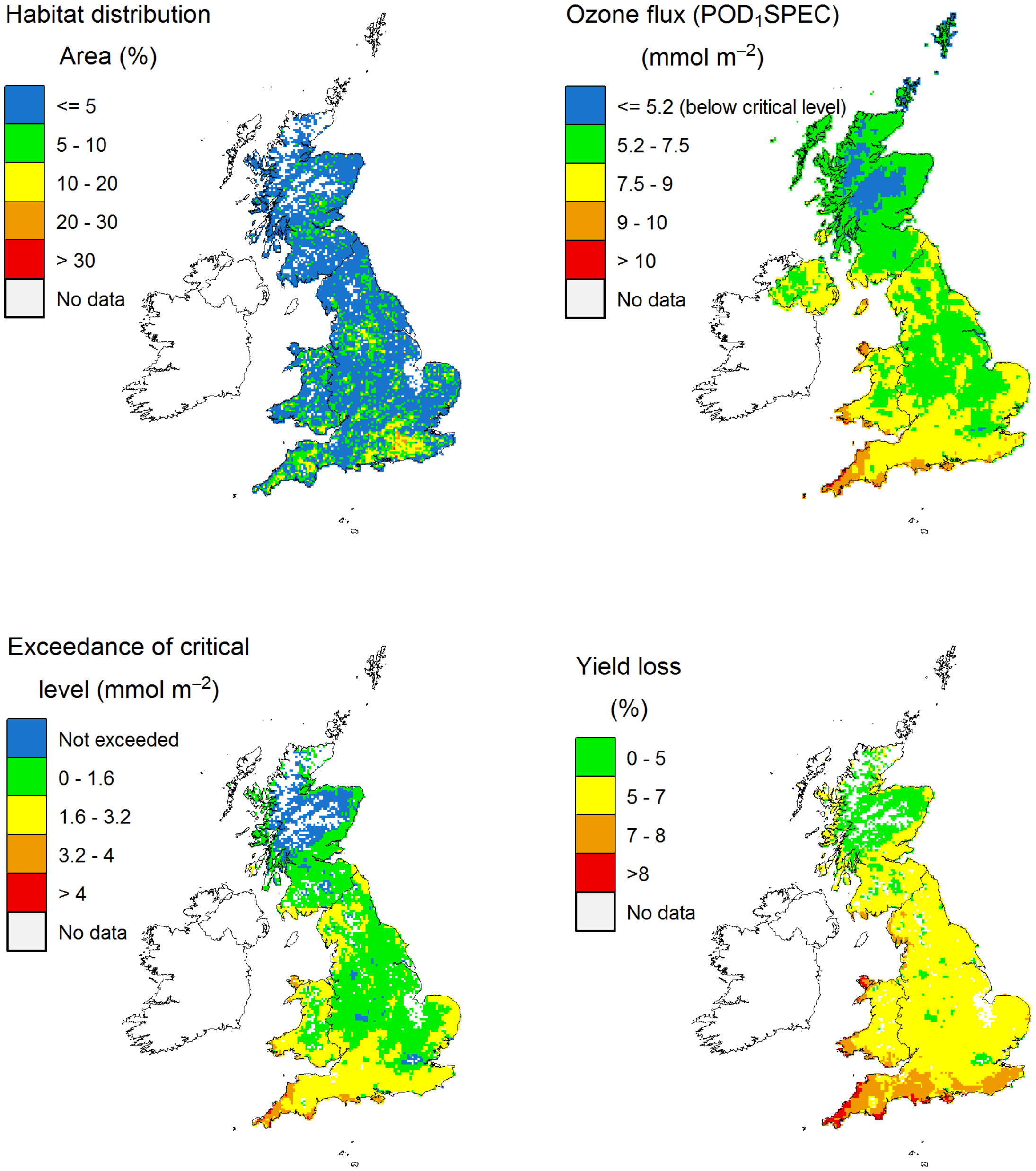

Figure 8: Impacts of ozone on managed broadleaf woodland in 2017 calculated using POD_1SPEC. (a) Distribution of managed broadleaf woodland as the percentage area of each 5km x5km grid square; (b) POD_1SPEC (mmol m^{-2}), all squares coloured blue have POD_1SPEC values below the **critical level of 5.2 mmol m^{-2}**; (c) exceedance of the critical level; (d) Percentage biomass loss (indicative risk only).

Unmanaged Beech woodland (POD$_1$SPEC for biomass increment)

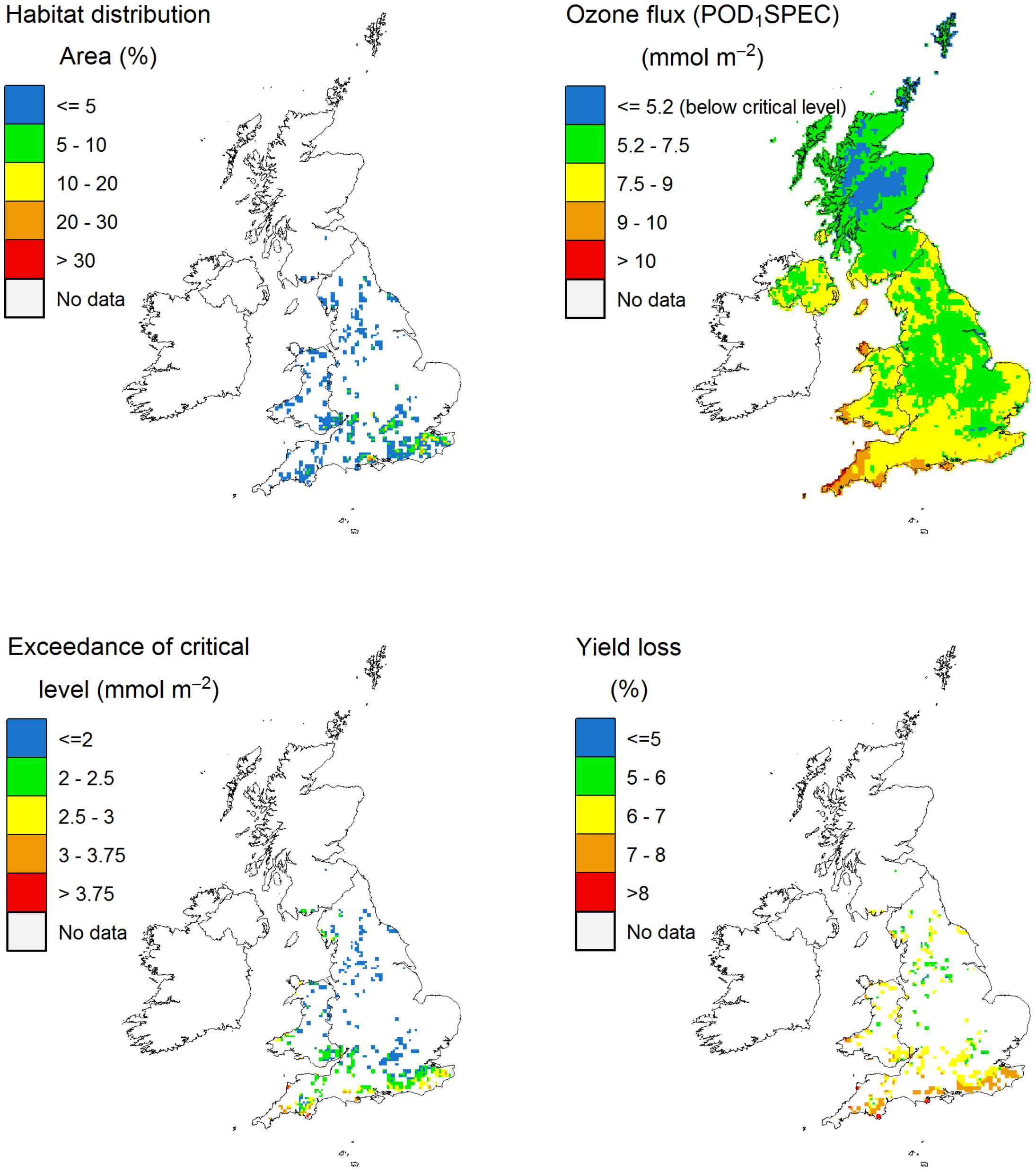

Figure 9: Impacts of ozone on unmanaged beech woodland in 2017 calculated using POD$_1$SPEC. (a) Distribution of unmanaged beech woodland as the percentage area of each 5km x 5km grid square; (b) POD$_1$SPEC (mmol m^{-2}), all squares coloured blue have POD$_1$SPEC values below the **critical level of 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)

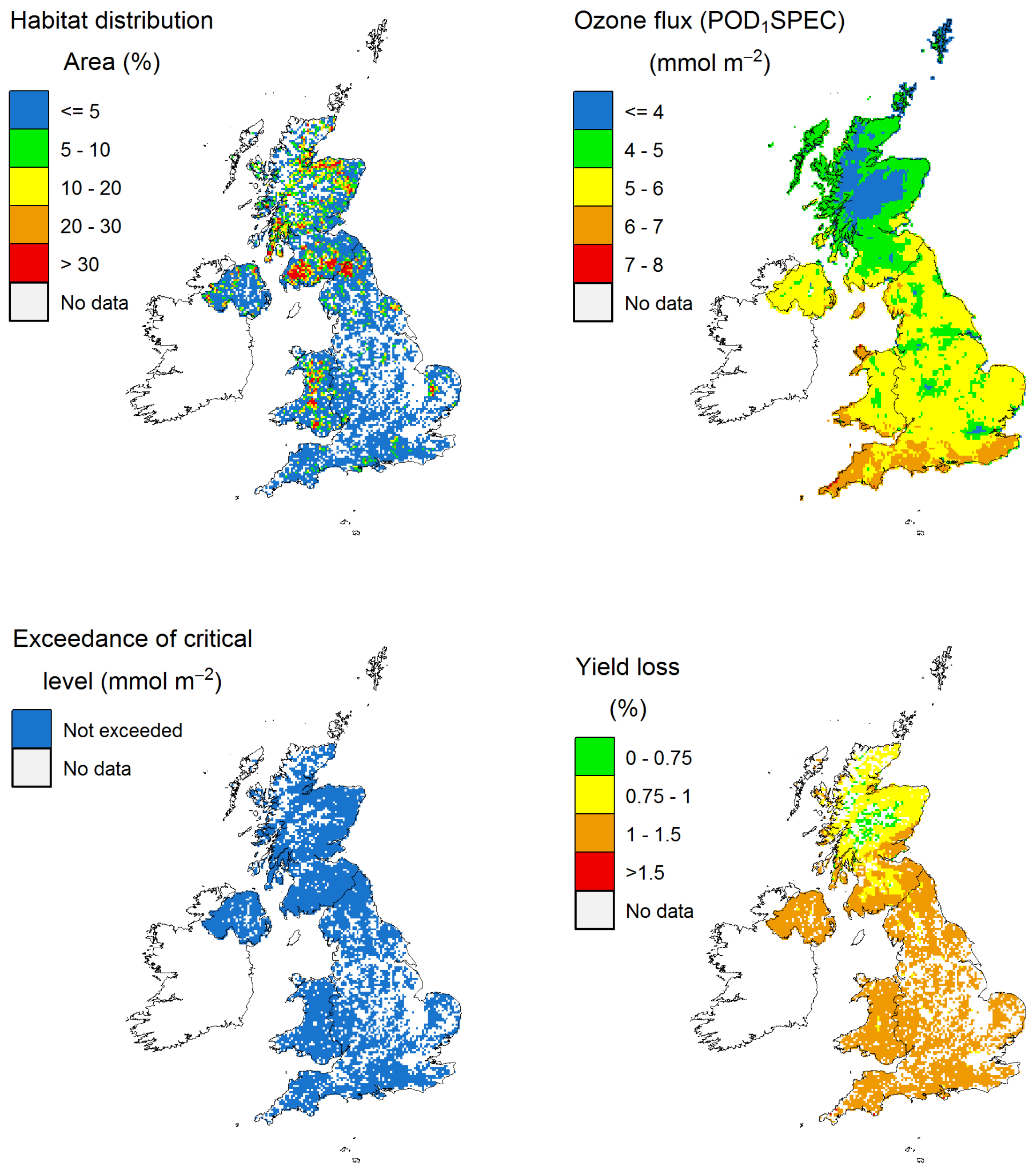

Figure 10: Impacts of ozone on managed coniferous woodland in 2017 calculated using POD_1SPEC. (a) Distribution of managed coniferous woodland as the percentage area of each 5km x5km grid square; (b) POD_1SPEC (mmol m^{-2}) (**critical level = 9.2 mmol m^{-2}**); (c) exceedance of the critical level; (d) Percentage yield loss (indicative risk only).

Perennial grassland (POD_1SPEC for flower numbers)

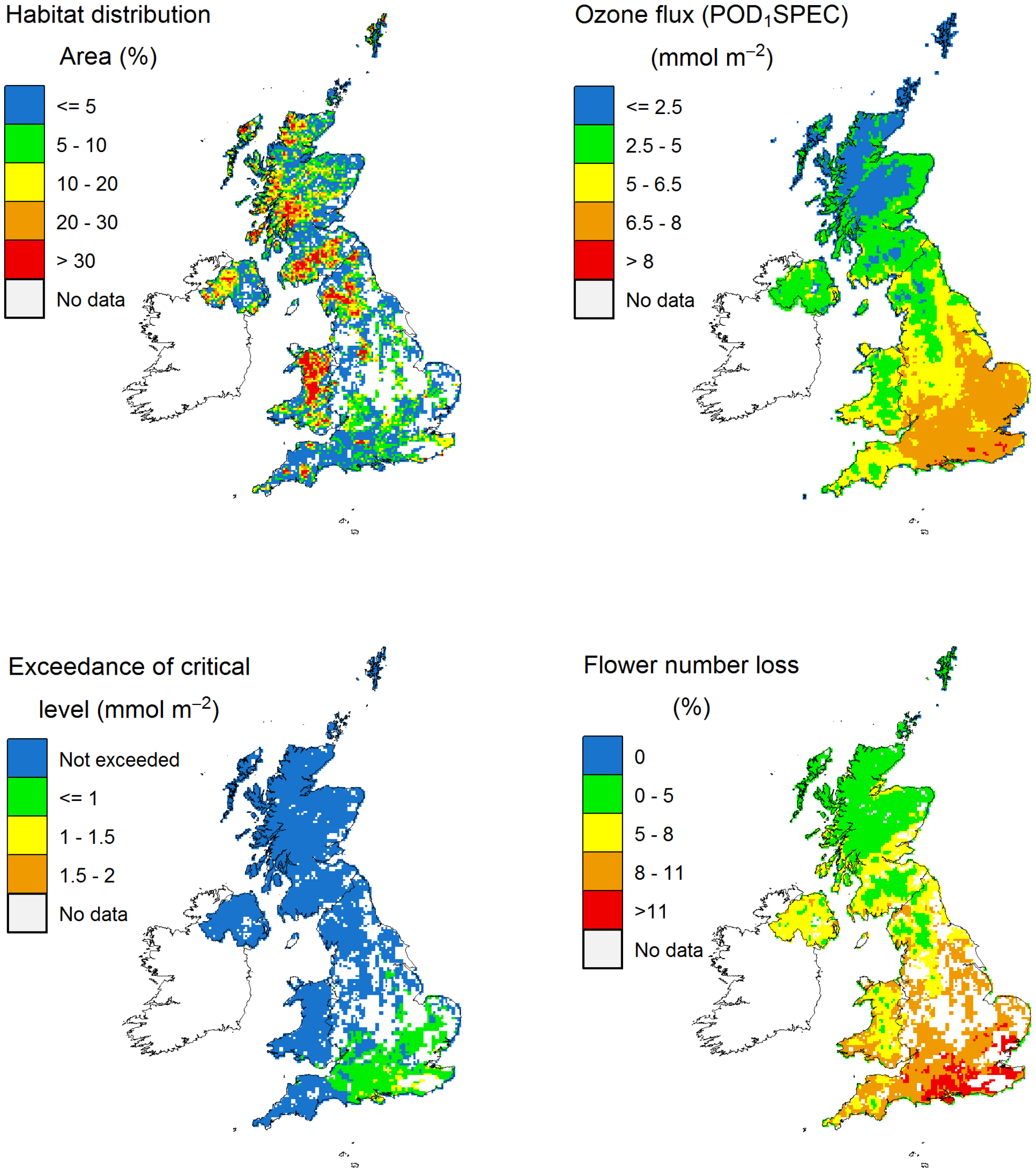

Figure 11: Impacts of ozone on perennial (semi-natural) grassland in 2017 calculated using POD_1SPEC. (a) Distribution of grassland as the percentage area of each 5x5 km grid square; (b) POD_1SPEC (mmol m^{-2}) (**critical level = 6.6 mmol m^{-2}**); (c) Exceedance of the critical level; (d) Percentage 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 different 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 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 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 2016 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 2017. The finest scale data that could be found for this conversion was regional totals per crop which will have introduced some uncertainty into the analysis, and there will have been some areas that were growing a crop in 2017 and 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 x10km cell in order to achieve the desired 5km x 5km resolution. Economic losses are provided as an indicative cost based on the mean price over the period 2014 - 2016. Prices were not updated to 2017 as this would have introduced a further source of variation into the reported results, making comparison between 2014 - 2016 and 2017 more difficult. The volatility in crop prices should be taken into account in a more detailed economic analysis.

The habitat distribution maps were generated for critical loads research (see Section 3.3.2) 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 x1km, 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).

5 Conclusions

This study was undertaken to build on the scoping study carried out for the year 2015 by Mills et al., (2017), and the study examining three consecutive years (2014 – 2016) of data for the UK on the exceedances of ozone flux-based critical levels and ozone impacts on vegetation. 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 2017.

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 2017 shows:

- Reduced UK wheat production by 5.7%, based on POD_6SPEC, amounting to a production loss of 930,000 tonnes with an economic value of £135 million (at average farm gate prices for 2014 – 2016).The highest production losses were indicated for eastern counties, particularly Cambridgeshire, Essex, Suffolk and Norfolk.
- Reduced UK potato yield by 2.9%, resulting in 187,000 lost tonnes of potato tubers worth £31 million, with the highest production losses in parts of Hertfordshire and Bedfordshire.
- Reduced oil seed rape production, however, the losses were lower than for the other crops. Ozone reduced UK oil seed rape production by 0.99% in 2017, amounting to 21,000 tonnes of lost production, worth £5.9 million. The highest production losses were predicted for central England.
- Total economic losses for wheat, potato and oil-seed rape in the UK of £171.9 million, with the majority of losses (>97%) occurring in England.
- Calculated annual biomass increment losses for the UK for managed broadleaf woodland of 6%. Impacts on managed and unmanaged broadleaf woodland tended to be greatest in the southern half of England, with additional areas of high biomass loss in north Wales for managed broadleaf.
- Reduced annual biomass increment losses of coniferous trees for the UK of 1.1%. Ozone reduced annual biomass increment of coniferous trees less than broadleaf trees. The risk of potential effects across England was uniform (between 1-1.5%).
- Reduced flower numbers in perennial grassland by 6.4%. Ozone had the potential to reduce flowering in wild plants primarily in the southern half of England, with the areas at highest risk being in southern and eastern counties.
- Reduced annual total biomass increment in perennial grassland by 1.5%.

We provided maps and tables showing the exceedance of the ozone critical levels relevant for UK vegetation. 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 greatest in England (71% of wheat growing areas). In Wales, exceedance was 22.7%. There was no exceedance for wheat in Scotland or Northern Ireland.
- Potato showed less critical level exceedance than wheat, with the only exceedances occurring in English potato growing areas (31.9% of growing area).
- Critical level exceedance for managed broadleaf and unmanaged beech woodlands was consistently high for England and Wales (>95%). While all of the unmanaged beech growing in Scotland was growing in areas exceeding the ozone critical level, exceedance for managed broadleaf was lower at 67.5%. The highest critical level exceedances tended to be in southern England.
- Critical levels for managed coniferous forest were not exceeded in the UK in 2017.
- The percentage of the grassland areas of England where the critical level for flowering was exceeded was 31.3%.The highest critical level exceedance was in central-south and south-east England. In Wales, only very small areas showed exceedance of the critical level (0.3% of habitat area).There was no critical level exceedance in Scotland or Northern Ireland for this habitat.
- The critical level for effects on the annual total biomass increment of grassland species was not exceeded in the UK.

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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_BEEC	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	#	#	#	#	#	#	#	#	#	#	#	#	#

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