NECD Reporting 2019 - Quantifying and mapping exceedances of ozone flux-based critical levels for vegetation in the UK (2014 – 2016)

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Contents

1 Executive Summary 4
2 Introduction 7
3 Methods 9
3.1 Modelling of the stomatal flux of ozone 9
3.2 Critical levels for ozone 11
3.3 Calculating critical level exceedances 11
3.4 Mapping crop and habitat distribution 12
3.4.1 Mapping the distribution of crop area and production 12
3.4.2 Defining habitat areas for woodlands and grasslands 12
3.5 Calculating losses due to ozone 13
3.5.1 Crops 13
3.5.2 Trees and grassland 13
4 Results 14
4.1 Crops: Ozone critical level exceedances and impacts on crop production 14
4.2 Impacts of ozone on broad habitats in the UK 18
4.3 Summary on spatial and temporal variation in ozone flux 23
4.4 Critical level exceedance maps for 2014, 2015 and 2016 24
5 Sources of uncertainty in analysis 30
5.1 Response functions and critical levels 30
5.2 Modelling $POD_Y SPEC$ 31
5.3 Mapping crop area, production and economic losses 31
5.4 Mapping habitat distribution 32
6 Conclusions 33
Acknowledgements 34
7 References 35
Annex 1 37
Annex 2 40
7.1 Crop maps for 2014, 2015 and 2016 40
7.2 Broad habitat maps for 2014, 15 and 16 58
..... 69

1 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. This study was undertaken to examine how Annex V of the Amended NECD Directive 2003/35/EC for monitoring the effects of air pollution on ecosystems could be interpreted for ozone in a UK context.

As a first approach to meet the requirements of Annex V to report on exceedances of flux-based critical levels for ozone and report on ozone damage to vegetation growth (including crop yield) and biodiversity, we mapped the modelled exceedances for vegetation for the years 2014, 2015 and 2016. We followed the same approach as previously used in a scoping study for the year 2015 (Mills et al., 2017). The critical level exceedance data and ozone impacts on crop yield, annual increment of tree biomass, grassland 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, grasslands and flowering of wild plants. Compared to the scoping study, an updated version of the EMEP4UK model was used to model ozone fluxes to vegetation for the UK, resulting in lower critical level exceedances and impacts on vegetation for 2015 in the current study.

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 2014, 2015 and 2016 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 at 5x5 km resolution 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 5x5 km resolution by applying flux-based response functions to gridded flux data.

Results

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

- Critical level exceedance was greatest for woodland habitats, intermediate for crops, and modest for flower number in grasslands.

- Critical level exceedances varied with year, particularly for crops and perennial grasslands.
- UK average values for percentage of area exceeding critical levels do not provide the full picture on the extent of ozone effects as there are spatial differences in exceedances within the UK.
- For wheat (POD_6SPEC), critical level exceedance depended on the year, with exceedance being greatest in England (31.6% (2014), 3.4% (2015) and 30.8% (2016) of wheat growing areas). In Wales, exceedance was 2.8% (2014), 0% (2015) and 47.9% (2016). There was no exceedance for wheat in Scotland or Northern Ireland.
- Potato (POD_6SPEC) showed considerably less critical level exceedance than wheat, with the only exceedances occurring in English potato growing areas in 2014 (2.5%) and 2015 (0.7%).
- Critical level exceedance for managed broadleaf and unmanaged beech woodlands was consistently high for England and Wales (>95% for all years). While all of the unmanaged beech growing in Scotland was growing in areas exceeding the critical level of POD_1SPEC, exceedance for managed broadleaf was 64% (2014), 50% (2015) and 75% (2016). The highest critical level exceedances tended to be in southern England.
- Critical levels for managed coniferous forest were not exceeded in the UK for the period 2014-2016.
- The percentage of the grassland areas of England where the critical level for flowering was exceeded varied with year (16.3% in 2014, 0.2% in 2015 and 0.4% in 2016).The highest critical level exceedance was in south-east England in 2014. In Wales, only very small areas showed exceedance of the critical level (0.03% in 2014, 0% in 2015 and 0.6% in 2016). There was no critical level exceedance in Scotland or Northern Ireland for this habitat.
- The critical level for effects on the annual total biomass of grassland species was not exceeded in the UK.

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. 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 shows:

- Spatial and temporal variation in ozone fluxes for the period 2014 - 2016. This seems to be mainly driven by differences in meteorology. For some vegetation types, the areas of the country showing the highest values varied with year. This in turn affected ozone impacts on crop yield and vegetation biomass.
- Reduced UK wheat production by 3.7% (2014), 2.2% (2015) and 3.6% (2016) based on POD_6SPEC. Economic losses due to ozone varied between years, with an estimated UK loss of £99.5 million in 2014, £62 million in 2015 and £73 million in 2016 (using average farm gate prices for 2014 – 2016). Areas of the UK with the highest production losses varied with year, but eastern England consistently showed the highest production and economic losses.
- Reduced UK potato production by an average of 2.3% (2014), 2.2% (2015) and 1.7% (2016). Economic losses due to ozone varied between years, with an estimated UK loss of £22 million in 2014, £20 million in 2015 and £14 million in 2016 (using average farm gate prices for 2014 – 2016). For each year, areas of high production and economic loss tended to be where areas of high potato production coincided with

higher ozone levels, for example in rural areas of Hertfordshire and Buckinghamshire.

- Reduced oil seed rape production, however, the losses were lower than for the other crops. Ozone reduced UK oil seed rape production by 0.8% (2014), 0.6% (2015) and 0.7% (2016). Economic losses due to ozone varied slightly between years, with an estimated UK loss of £6 million in 2014, £4 million in 2015 and £4 million in 2016 (using average farm gate prices for 2014 – 2016). Each year, the highest production losses were predicted for central England.
- Total economic losses for wheat, potato and oil-seed rape in the UK of £128, £86 and £91 million in 2014, 2015 and 2016 respectively, with the majority of losses (>97%) occurring in England.
- Calculated annual biomass increment losses for the UK for managed broadleaf woodland of 6.5% (2014), 5.9% (2015) and 6.1% (2016). Impacts on managed and unmanaged broadleaf woodland tended to be greatest in the southern half of England and Wales. The area of the country with the greatest biomass losses varied between years (e.g. south-east and south-west England in 2014 but only south-west England in 2015 for managed broadleaf woodland).
- Reduced annual biomass increment of coniferous trees for the UK of 1.2% (2014), 1.1% (2015) and 1.1% (2016). Ozone reduced annual biomass increment of coniferous trees less than broadleaf trees, but with similar areas tending to have the highest risk of potential effects.
- Reduced flower numbers in perennial grassland by 5.8% (2014), 3.7% (2015) and 6.1% (2016). Ozone had the potential to reduce flowering in wild plants in the southern half of England and parts of Wales, with the areas at highest risk being in southern and eastern counties (Hampshire, Dorset, Sussex and parts of East Anglia).
- Reduced annual total biomass in perennial grassland by 1.3% (2014), 0.8% (2015) and 1.4% (2016), which is well below the critical level for the annual total biomass increment of grassland (10% loss).

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 2014-16 from 2006 and 2008 data; combining sources of differing spatial resolution for habitat distribution mapping.

Further work

Here 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 flux-based modelling for the UK would be beneficial too.

2 Introduction

Objective

Report on the modelled exceedances of ozone flux-based critical levels for vegetation in the UK and impacts on crop yield, forest annual biomass increment, grassland biomass and flower number for the years 2014, 2015 and 2016, as part of the UK reporting requirements for the amended European Union's National Emission Ceilings Directive (NECD; Directive (EU) 2016/2284).

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 (Communication 2019/C 92/01, Office Journal of the European Commission 62, C92, 11 March 2019).

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). Our earlier 2011 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 re-assessing existing critical levels, revising them where necessary, and developing new critical levels. Under our leadership, the methodology was reviewed and further developed at LRTAP Convention Workshops in Sweden (November, 2015) and the UK (June, 2016), with new critical levels discussed at a further workshop in Spain (November, 2016) and finalised and agreed at the 30th ICP Vegetation Task Force Meeting in Poland (February, 2017). As part of this process, the number of critical levels available increased from 10 to 21, with 8 of these suitable for application in UK climatic conditions. Under the auspices of the ICP Vegetation, Chapter 3 of the LRTAP Convention's Modelling and Mapping Manual has been fully revised based on these decisions (CLRTAP, 2017). The Chapter was presented to the ICP Modelling and Mapping Task Force Meeting in April 2017 (Wallingford, UK), the EMEP/WGE meeting in September 2017 and the Executive Body meeting in December 2017 to finalise adoption.

Here, we repeat the methodology used in the 2017 scoping study using data for the years 2014, 2015 and 2016, with the most recent version of the EMEP4UK ozone model, to provide information on the spatial and temporal variation in critical level exceedance and subsequent impacts on crops, trees and grasslands.

Considering the indicators itemised for optional reporting under Annex V of the NECD, the following indicators are included:

"*(c) For terrestrial ecosystems: assessing ozone damage to vegetation growth and biodiversity. (i) The key indicator vegetation growth and foliar damage and the supporting indicator carbon flux (C flux), frequency of sampling: every year"*

> Here, we quantify effects on growth by mapping effects on crop yield (quantity, economic value), tree and grassland annual biomass. Impacts on carbon flux can be inferred from effects on growth but several more stages are needed before this can be calculated such as conversion of response functions for effects on young trees under 10 years old to effects on mature trees (beyond the scope of the current study). Although we do not currently have a method for mapping incidences of foliar injury, this might be possible in the future after re-analysis of the ICP vegetation ozone injury database (beyond the scope of the current study).

"(ii) The key indicator exceedance of flux-based critical levels, frequency of sampling: every year during the growing season"

> Here, we provide maps and tables showing the exceedance of those critical levels relevant for UK vegetation. For crops, we quantify exceedance of critical levels for effects on wheat and potato yield and provide maps showing the agricultural areas most at risk, whilst for relevant broad habitats containing deciduous and coniferous trees, and types of grassland, we quantify effects on biomass. We also provide maps showing areas where the critical level for effects on flowering of ozone-sensitive forbs (classified in simple terms as wild flowers) is exceeded for acid, calcareous and dune grassland as a potential indicator of effects on biodiversity.

3 Methods

3.1 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 O_3 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 O_3 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 and a thinner surface layer. 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 WRF version 3.7.1 is used to calculate hourly 3D meteorological data used to drive the EMEP4UK model for the years 2014, 2015 and 2016. 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, NH3, SO2, primary PM2.5, primary coarse PM, CO and non-methane VOC for the UK are derived from the 2015 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. Shipping emissions estimates from the Finnish Meteorological Institute (FMI) for the year 2011 are used in this work (Jalkanen et al., 2016).

It should be noted that the version of EMEP4UK used for the current report is an update of that used for the Mills et al. (2017) report (which was rv4.10). Model outputs for ozone flux are predicted to differ (lower values) than outputs from the previous model version 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 this newer 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). The years selected were 2014, 2015 and 2016, allowing an examination of annual variation in ozone values. Time periods for accumulation of POD_YSPEC match the Modelling and Mapping Manual (LRTAP Convention, 2017) specifications and are defined by SGS50 and EGS50 (Annex 1, Table 1).

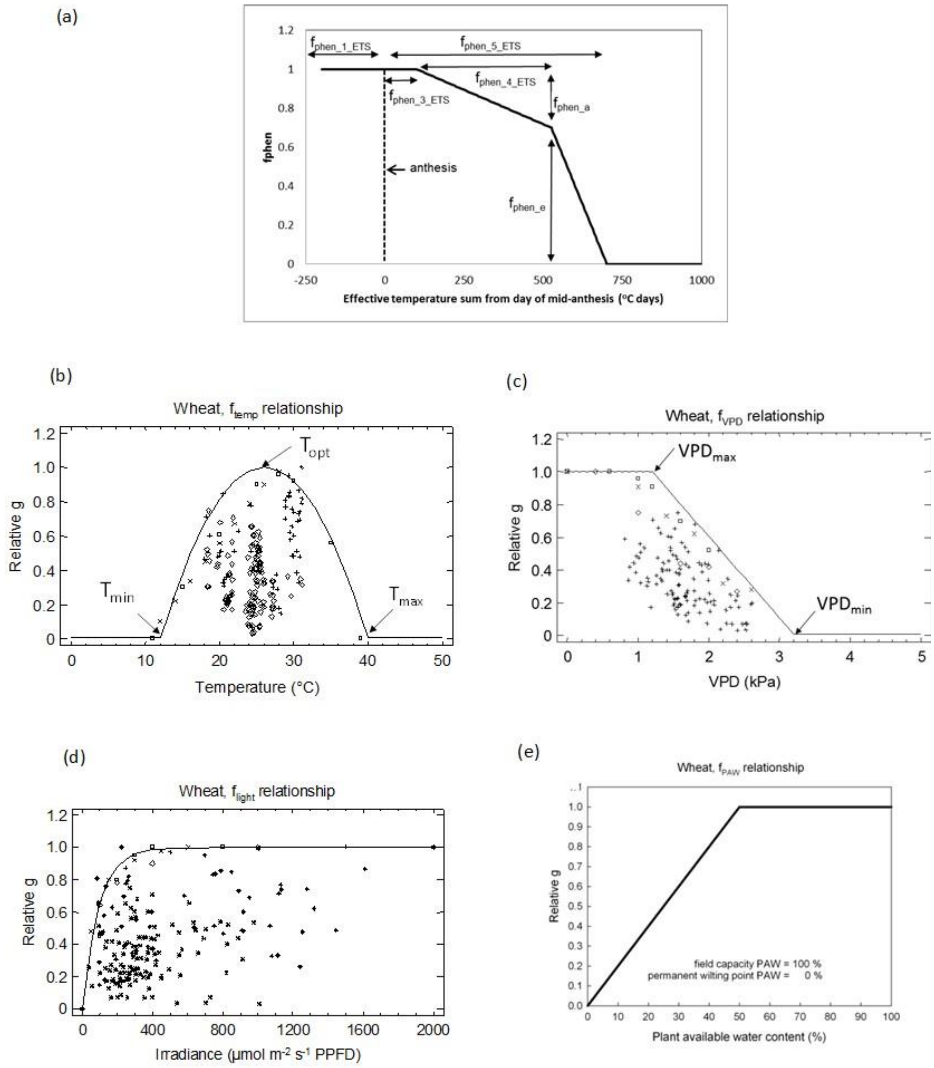

Figure 1 Illustration of the components of the DO_3SE stomatal flux model, showing for wheat how the stomatal conductance is modified by (a) phenology (growth stage), (b) temperature, (c) vapour pressure deficit - a measure of air humidity, (d), light and (e) plant available water - a measure of the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

3.2 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).

3.3 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 (2014, 2015 or 2016) 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.

3.4 Mapping crop and habitat distribution

3.4.1 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 2014, 2015 and 2016 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 2014, 2015, 2016. A conversion factor for 2014, 2015 and 2016 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, for example, for 2014: '2014 values/2006-08 mean value'. The 2006-08 crop production and distribution data were then multiplied by the conversion factor for each year (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 and maps were created using R (R Core Team, 2018).

3.4.2 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

3.5 Calculating losses due to ozone

3.5.1 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:

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

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).

3.5.2 Trees and grassland

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

$$\text{\% reduction} = (POD_1SPEC - \text{Ref10 } POD_1SPEC) \times \text{rate of reduction (\%)}$$

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

4 Results

Note: Critical level exceedance maps (Figures 2 – 8) are presented at the end of the results section to avoid breaking up the text.

4.1 Crops: Ozone critical level exceedances and impacts on crop production

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 2014, 31.6% was grown in areas exceeding the critical level of 1.3 mmol m^{-2} using the POD_6SPEC metric. The average yield loss was 4.2% and the loss in production was 0.67 million tonnes with an economic value of £97 million (Table 3). Only 2.8% of the wheat grown in Wales 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, Figs. 2 & A1). Overall, our analysis indicated that 29.5% of the UK wheat production in 2014 was in areas where the critical level was exceeded. The average yield loss for the UK was 3.7% resulting in a production loss of 0.68 million tonnes of economic value £99.5 million. Whilst the highest POD_6SPEC values in 2014 were in the southern counties of Hampshire and West and East Sussex (Figure A1), the highest production losses were indicated for eastern counties of England, particularly Cambridgeshire, Essex and Suffolk where POD_6SPEC values above the critical level were predicted for areas with high production of over 5500 tonnes per 5x5 km grid square (Figure A2). Some of the highest economic losses per individual grid square, (>£45,000) were predicted in rural areas near Peterborough and Chelmsford (Figure A2).

In 2015, POD_6SPEC values across the UK were lower, and in England only 3.4% of wheat was grown in areas exceeding the critical level and thr predicted average yield loss was 2.6% and the loss in production was 0.42 million tonnes with an economic value of £61 million (Table 4). None of the wheat grown in Wales, N. Ireland or Scotland was in areas where the critical level was exceeded (Table 4, Figs. 2 & A3). Overall, our analysis indicated that 3.1% of the UK wheat production in 2015 was in areas where the critical level was exceeded. The average yield loss for the UK was 2.2% resulting in a production loss of 0.42 million tonnes of economic value £62 million. In 2015, the highest values for POD_6SPEC were in southern England, in the counties of West and East Sussex (Fig. A3), however as wheat production is low in these counties, the highest losses were still in the eastern counties of England, including Cambridgeshire, Hertfordshire and parts of Norfolk and Suffolk (Fig. A4).

In 2016, POD_6SPEC values for wheat increased again. In England, 30.8% was grown in areas exceeding the critical level and the predicted average yield loss was 4.1% and the loss in production was 0.49 million tonnes with an economic value of £72 million (Table 5). For Wales, the exceeded area was 47.9%, leading to a predicted economic loss of £0.9 million, while for N. Ireland, 26.7% of the wheat growing area exceeded the critical level, with a predicted loss of £0.2 million. Overall, our analysis showed that 29.1% of the wheat production in 2016 was in areas where the critical level was exceeded. The average yield loss for the UK was 3.6% resulting in a production loss of 0.5 million tonnes of economic value £73 million. In 2016, the spatial pattern of higher POD_6SPEC values for wheat differed from 2014 and 15, with higher values shown in western England and southern Wales (Figs. 2, A5). The highest production losses were seen again in counties of eastern England, but also areas of central/western and southern England, for example Shropshire and Dorset (Fig. A6).

Table 3 Impacts of ozone on wheat in 2014, 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	1763598	558065	31.6	15183	666	4.2	97
Wales	20563	567	2.8	136	3.4	2.4	0.5
Scotland	102314	0	0	899	13.8	1.3	2
NI	7174	0	0	38	0.18	0.5	0.03
UK	1893649	558632	29.5	16256	683	3.7	99.5

Table 4 Impacts of ozone on wheat in 2015, 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	1661649	55726	3.4	14971	417	2.6	61
Wales	20981	0	0	146	1.9	1.2	0.28
Scotland	97815	0	0	927	2.5	0.2	0.36
NI	6733	0	0	33	0.09	0.3	0.01
UK	1787178	55726	3.1	16077	421	2.2	62

Table 5 Impacts of ozone on wheat in 2016, 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	1656773	509973	30.8	13052	494	4.1	72
Wales	20979	10049	47.9	129	6.2	4.9	0.9
Scotland	102717	0	0	842	2.4	0.3	0.4
NI	7545	2017	26.7	35	1.5	4.1	0.2
UK	1788014	522039	29.1	14058	504	3.6	73

Potato is classed as moderately sensitive to ozone and is thus less sensitive than wheat (Mills et al., 2007). In 2014, only 2.5% of the potato growing areas in England had POD_6SPEC values that exceeded the critical level of 3.8 mmol m^{-2}, with zero exceedance in Wales, Scotland and N. Ireland (Table 6, Fig. 3). Across all of the UK potato production areas, the mean yield loss was 2.3%, resulting in 133,000 lost tonnes of potato tubers worth £22 million at average farm gate prices (2014 – 2016). The area with the highest exceedance of the critical level was primarily in East and West Sussex where very low amounts of the crop are grown (Figs. 3, A7). Maps show pockets of high production and economic loss, for example in parts of Hertfordshire and Buckinghamshire (Fig. A8). In 2015, only 0.7% of the English potato growing areas had POD_6SPEC values that exceeded the critical level, with zero exceedance in Wales, Scotland and N. Ireland (Table 7, Fig. A9). Across all of the UK potato production areas, the mean yield loss was 2.2%, resulting in

124,000 lost tonnes of potato tubers worth £20 million. In 2016, there was no exceedance of the critical level for potato growing areas in the UK (Table 8, Fig. A11). Across all of the UK potato production areas, the mean yield loss was 1.7%, resulting in 85,000 lost tonnes of potato tubers worth £14 million. As for 2014, maps for 2015 and 16 show small areas with high production and economic loss, where areas of high production coincide with higher levels of POD_6SPEC (Figs. A10, A12).

Table 6 Impacts of ozone on potato in 2014, 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	97609	2399	2.5	4109	126	3.1	21
Wales	2156	0	0	41	1	2.5	0.2
Scotland	25302	0	0	963	5.5	0.6	0.9
NI	3578	0	0	130	0.6	0.5	0.1
UK	128644	2399	1.9	5243	133	2.3	22

Table 7 Impacts of ozone on potato in 2015, 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	91150	622	0.7	3935	115	2.9	19
Wales	1806	0	0	47	0.9	1.9	0.1
Scotland	27226	0	0	891	6.8	0.7	1.1
NI	2960	0	0	108	0.6	0.6	0.1
UK	123142	622	0.5	4981	124	2.2	20

Table 8 Impacts of ozone on potato in 2016, 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	91439	0	0	3541	80	2.3	13
Wales	2044	0	0	35	0.7	1.9	0.1
Scotland	25224	0	0	950	2.6	0.3	0.4
NI	3291	0	0	107	1.6	1.4	0.3
UK	121998	0	0	4633	85	1.7	14

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 2014, 2015 and 2016 (Figs. A13 – A18).

In 2014, the average yield loss for the UK is predicted to be low at 0.8%, amounting to 21,000 tonnes of lost production, worth £6 million (Table 9). Based on POD_6SPEC alone, the majority of oilseed rape areas in England have potential yield losses of 1 – 1.5%, and a few areas in East and West Sussex have yield loss > 1.5% (Fig. A13). The highest production and economic losses (> 45 tonnes and > £10,000 per 5 by 5km square respectively) are predicted for central England where moderate POD_6SPEC values, coincide with areas of high oilseed rape production per 5x5 km grid square (Fig. A14). Similarly for 2015, the average yield loss for the UK is predicted to be 0.6%, amounting to 14,900 tonnes of lost production, worth £4.1 million (Table 10). In England, yield loss is slightly lower than for 2014, with the majority of grid cells in southern England having potential losses of 0.75 – 1% (Fig. A15). For 2016, the average yield loss for the UK is predicted to be 0.7%, amounting to 14,600 tonnes of lost production, worth £4.1 million (Table 11). The spatial pattern for yield loss is similar to that for 2015, with the majority of values in southern parts of England predicted to be between 0.75 – 1% (Fig. A17). As for 2014, the highest production and economic losses in 2015 and 16 are predicted to occur in central England (Figs. A16, A18).

Table 9 Impacts of ozone on oilseed rape in 2014, 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 (%)	Product-ion (thousand tonnes)	Production loss (thousand tonnes)	Yield loss (%, average)	Economic loss (£ Million)
England	626782	NA	NA	2216	21	0.9	5.9
Wales	5911	NA	NA	10	0.07	0.7	0.02
Scotland	35077	NA	NA	103	0.3	0.3	0.08
NI	409	NA	NA	NA	NA	NA	NA
UK	668178	NA	NA	2329	21	0.8	6

NA: Not applicable

Table 10 Impacts of ozone on oilseed rape in 2015, 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	613452	NA	NA	2319	14.7	0.7	4.1
Wales	5250	NA	NA	9	0.06	0.6	0.02
Scotland	33821	NA	NA	101	0.14	0.1	0.04
NI	519	NA	NA	NA	NA	NA	NA
UK	653042	NA	NA	2429	14.9	0.6	4.1

Table 11 Impacts of ozone on oilseed rape in 2016, 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	541683	NA	NA	1938	13.97	0.7	3.9
Wales	5534	NA	NA	9	0.07	0.8	0.02
Scotland	29132	NA	NA	94	0.5	0.6	0.1
NI	475	NA	NA	NA	NA	NA	NA
UK	576824	NA	NA	2041	14.5	0.7	4

4.2 Impacts of ozone on broad habitats in the UK

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 A19).

In 2014, the critical level of 5.2 mmol m^{-2} was exceeded in 99.6%, 100% and 64% of the area of this habitat in England, Wales and Scotland respectively (Table 12a). The overall exceeded area for the UK was 94%, with an average indicative biomass increment loss of 6.5%. The level of exceedance was greatest for woodland areas in south-east England (Kent and Sussex) (Fig. 4). The largest area showing no exceedance of the critical level was in northern Scotland. Predicted biomass increment loss was highest in south-east England (>8%), with other small areas of high loss, for example in south-west England and Wales (Fig. A19). Similarly in 2015, the critical level was exceeded in 98.5%, 99.9% and 50% of the area of this habitat in England, Wales and Scotland respectively (Table 13a). The overall exceeded area for the UK was 91.6%, with an average indicative biomass loss of 5.9%. The highest exceedance was shown in south-west England (Fig. 4), with predicted biomass increment losses of >8% in this area of the country (Fig. A20). In 2016, the critical level was exceeded in 99%, 100% and 75% of the area of this habitat in England, Wales and Scotland respectively (Table 14a). The overall exceeded area for the UK was 95.7%, with an average indicative biomass increment loss of 6.1%. The areas with the highest exceedance of the critical level were again in south-west England, but were slightly lower than in 2015, (3.2 - 4 above the critical level) (Fig. 4). The highest areas of predicted biomass increment losses were 7-8%, in south-west England, and also in south-west and north Wales, south and south-east England (Fig. A21).

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%) (Fig. A22). In 2014, all areas of this habitat were present in parts of the UK where the critical level of 5.2 mmol m^{-2} was exceeded (Table 12b). For the UK overall, the average indicative biomass increment loss was 7.3%. The level of exceedance was greatest in the south-east of England, including Kent and Sussex (Fig. 5), where biomass increment losses of >8% were predicted (Fig. A22). In 2015, the critical level was exceeded in 99.7%, 100% and 94.9% of the area of this habitat in England, Wales and Scotland respectively (Table 13b). The overall exceeded area for the UK was 99.7%, with an average indicative biomass increment loss of 6.6%. In contrast to 2014, the level of exceedance was greatest in the south-west of England (Fig. 5), where biomass increment losses of >8% were predicted (Fig. A23). In 2016, the critical level was exceeded in 99.8% of the area of this habitat in England, and 100% in Wales and Scotland (Table 14b). The overall exceeded area for the UK was 99.8%, with an average indicative biomass increment loss of 6.6%.Compared to 2014 and 15, the exceedance of the critical level was slightly lower in 2016 (Fig. 5), with the highest predicted biomass increment loss (7-8%) seen primarily in the south-east and south-west of England (Fig. A24).

Managed coniferous woodland

As coniferous species are less sensitive to ozone than broadleaf species, the critical level is higher at a POD_1SPEC of 9.2 mmol m^{-2}. The critical level was not exceeded in any of the areas in the UK where this habitat is found, for 2014 – 2016 (Table 12c, 13c, 14c, Fig. 6). Indicative biomass increment loss was lower than for broadleaf woodland, with all predicted losses being below 2%. In 2014, the areas with the highest predicted biomass increment losses (>1.5%) were primarily in south-east England and East Anglia (Fig. A25). In 2015, the areas with the highest predicted biomass increment losses (>1.5%) were primarily in the south-west of England (Fig. A26), while in 2016, biomass increment loss was predicted to be between 1-1.5% across England, Wales and N. Ireland, with lower values in northern Scotland (Fig. A27).

Table 12 Impacts of ozone on woodland habitats in the UK in 2014, 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	556096	553636	99.6	7.1
Wales	80382	80367	100	7.1
Scotland	108649	69507	64	5
NI	NA	NA	NA	NA
UK	745127	703510	94.4	6.5

Country	(b) Unmanaged Beech woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	58053	58053	100	7.4
Wales	5821	5821	100	7.1
Scotland	312	312	100	6
NI	NA	NA	NA	NA
UK	64186	64186	100	7.3

Country	(c) Managed coniferous woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	171273	0	0	1.3
Wales	105262	0	0	1.3
Scotland	511527	0	0	1
NI	50148	0	0	1
UK	838210	0	0	1.2

Table 13 Impacts of ozone on woodland habitats in the UK in 2015, 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	556096	547614	98.5	6.5
Wales	80382	80322	99.9	6.9
Scotland	108649	54336	50	4.3
NI	NA	NA	NA	NA
UK	745127	682272	91.6	5.9

Country	(b) Unmanaged Beech woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	58053	57883	99.7	6.6
Wales	5821	5821	100	7.1
Scotland	312	296	94.9	6.1
NI	NA	NA	NA	NA
UK	64186	64000	99.7	6.6

Country	(c) Managed coniferous woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	171273	0	0	1.3
Wales	105262	0	0	1.3
Scotland	511527	0	0	0.9
NI	50148	0	0	1.1
UK	838210	0	0	1.1

Table 14 Impacts of ozone on woodland habitats in the UK in 2016, 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	556096	550725	99	6.4
Wales	80382	80382	100	6.6
Scotland	108649	81904	75.4	5.2
NI	NA	NA	NA	NA
UK	745127	713011	95.7	6.1

Country	(b) Unmanaged Beech woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	58053	57910	99.8	6.6
Wales	5821	5821	100	6.6
Scotland	312	312	100	6.8
NI	NA	NA	NA	NA
UK	64186	64043	99.8	6.6

Country	(c) Managed coniferous woodland			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	171273	0	0	1.2
Wales	105262	0	0	1.2
Scotland	511527	0	0	1
NI	50148	0	0	1.2
UK	838211	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 higher effects of 10% than critical 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 2014, the critical level for effects of ozone on flowering of ozone-sensitive grassland species of a POD_1SPEC of 6.6 mmol m^{-2} was exceeded for 16.3% of the area of this grassland type in England and 0.03% in Wales (Table 15a). The critical level was not exceeded for Scotland or N. Ireland in 2014 (Fig. 7). The indicative risk analysis suggested an average of 5.8% loss in flower number for the UK, with the highest losses (>11%) occurring in areas of south-east England (Fig. A28). This could potentially affect plant species composition and/or diversity. In 2015, only 0.2% of the area of this habitat in England showed exceedance of the critical level, while there were no areas of exceedance in Wales, Scotland or N. Ireland (Table 16a, Fig. 7). The average predicted loss in flower number for the UK was 3.7%, with the highest losses predicted for counties in southern

England (8-11%), including Hampshire, Dorset, and parts of East Anglia (Fig. A29). In 2016, only 0.4% of the area of this habitat in England and 0.6% of the habitat area in Wales showed exceedance of the critical level (Table 17a, Fig. 7). The critical level was not exceeded in Scotland or N. Ireland. The indicative risk analysis suggested an average of 6.1% loss in flower number for the UK, with the highest losses (8-11%) suggested to occur across central, eastern and southern England, and south-west Wales (Fig. A30).

The critical level for effects of ozone on grassland annual total biomass is higher at 16.2 mmol m^{-2} POD_1SPEC and was not exceeded anywhere for this habitat in the UK in 2014, 2015 or 2016 (Table 15b, 16b, 17b; maps not presented). Hence, biomass losses were well below 10% (as defined by the critical level) and did not exceed 1.4% on average in the UK.

Table 15 Impacts of ozone on (a) flowering and (b) total biomass of grassland habitats in the UK in 2014, 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	849750	138171	16.3	8.3
Wales	443128	112	0	6.5
Scotland	2829753	0	0	3.2
NI	222435	0	0	4.9
UK	4345066	138283	3.18	5.8

Country	(b) Grassland total biomass			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	847460	0	0	1.9
Wales	442221	0	0	1.4
Scotland	2789708	0	0	0.6
NI	222128	0	0	0.9
UK	4301517	0	0	1.3

Table 16 Impacts of ozone on (a) flowering and (b) total biomass of grassland habitats in the UK in 2015, 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	849447	1894	0.2	6.3
Wales	443063	0	0	4.3
Scotland	2748081	0	0	1.1
NI	222818	0	0	2.4
UK	4263409	1894	0.04	3.7

Country	(b) Grassland total biomass			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	847503	0	0	1.4
Wales	442289	0	0	0.9
Scotland	2367692	0	0	0.2
NI	222128	0	0	0.4
UK	3879612	0	0	0.8

Table 17 Impacts of ozone on (a) flowering and (b) total biomass of grassland habitats in the UK in 2016, 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	849775	3356	0.4	7.5
Wales	443128	2540	0.6	7.4
Scotland	2860682	0	0	4
NI	224653	0	0	7.1
UK	4378238	5896	0.13	6.1

Country	(b) Grassland total biomass			
	Total area (ha)	Total area (ha) exceeding critical level	Exceeded area (%)	Loss (%) (Average)
England	849482	0	0	1.7
Wales	443128	0	0	1.8
Scotland	2852661	0	0	0.9
NI	224653	0	0	1.8
UK	4369924	0	0	1.4

4.3 Summary on spatial and temporal variation in ozone flux

The results of this study suggest temporal and spatial variation in ozone flux values for the UK, during the period 2014 – 2016. Examination of model inputs indicates that these differences are mainly driven by meteorology. 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. As the results presented show, these variations in ozone flux can result in increased or decreased production and economic losses of crops due to ozone (for example, for wheat, using the POD_6SPEC metric, estimated economic losses due to ozone are £30 million greater in 2014 than in 2015). While differences in ozone values are driven mostly by weather in this short term study, a longer term study would also provide information on how differences in emissions affect ozone flux and impacts on crop and other vegetation types.

4.4 Critical level exceedance maps for 2014, 2015 and 2016

Wheat (POD_6SPEC for grain yield)

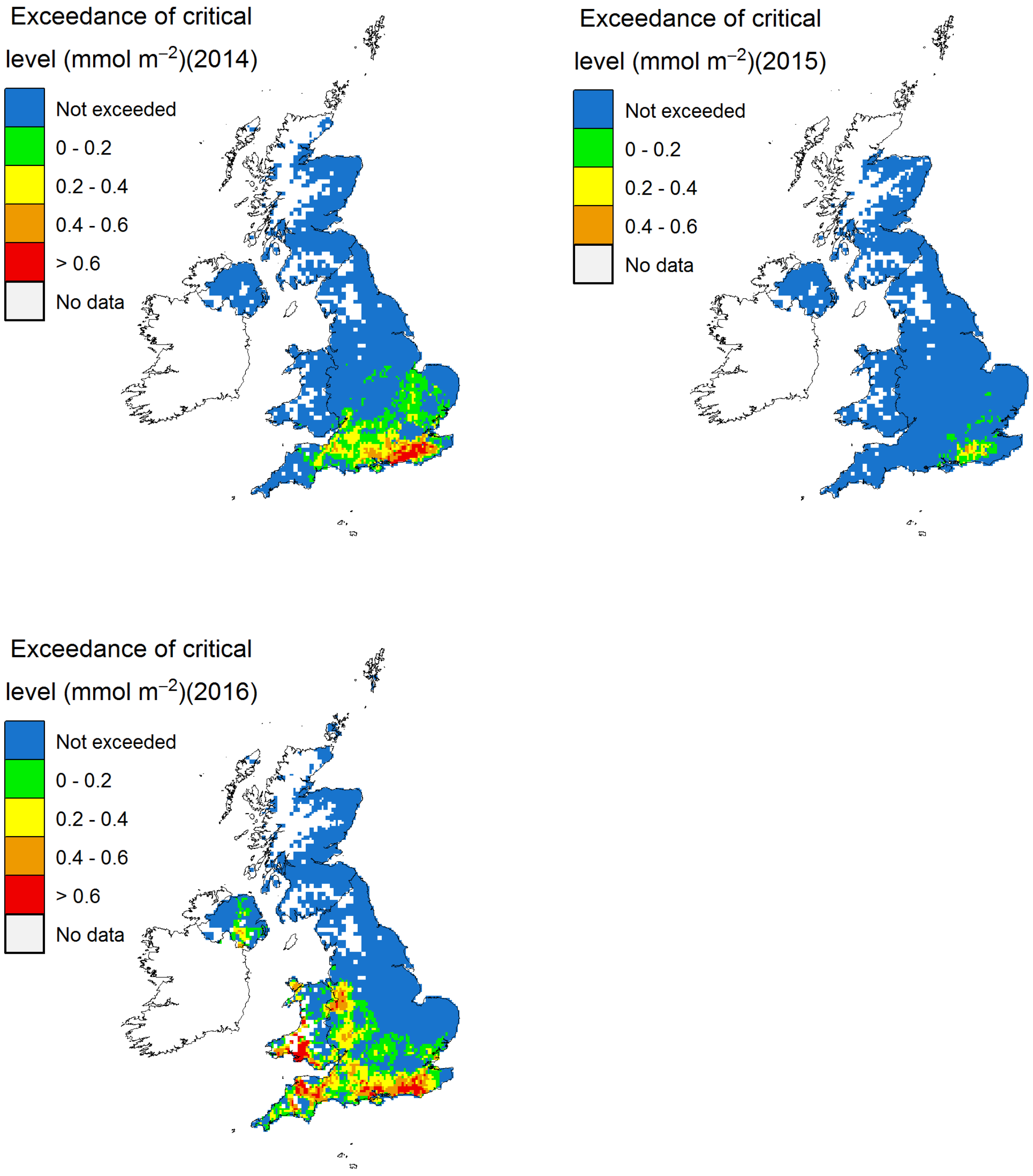

Figure 2: Exceedance of the ozone critical level for wheat grain yield (POD_6SPEC) in 2014, 2015 and 2016.

Potato (POD_6SPEC for tuber yield)

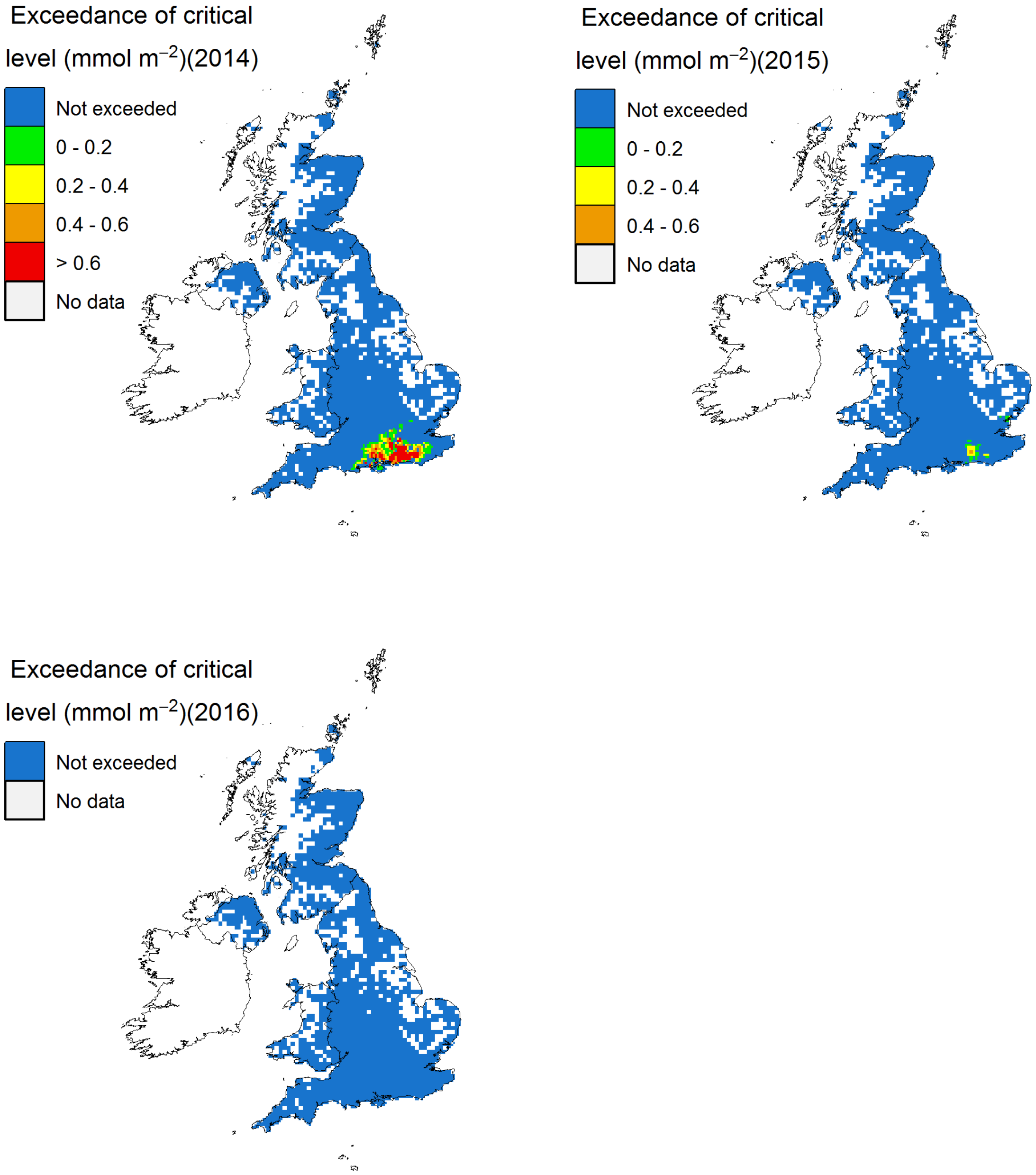

Figure 3: Exceedance of the ozone critical level for potato tuber yield (POD_6SPEC) in 2014, 2015 and 2016.

Managed broadleaved woodland (POD_1SPEC for biomass increment)

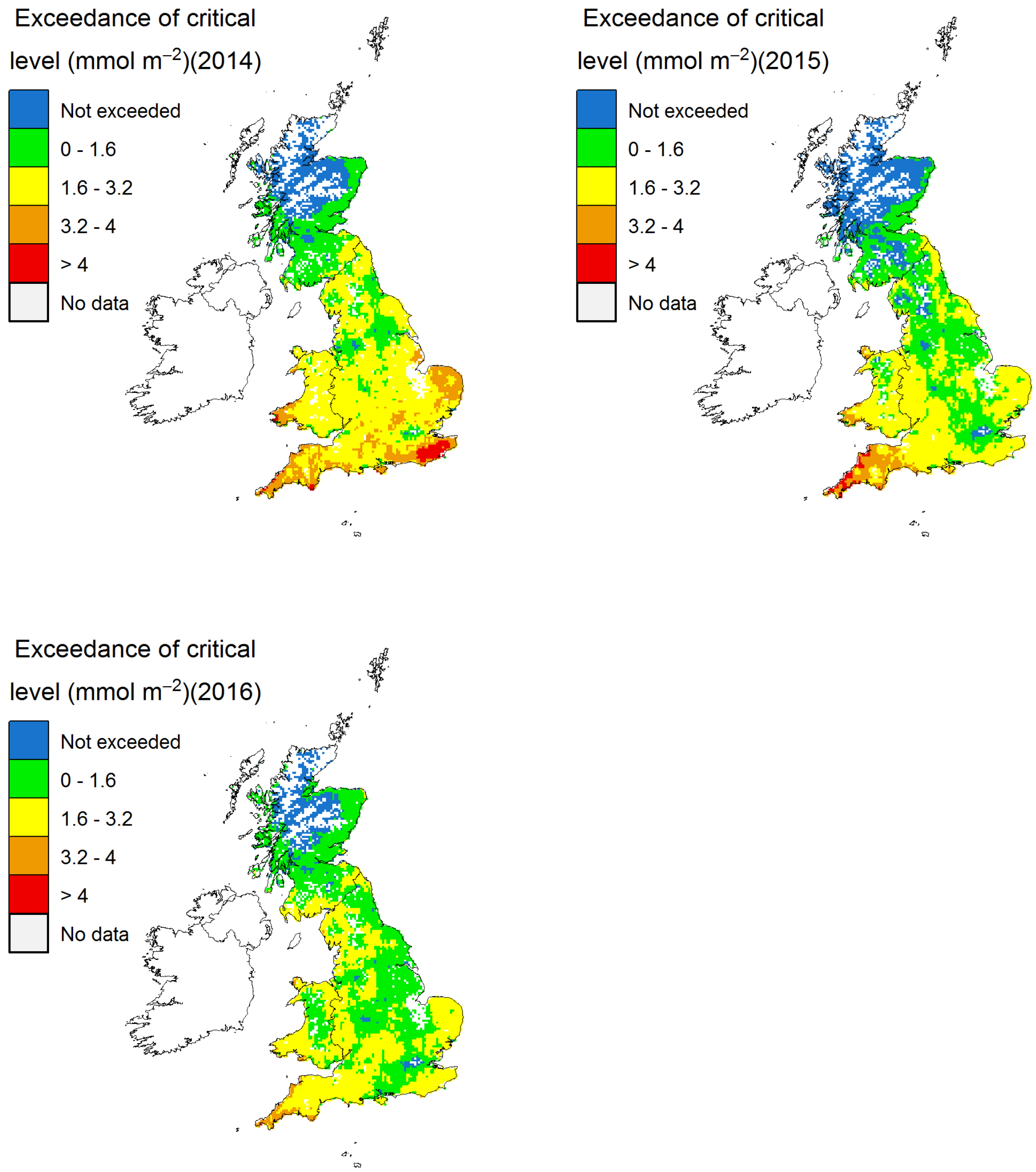

Figure 4: Exceedance of the ozone critical level for managed broadleaved woodland biomass increment (POD_1SPEC) in 2014, 2015 and 2016.

Unmanaged Beech woodland (POD_1SPEC for biomass increment)

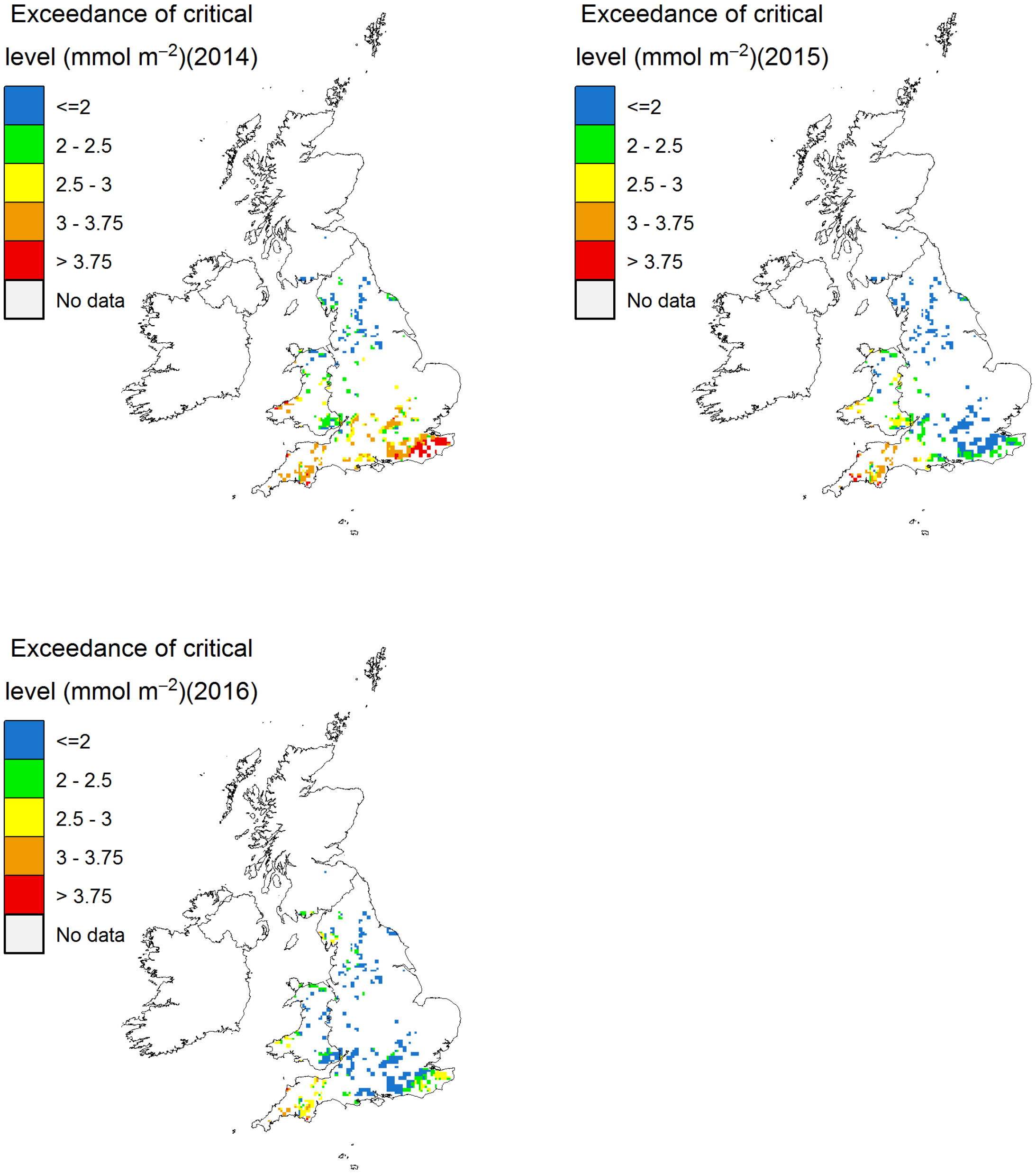

Figure 5: Exceedance of the ozone critical level for unmanaged Beech woodland biomass increment (POD_1SPEC) in 2014, 2015 and 2016.

Managed coniferous woodland (POD_1SPEC for biomass increment)

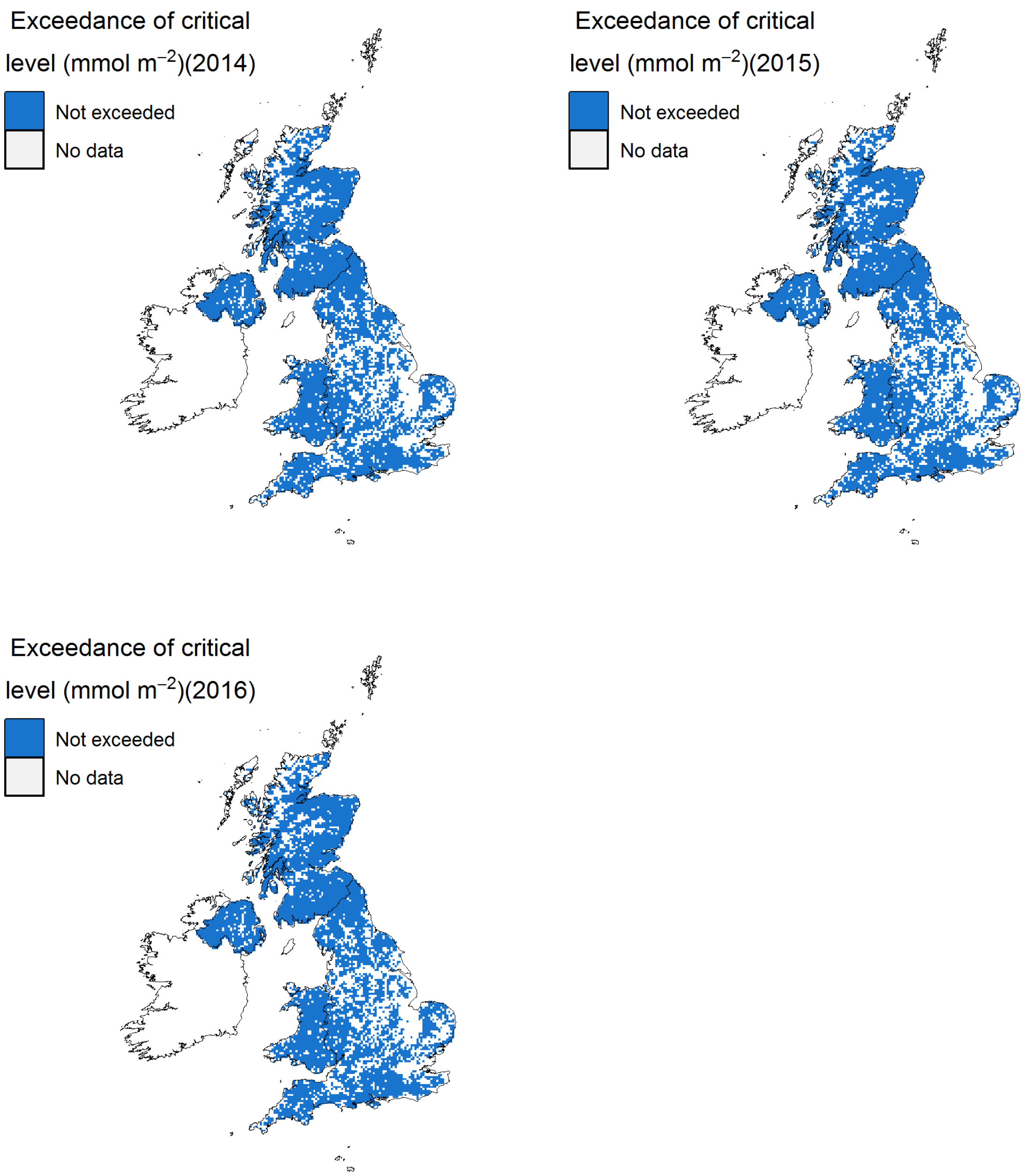

Figure 6: Exceedance of the ozone critical level for managed coniferous woodland biomass increment (POD_1SPEC) in 2014, 2015 and 2016.

Perennial grassland (POD_1SPEC for flower numbers)

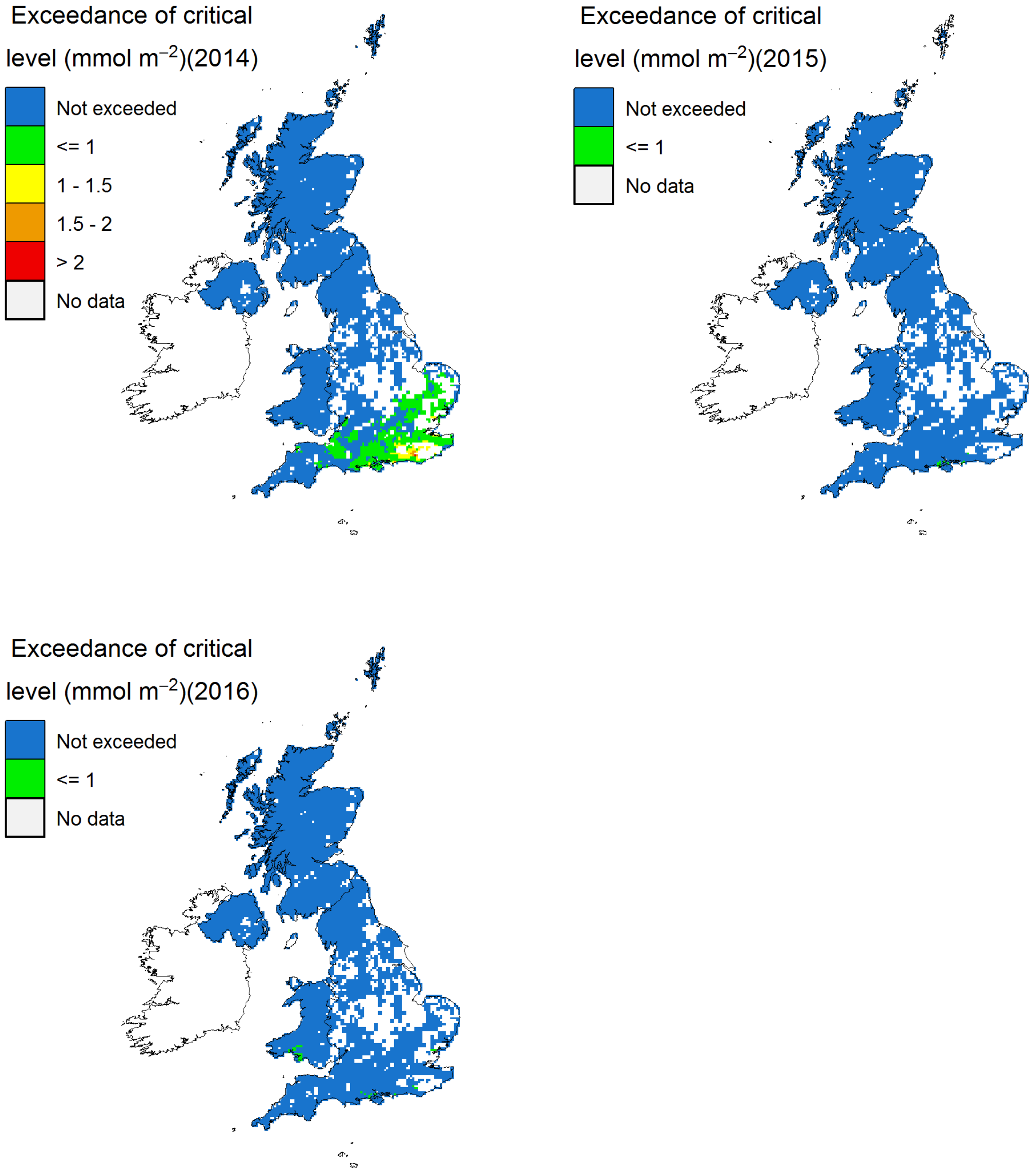

Figure 7: Exceedance of the ozone critical level for flower numbers in perennial (semi-natural) grasslands (POD_1SPEC) in 2014, 2015 and 2016.

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

5.1 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, 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 effects for trees should be interpreted with more caution as these are predicting effects on the living biomass 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 biomass 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 CEH solar domes 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.

5.2 Modelling POD$_Y$SPEC

Anthropogenic emissions of NOx, NH3, SO2, primary PM2.5, primary coarse PM, CO and non-methane VOC for the UK are derived from the 2015 National Atmospheric Emission Inventory estimate (NAEI, http://naei.defra.gov.uk). The NAEI 2015 emission estimate is rescaled to the year 2014 but the 2015 emissions are used for the year 2016. 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. Shipping emissions estimates from the Finnish Meteorological Institute (FMI) for the year 2011 are used in this work (Jalkanen et al., 2016) and no annual rescaling is applied to this dataset. Moreover, the FMI shipping emissions dataset used here did not included estimate for NMVOC, nor split between coarse and fine fraction of particulate matter (PM). A rescaling based on the EMEP shipping emission estimate for NMVOC and PM is used here as follow; NMVOC=0.029*NOx, PM2.5 = 0.95*PM, and PMco=0.05*PM. Explicitly timed volcanoes emissions and the Fire Inventory from NCAR (FINN) daily biomass burning are also included for 2014 and 2015, but not for 2016. 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) no formal validation for the meteorology have 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. A major difference between the official EMEP MSC-W model output and the EMEP4UK is the height of the lowest surface layer used, which for the EMEP4UK is about 45 m, whereas the EMEP MSC-W is approx. 90 m. This allows the EMEP4UK model to better represent the strong gradient of concentrations such as NOx in cities and therefore better represent the titration of ozone by NO in these areas. Also the spatial scale ~5km for EMEP4UK and 10km for EMEP MSC-W may play a role in any differences between model outputs.

5.3 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 2014, 2015 and 2016. 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 the 2014 – 16 period 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 10x10 km resolution, we introduced some error by assuming that the crop production and distribution is spread equally across each 10x10 km cell in order to achieve the desired 5x5 km resolution. Economic losses are provided as an indicative cost based on the mean price over the period 2014-2016. The volatility in crop prices should be taken into account in a more detailed economic analysis. Recently, more fine-scale crop distribution data has become freely available for use within CEH, which might reduce uncertainty in crop distribution data in any future analyses. Previously, high licencing costs prohibited the use of such data.

5.4 Mapping habitat distribution

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 1x1 km, species distributions at 10x10 km); the habitat distribution maps have been aggregated from 1x1 km to 5x5 km 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).

6 Conclusions

This study was undertaken to build on the scoping study carried out for the year 2015 by Mills et al., (2017), to provide three consecutive years (2014 – 2016) of data for the UK on the spatial distribution and annual variation of 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). The study contributes to the assessment of exceedances of ozone flux-based critical levels and ozone damage to crop yield, vegetation growth and biodiversity of terrestrial ecosystems.

In summary, we found that:

- Critical level exceedance was greatest for woodland habitats, intermediate for crops, and modest for flower number in grasslands.
- Critical level exceedances varied with year, particularly for crops and perennial grasslands.
- UK average values for percentage of area exceeding critical levels do not provide the full picture on the extent of ozone effects as there are spatial differences in exceedances within the UK.
- For wheat (POD_6SPEC), critical level exceedance depended on the year, with exceedance being greatest in England (31.6% (2014), 3.4% (2015) and 30.8% (2016) of wheat growing areas). In Wales, exceedance was 2.8% (2014), 0% (2015) and 47.9% (2016). There was no exceedance for wheat in Scotland or Northern Ireland.
- Potato (POD_6SPEC) showed considerably less critical level exceedance than wheat, with the only exceedances occurring in English potato growing areas in 2014 (2.5%) and 2015 (0.7%).
- Critical level exceedance for managed broadleaf and unmanaged beech woodlands was consistently high for England and Wales (>95% for all years). While all of the unmanaged beech growing in Scotland was growing in areas exceeding the critical level of POD_1SPEC, exceedance for managed broadleaf was 64% (2014), 50% (2015) and 75% (2016). The highest critical level exceedances tended to be in southern England.
- Critical levels for managed coniferous forest were not exceeded in the UK for the period 2014-2016.
- The percentage of the grassland areas of England where the critical level for flowering was exceeded varied with year (16.3% in 2014, 0.2% in 2015 and 0.4% in 2016). The highest critical level exceedance was in south-east England in 2014. In Wales, only very small areas showed exceedance of the critical level (0.03% in 2014, 0% in 2015 and 0.6% in 2016). There was no critical level exceedance in Scotland or Northern Ireland for this habitat.
- The critical level for effects on the annual total biomass of grassland species was not exceeded in the UK.

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. 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 shows:

- Spatial and temporal variation in ozone fluxes for the period 2014 - 2016. This seems to be mainly driven by differences in meteorology between years. For some vegetation types, the areas of the country showing the highest values varied with year. This in turn affected ozone impacts on crop yield and vegetation biomass.
- Reduced UK wheat production by 3.7% (2014), 2.2% (2015) and 3.6% (2016) based on POD_6SPEC. Economic losses due to ozone varied between years, with an estimated UK loss of £99.5 million in 2014, £62 million in 2015 and £73 million in 2016 (using average farm gate prices for 2014 – 2016). Areas of the UK with the highest production losses varied with year, but eastern England consistently showed the highest production and economic losses.
- Reduced UK potato production by an average of 2.3% (2014), 2.2% (2015) and 1.7% (2016). Economic losses due to ozone varied between years, with an estimated UK loss of £22 million in 2014, £20 million in 2015 and £14 million in 2016 (using average farm gate prices for 2014 – 2016). For each year, areas of high production and economic loss tended to be where areas of high potato production coincided with higher ozone levels, for example in rural areas of Hertfordshire and Buckinghamshire.
- Reduced oil seed rape losses, however, the losses were lower than for the other crops. Ozone reduced UK oil seed rape production by 0.8% (2014), 0.6% (2015) and 0.7% (2016). Economic losses due to ozone varied slightly between years, with an estimated UK loss of £6 million in 2014, £4 million in 2015 and £4 million in 2016 (using average farm gate prices for 2014 – 2016). Each year, the highest production losses were predicted for central England.
- Total economic losses for wheat, potato and oil-seed rape in the UK of £128, £86 and £91 million in 2014, 2015 and 2016 respectively, with the majority of losses (>97%) occurring in England.
- Calculated annual biomass increment losses for the UK for managed broadleaf woodland of 6.5% (2014), 5.9% (2015) and 6.1% (2016). Impacts on managed and unmanaged broadleaf woodland tended to be greatest in the southern half of England and Wales. The area of the country with the greatest biomass increment losses varied between years (e.g. south-east and south-west England in 2014 but only south-west England in 2015 for managed broadleaf woodland).
- Reduced annual biomass increment losses of coniferous trees for the UK of 1.2% (2014), 1.1% (2015) and 1.1% (2016). Ozone reduced annual biomass increment of coniferous trees less than broadleaf trees, but with similar areas tending to have the highest risk of potential effects.
- Reduced flower numbers in perennial grassland by 5.8% (2014), 3.7% (2015) and 6.1% (2016). Ozone had the potential to reduce flowering in wild plants in the southern half of England and parts of Wales, with the areas at highest risk being in southern and eastern counties (Hampshire, Dorset, Sussex and parts of East Anglia).
- Reduced annual total biomass in perennial grassland by 1.3% (2014), 0.8% (2015) and 1.4% (2016), which is well below the critical level for the annual total biomass of grassland (10% loss).

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Annex 1

Annex1, 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 1, 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.)

Annex 1, Table 2: Input parameterisation for DO3SE within EMEP4UK

For explanation of parameters see EMEP user manual (http://emep.int/mscw/index_mscw.html)

#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	#	#	#	#	#	#	#	#	#	#	#	#	#

Annex 2

7.1 Crop maps for 2014, 2015 and 2016

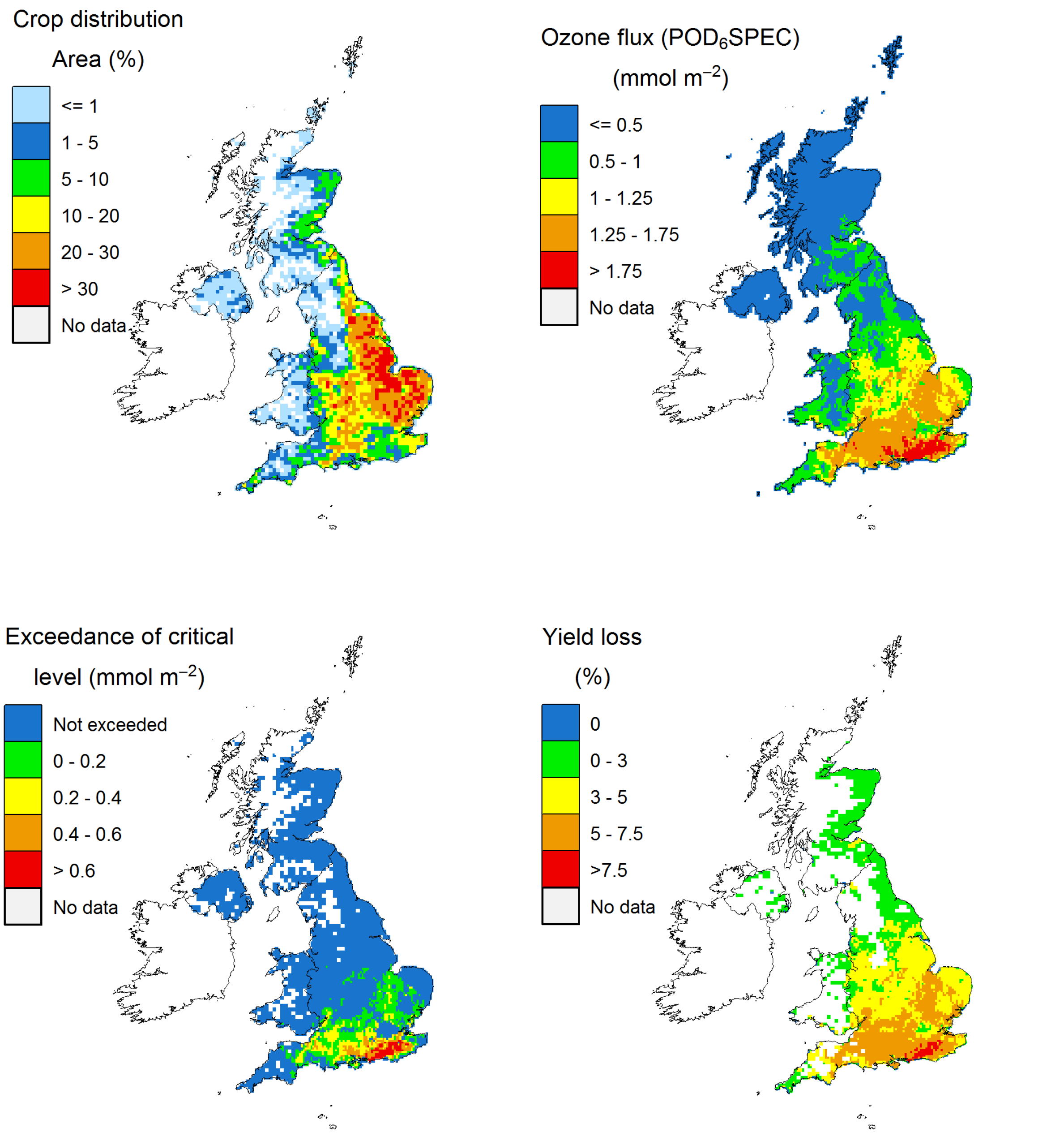

Figure A1: Impacts of ozone on **wheat** production in **2014** calculated using **POD_6SPEC**. (a) Distribution of wheat presented as the percentage of each 5 x 5 km grid square sown with wheat; (b) POD_6SPEC (mmol m^{-2}) (**critical level = 1.3**); (c) Exceedance of the critical level; (d) Percentage yield loss.

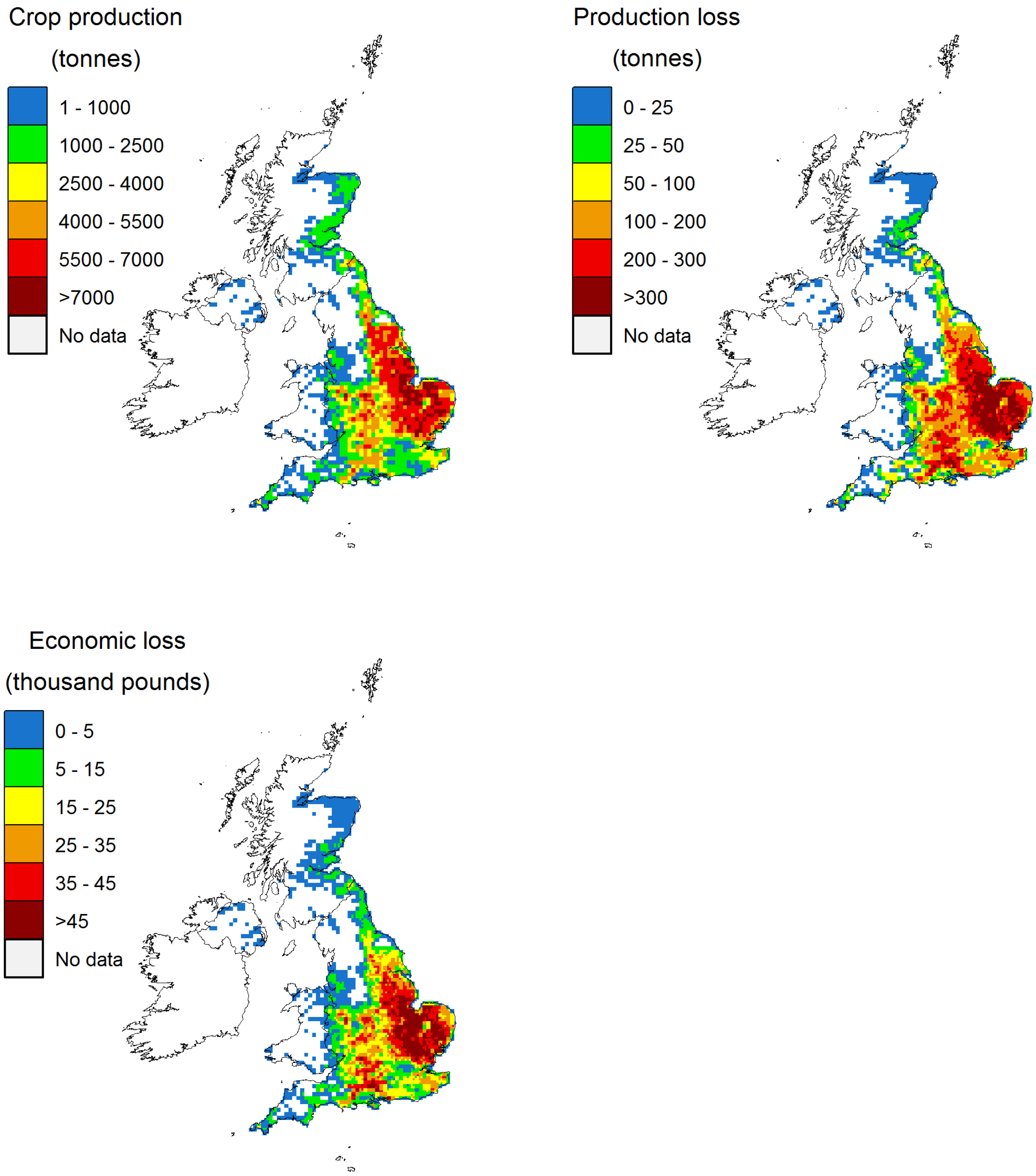

Figure A2: Impacts of ozone on **wheat** production in **2014** calculated using **POD_{6}SPEC**. (a) Wheat production in the UK in tonnes per 5x5 km grid square; (b) Production loss due to ozone in tonnes per 5x5 km grid square; and (c) Economic loss in thousand £UK per 5x5 km grid square, based on mean price 2014-16.

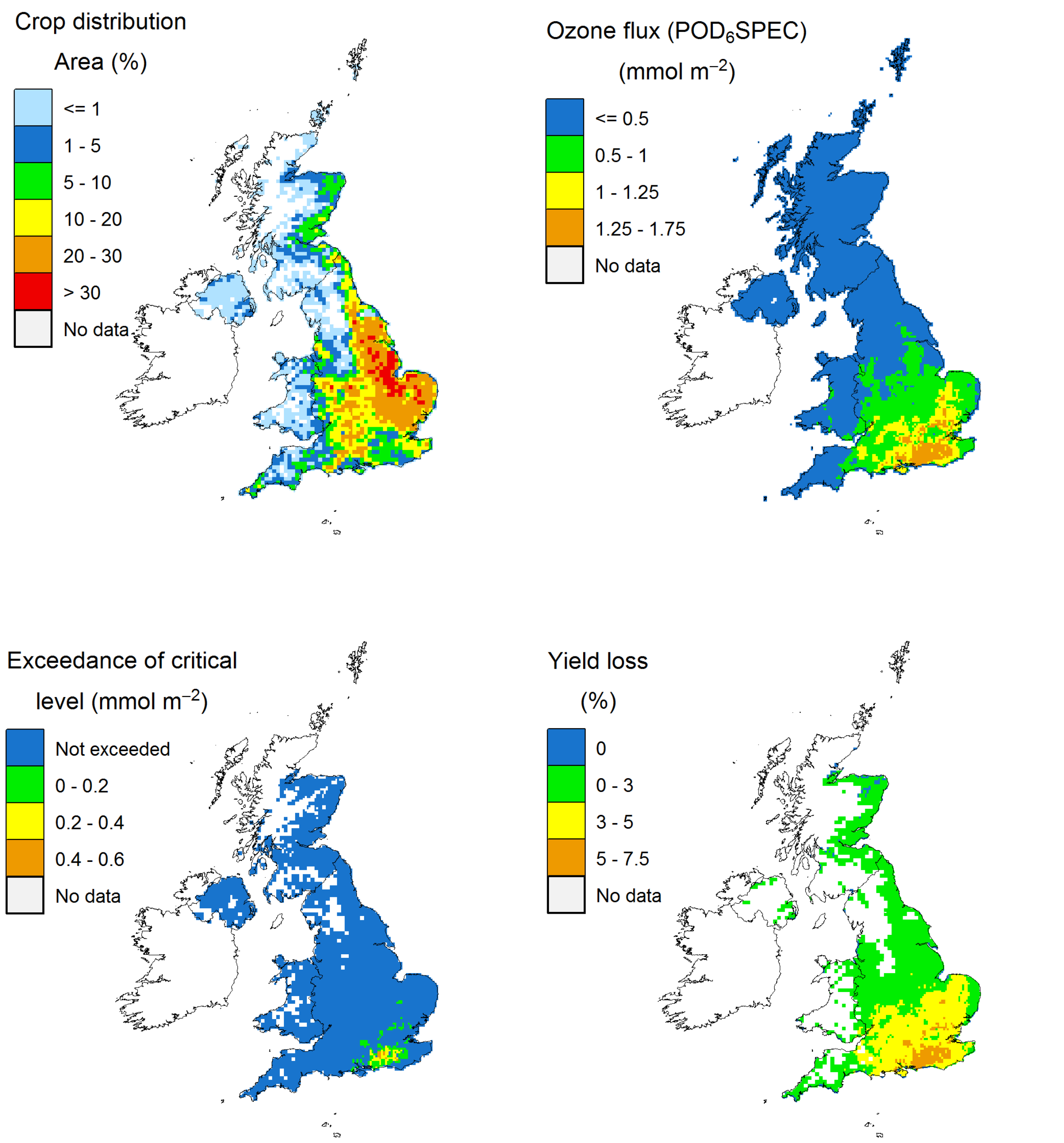

Figure A3: Impacts of ozone on **wheat** production in **2015** calculated using **POD_6SPEC**. (a) Distribution of wheat presented as the percentage of each 5x5 km grid square sown with wheat; (b) POD_6SPEC (mmol m^{-2}) (**critical level = 1.3**); (c) Exceedance of the critical level; (d) Percentage yield loss.

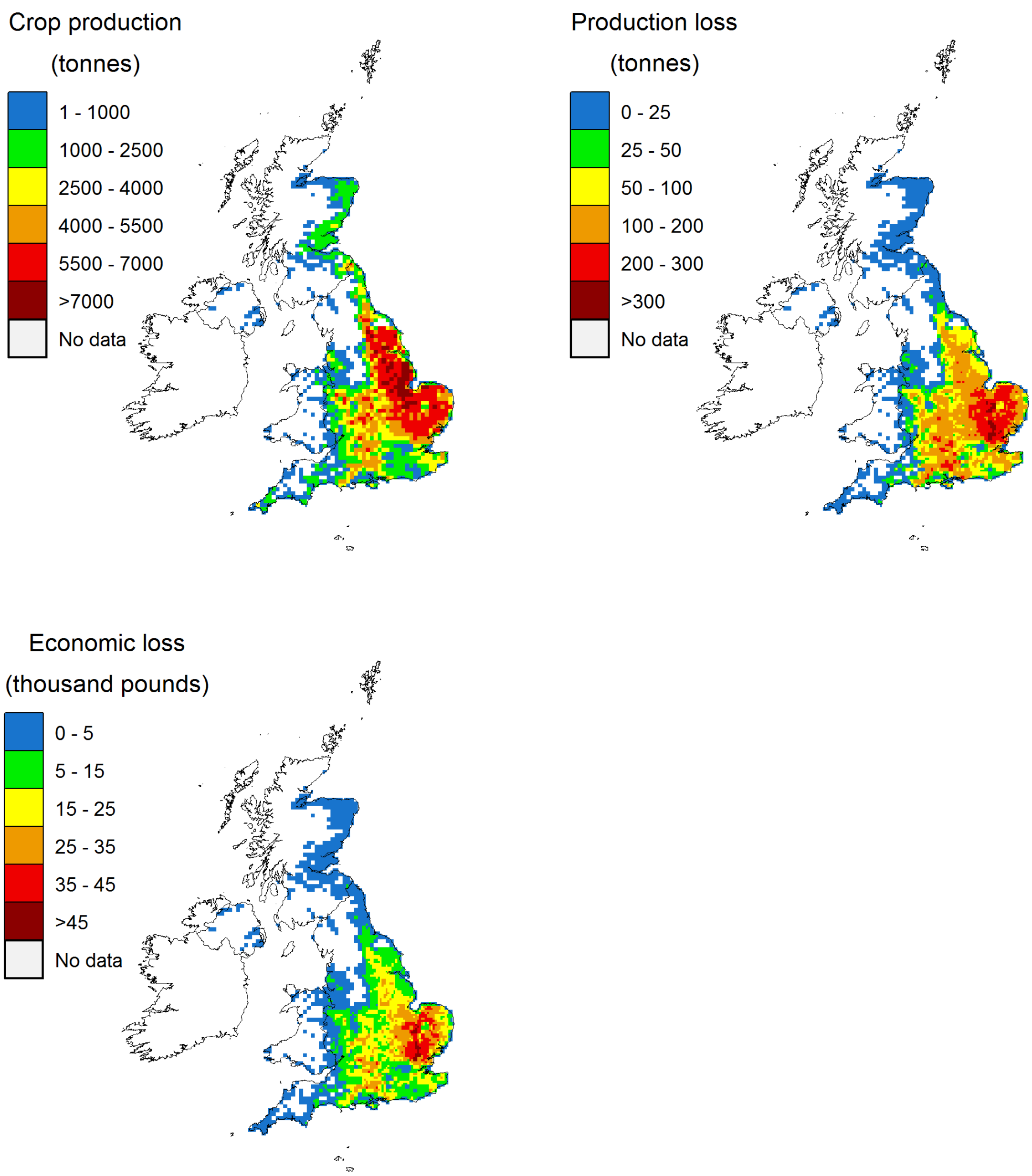

Figure A4: Impacts of ozone on **wheat** production in **2015** calculated using **POD_6SPEC**. (a) Wheat production in the UK in tonnes per 5x5 km grid square; (b) Production loss due to ozone in tonnes per 5x5 km grid square; and (c) Economic loss in thousand £UK per 5x5 km grid square, based on mean price 2014-16.

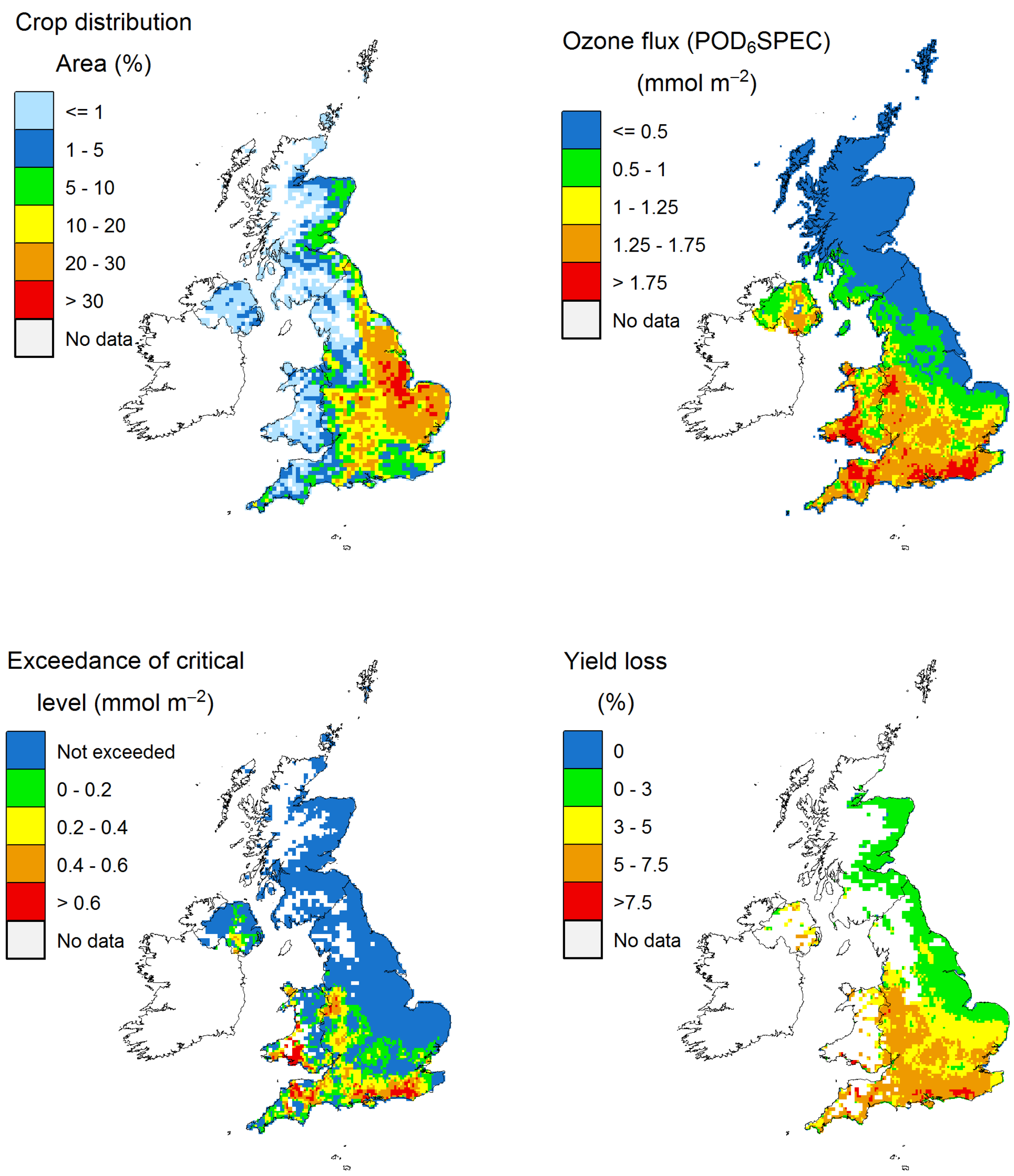

Figure A5: Impacts of ozone on **wheat** production in **2016** calculated using **POD_6SPEC**. (a) Distribution of wheat presented as the percentage of each 5x5 km grid square sown with wheat; (b) POD_6SPEC (mmol m^{-2}) (**critical level = 1.3**); (c) Exceedance of the critical level; (d) Percentage yield loss.

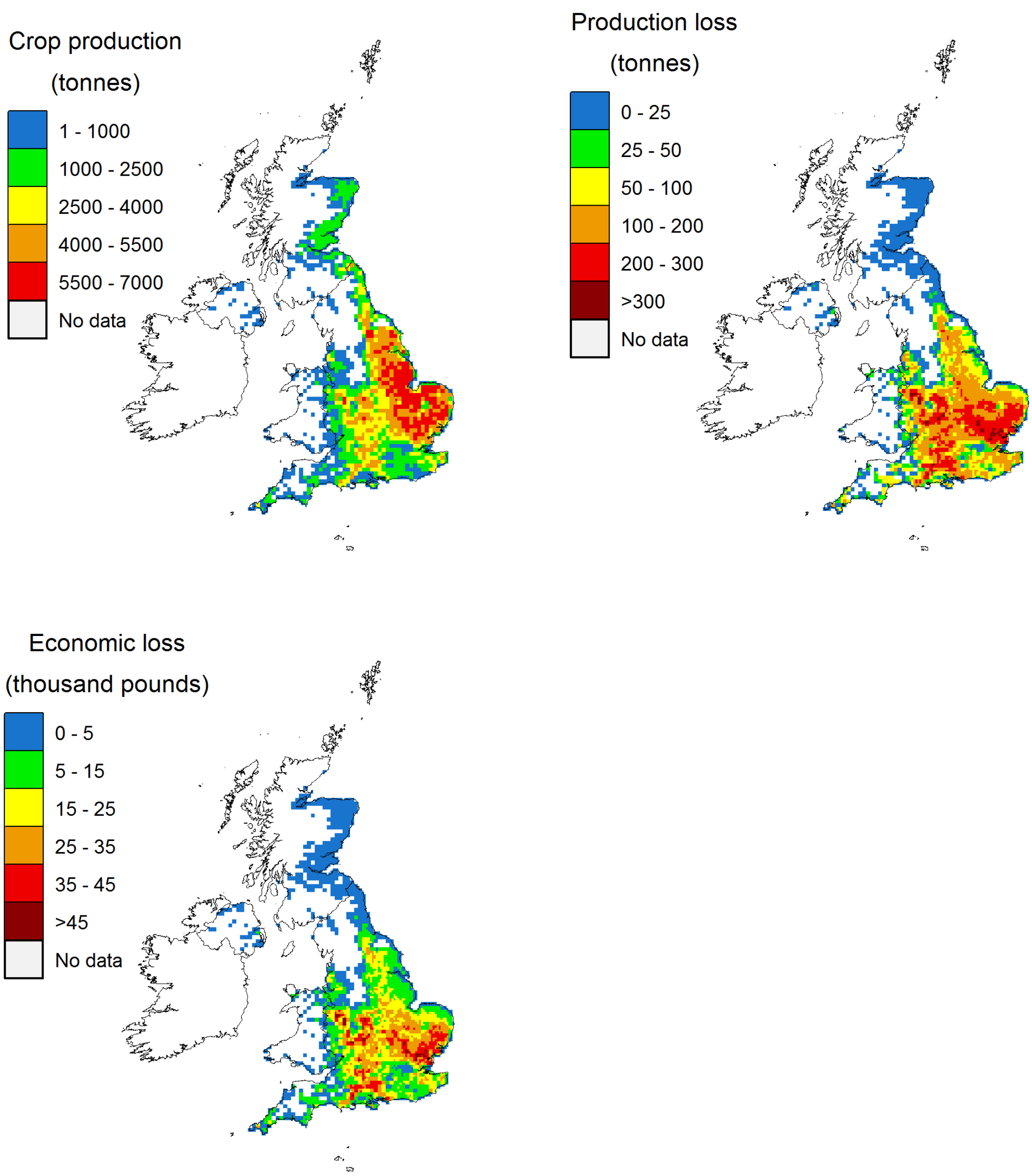

Figure A6: Impacts of ozone on **wheat** production in **2016** calculated using **POD_6SPEC**. (a) Wheat production in the UK in tonnes per 5x5 km grid square; (b) Production loss due to ozone in tonnes per 5x5 km grid square; and (c) Economic loss in thousand £UK per 5x5 km grid square, based on mean price 2014-16.

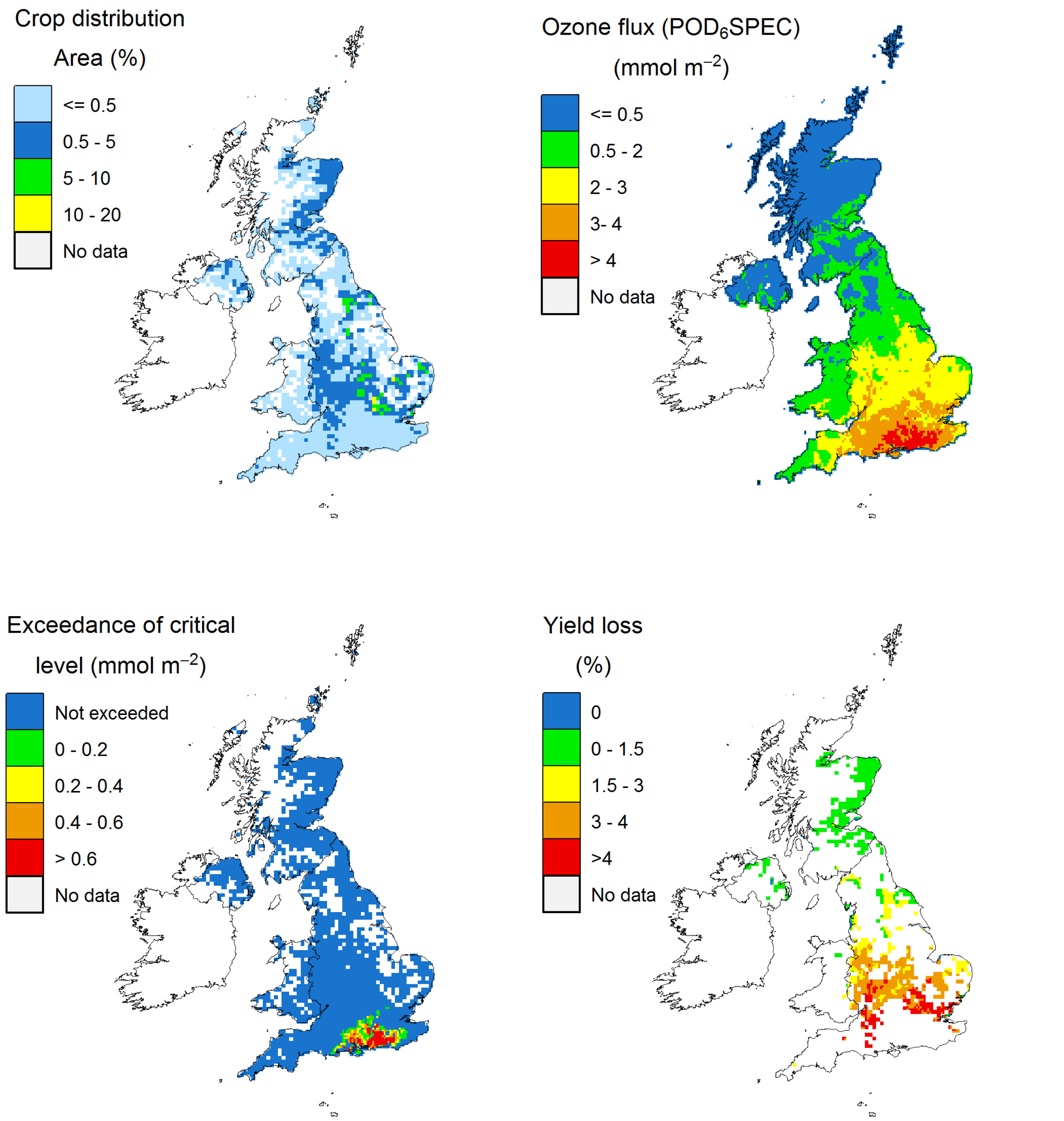

Figure A7: Impacts of ozone on **potato** production in **2014** calculated using POD_6SPEC. (a) Distribution of potato presented as the percentage of each 5x5 km grid square sown with potato; (b) POD_6SPEC (mmol m^{-2}) (**critical level = 3.8**); (c) Exceedance of the critical level; (d) Percentage yield loss.

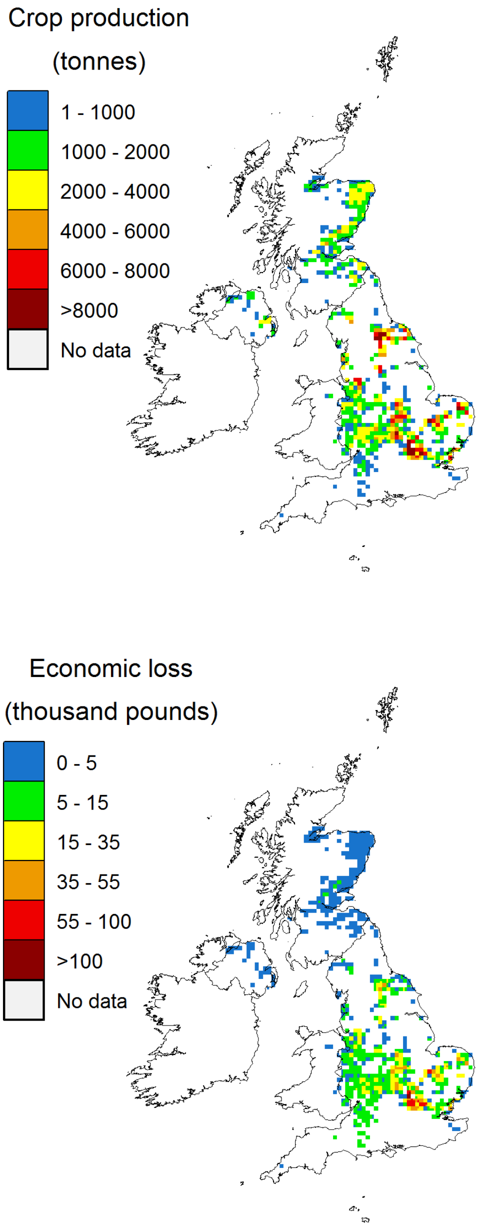

Figure A8: Impacts of ozone on **potato** production in **2014** calculated using POD_6SPEC. (a) Potato production in the UK in tonnes per 5x5 km grid square; (b) Production loss due to ozone in tonnes per 5x5 km grid square; and (c) Economic loss in thousand UK£ per 5x5 km grid square, based on mean price 2014-16.

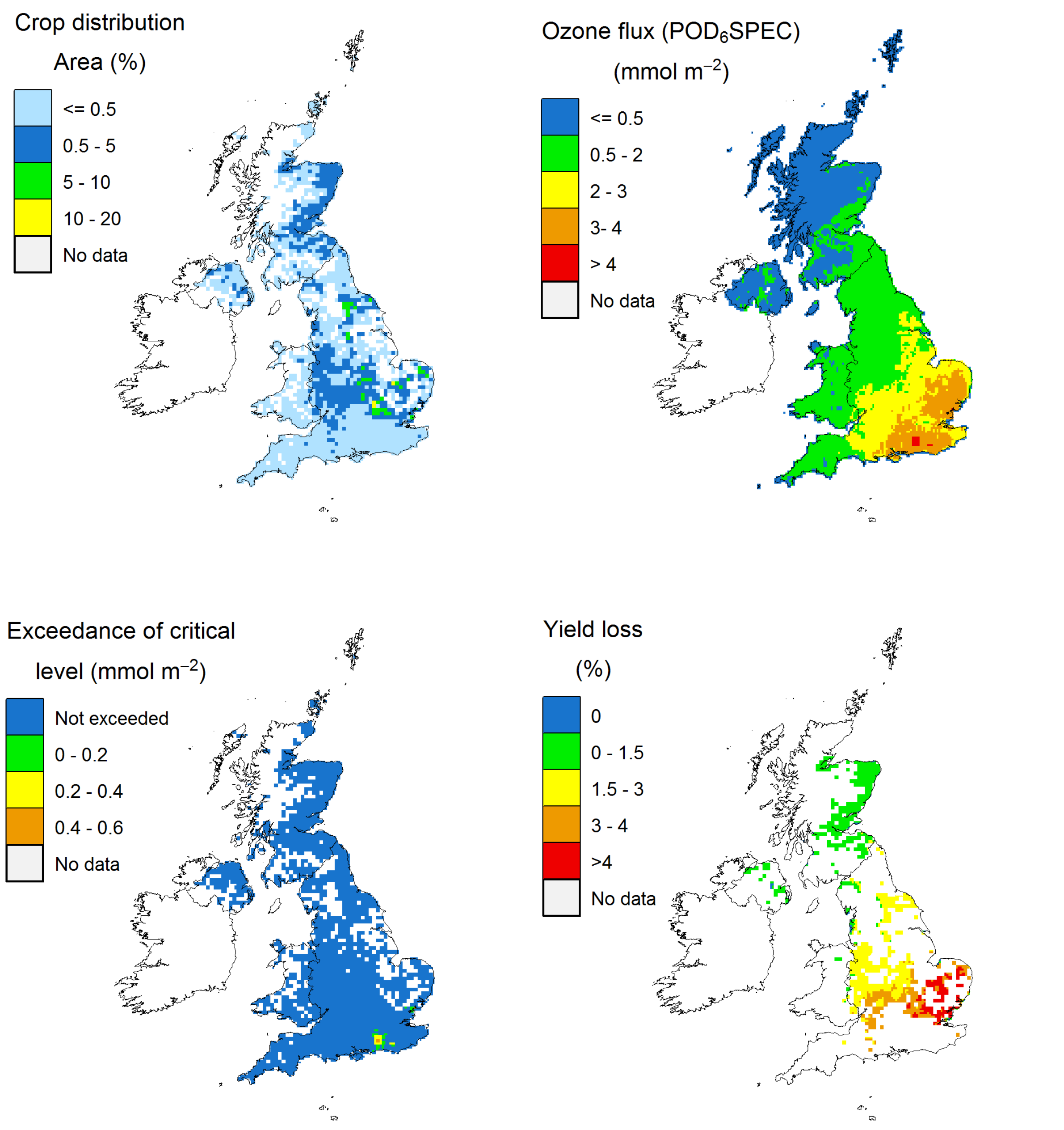

Figure A9: Impacts of ozone on **potato** production in **2015** calculated using POD_6SPEC. (a) Distribution of potato presented as the percentage of each 5x5 km grid square sown with potato; (b) POD_6SPEC (mmol m^{-2}) (**critical level = 3.8**); (c) Exceedance of the critical level; (d) Percentage yield loss.

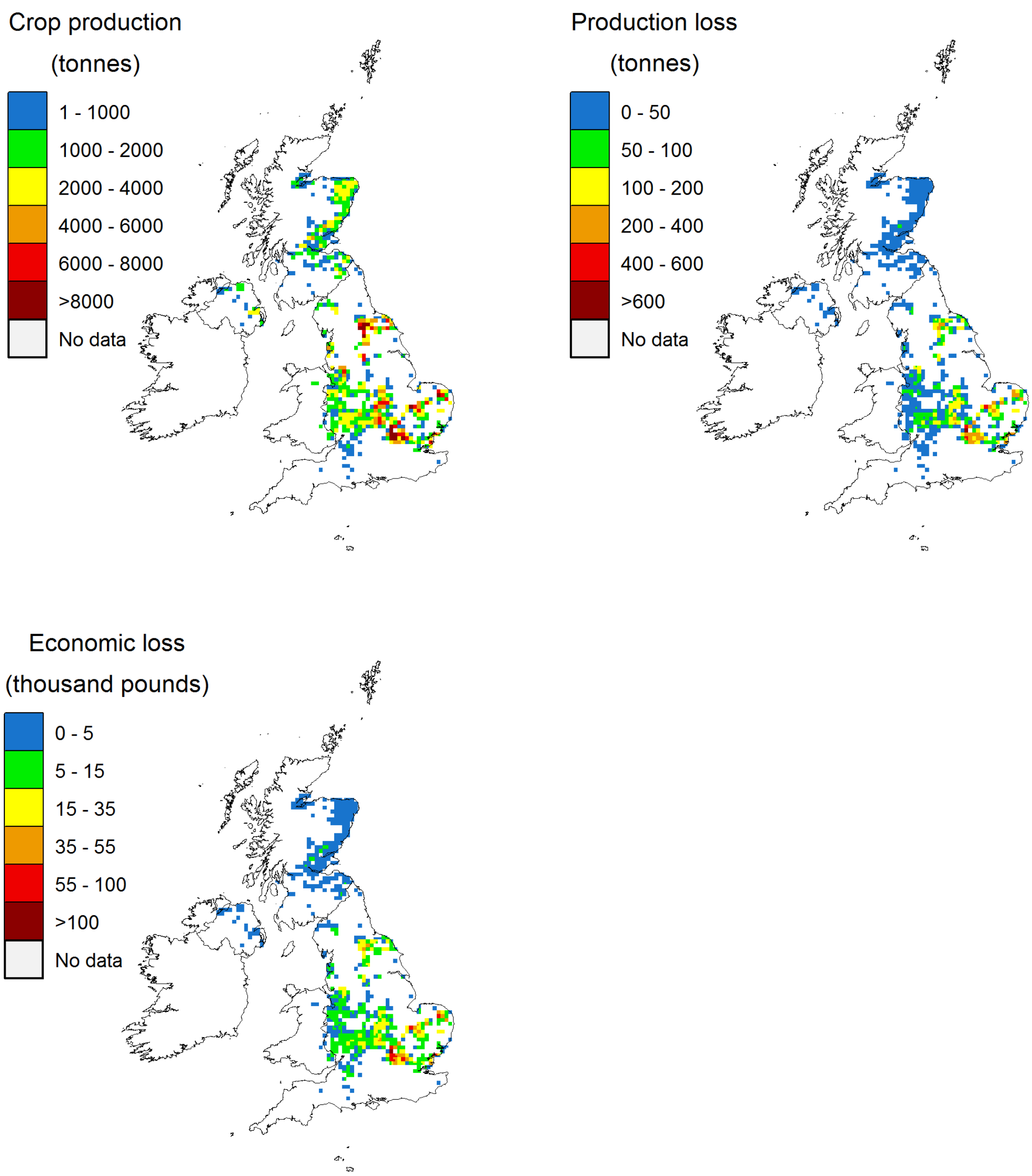

Figure A10: Impacts of ozone on **potato** production in **2015** calculated using POD_6SPEC. (a) Potato production in the UK in tonnes per 5x5 km grid square; (b) Production loss due to ozone in tonnes per 5x5 km grid square; and (c) Economic loss in thousand UK£ per 5x5 km grid square, based on mean price 2014-16.

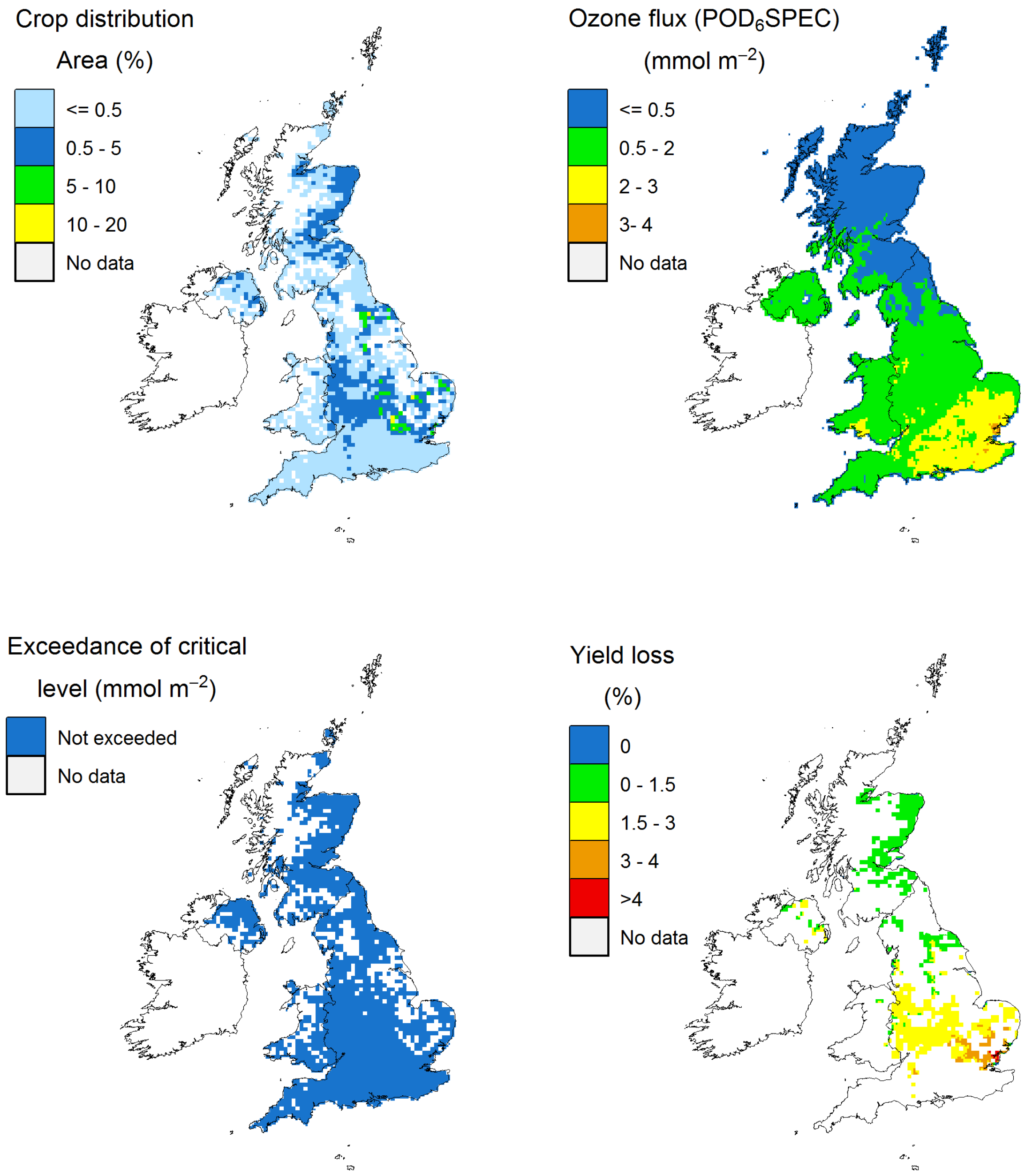

Figure A11: Impacts of ozone on **potato** production in **2016** calculated using POD$_6$SPEC. (a) Distribution of potato presented as the percentage of each 5x5 km grid square sown with potato; (b) POD$_6$SPEC (mmol m^{-2}) (**critical level = 3.8**); (c) Exceedance of the critical level; (d) Percentage yield loss.

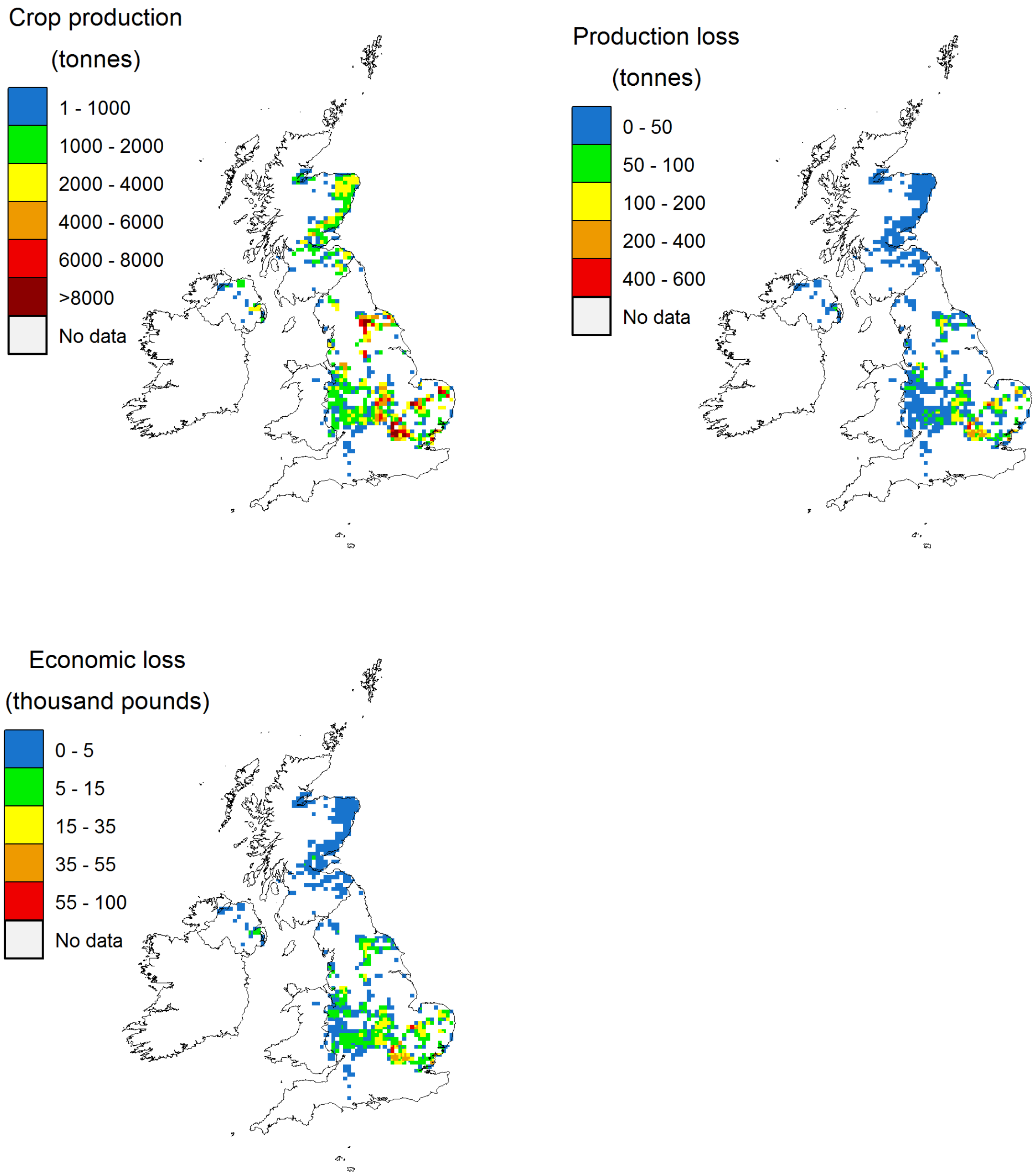

Figure A12: Impacts of ozone on **potato** production in **2016** calculated using POD_6SPEC. (a) Potato production in the UK in tonnes per 5x5 km grid square; (b) Production loss due to ozone in tonnes per 5x5 km grid square; and (c) Economic loss in thousand UK£ per 5x5 km grid square, based on mean price 2014-16.

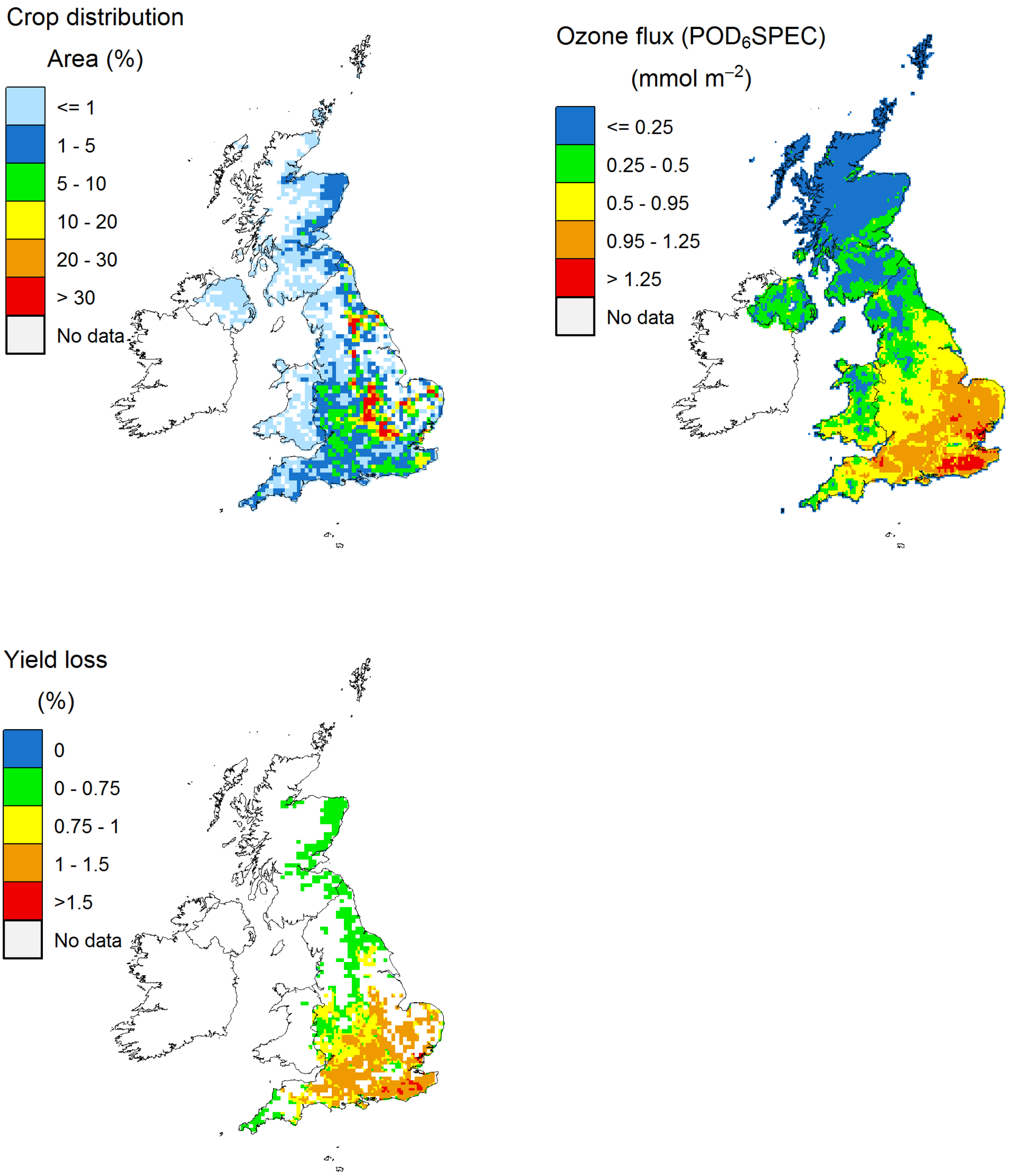

Figure A13: Impacts of ozone on **oilseed rape** production in **2014** calculated using POD_6SPEC. (a) Distribution of oilseed rape presented as the percentage of each 5x5 km grid square sown with oilseed rape; (b) POD_6SPEC (mmol m^{-2}); (c) Percentage yield loss.

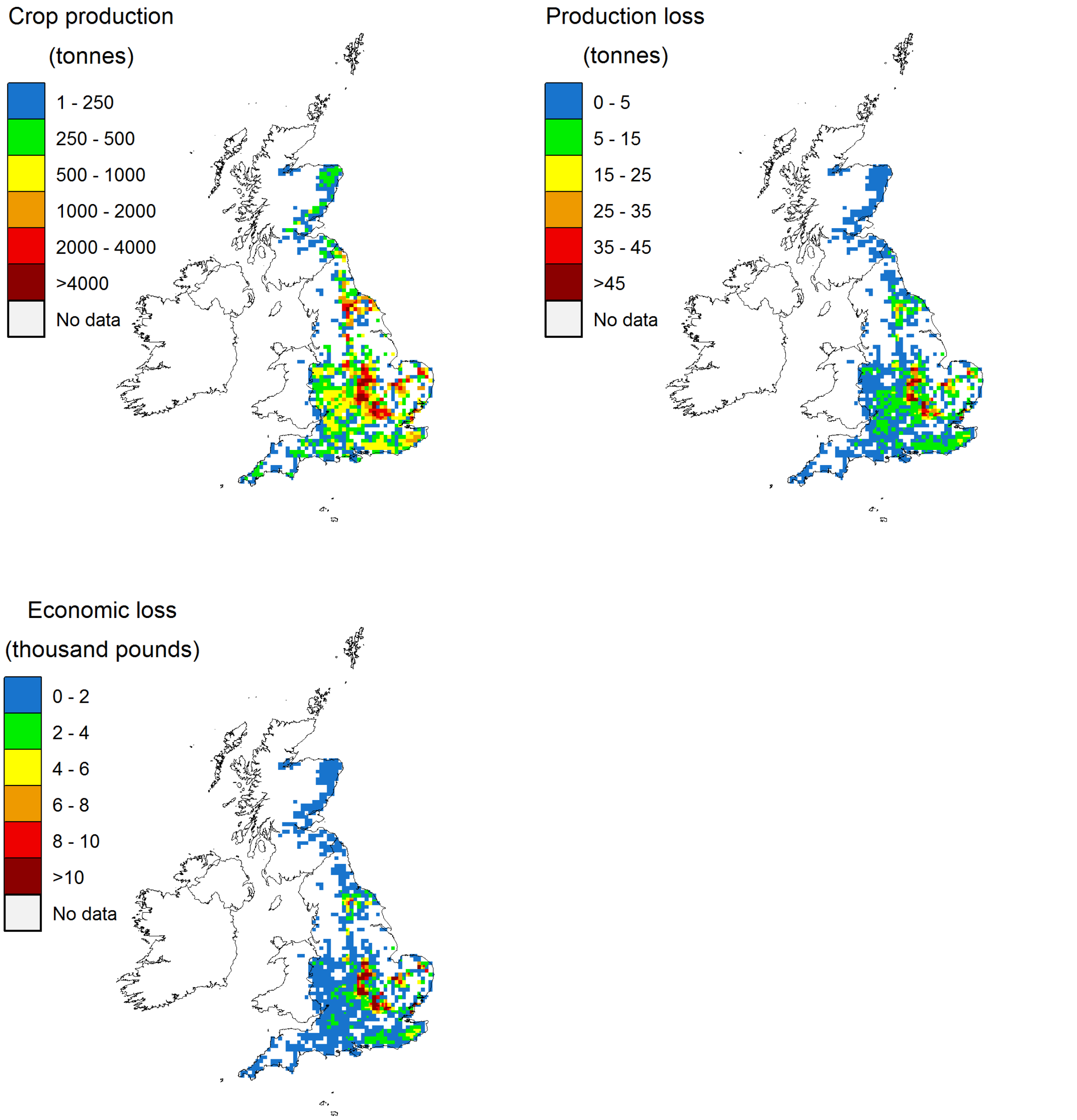

Figure A14: Impacts of ozone on **oilseed** rape production in **2014** calculated using POD_6SPEC. (a) Oilseed rape production in the UK in tonnes per 5x5 km grid square; (b) Production loss due to ozone in tonnes per 5x5 km grid square; and (c) Economic loss in thousand UK£ per 5x5 km grid square, based on mean price 2014-16.

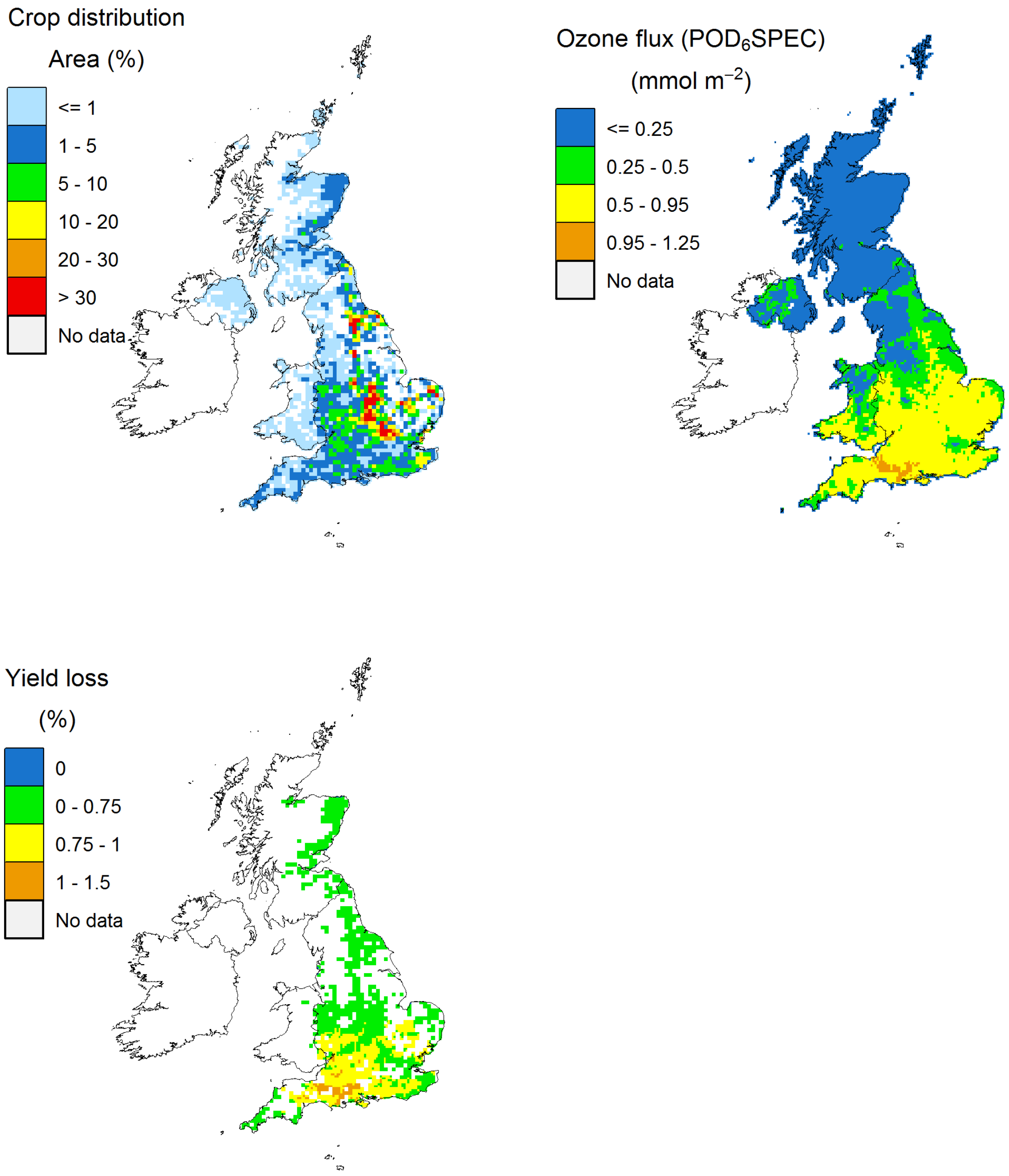

Figure A15: Impacts of ozone on **oilseed rape** production in **2015** calculated using POD_6SPEC. (a) Distribution of oilseed rape presented as the percentage of each 5x5 km grid square sown with oilseed rape; (b) POD_6SPEC (mmol m^{-2}); (c) Percentage yield loss.

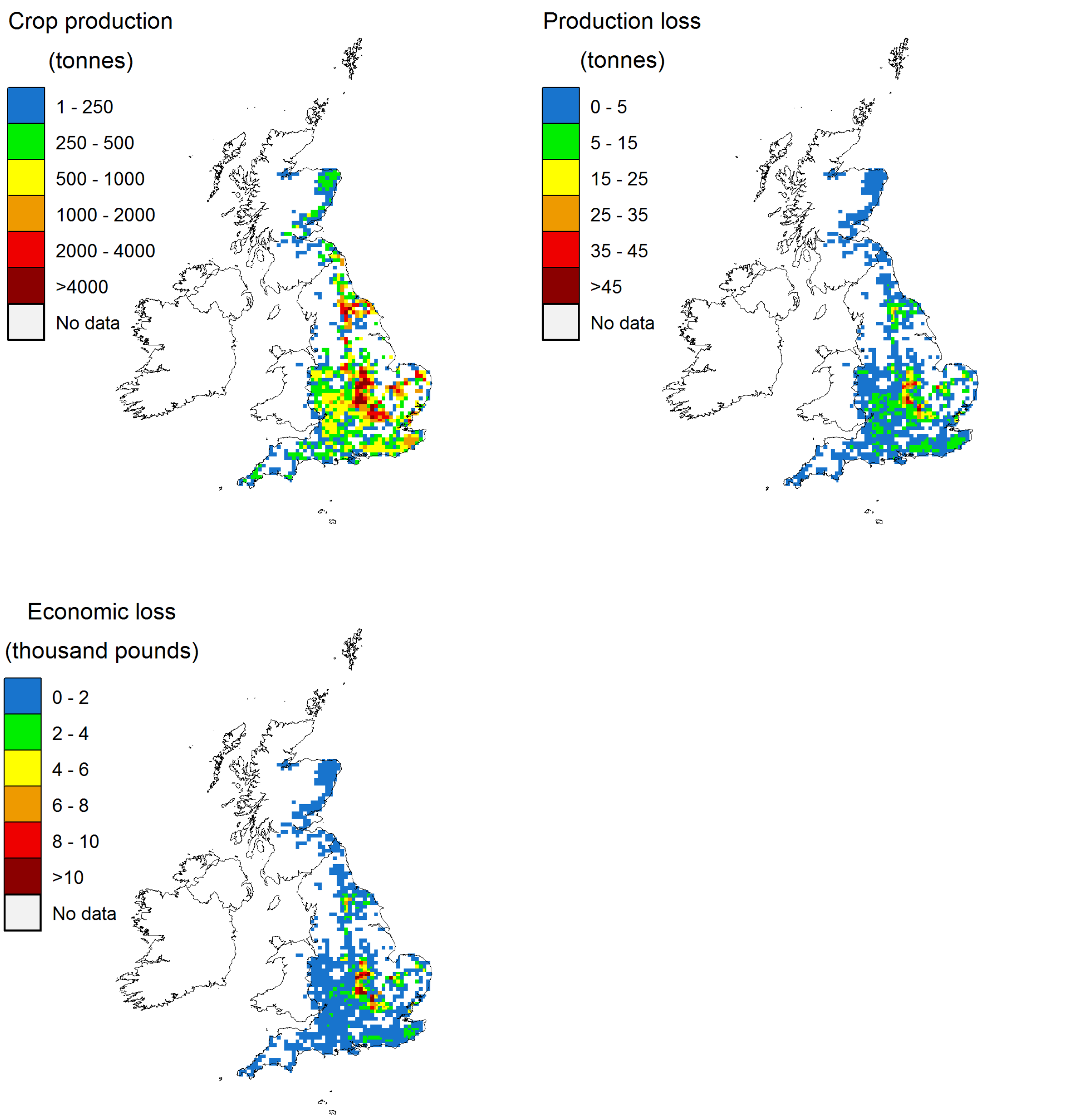

Figure A16: Impacts of ozone on **oilseed rape** production in **2015** calculated using POD_6SPEC. (a) Oilseed rape production in the UK in tonnes per 5x5 km grid square; (b) Production loss due to ozone in tonnes per 5x5 km grid square; and (c) Economic loss in thousand UK£ per 5x5 km grid square, based on mean price 2014-16.

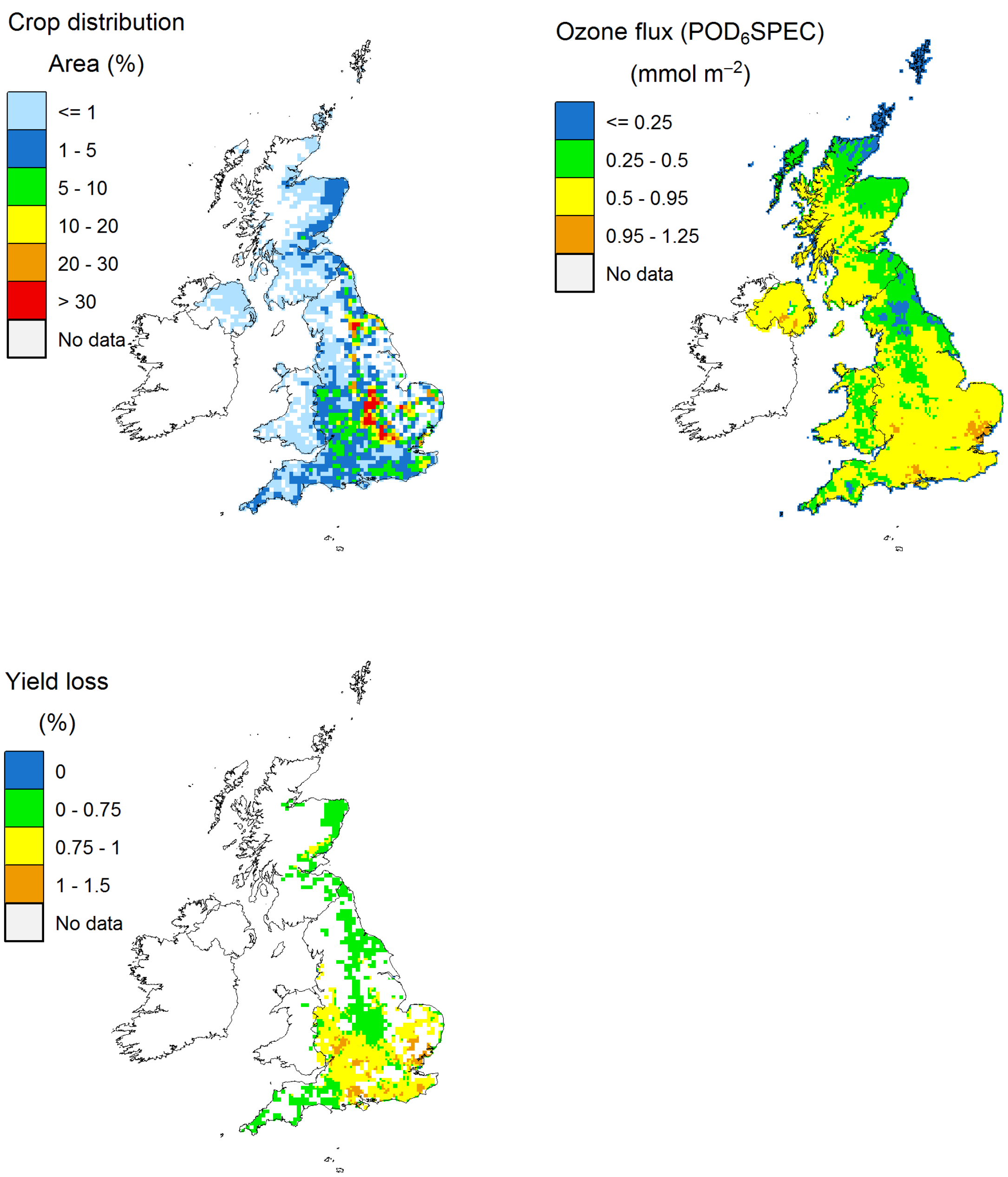

Figure A17: Impacts of ozone on **oilseed rape** production in **2016** calculated using POD_6SPEC. (a) Distribution of oilseed rape presented as the percentage of each 5x5 km grid square sown with oilseed rape; (b) POD_6SPEC (mmol m^{-2}); (c) Percentage yield loss.

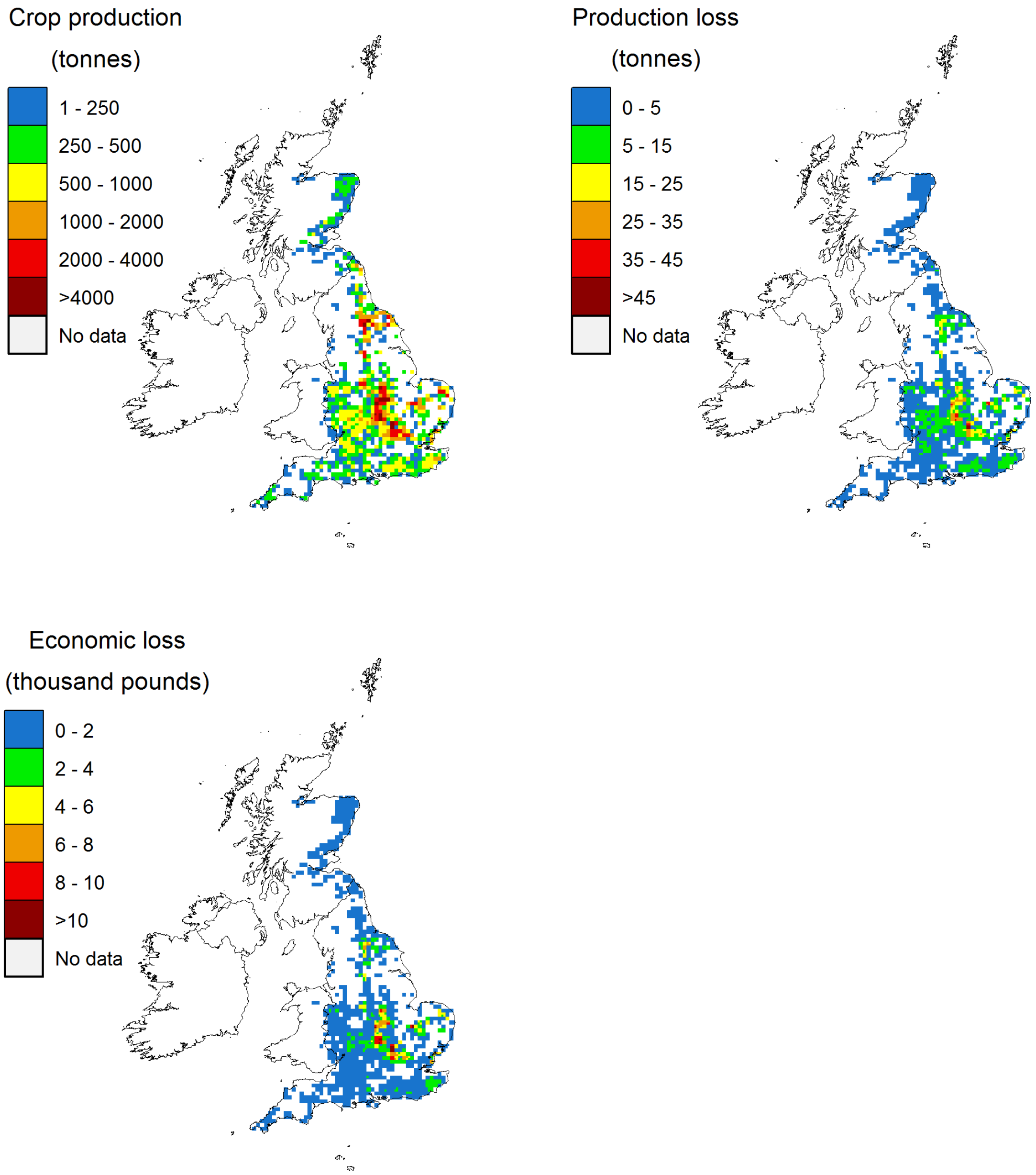

Figure A18: Impacts of ozone on **oilseed rape** production in **2016** calculated using POD_6SPEC. (a) Oilseed rape production in the UK in tonnes per 5x5 km grid square; (b) Production loss due to ozone in tonnes per 5x5 km grid square; and (c) Economic loss in thousand UK£ per 5x5 km grid square, based on mean price 2014-16.

7.2 Broad habitat maps for 2014, 15 and 16

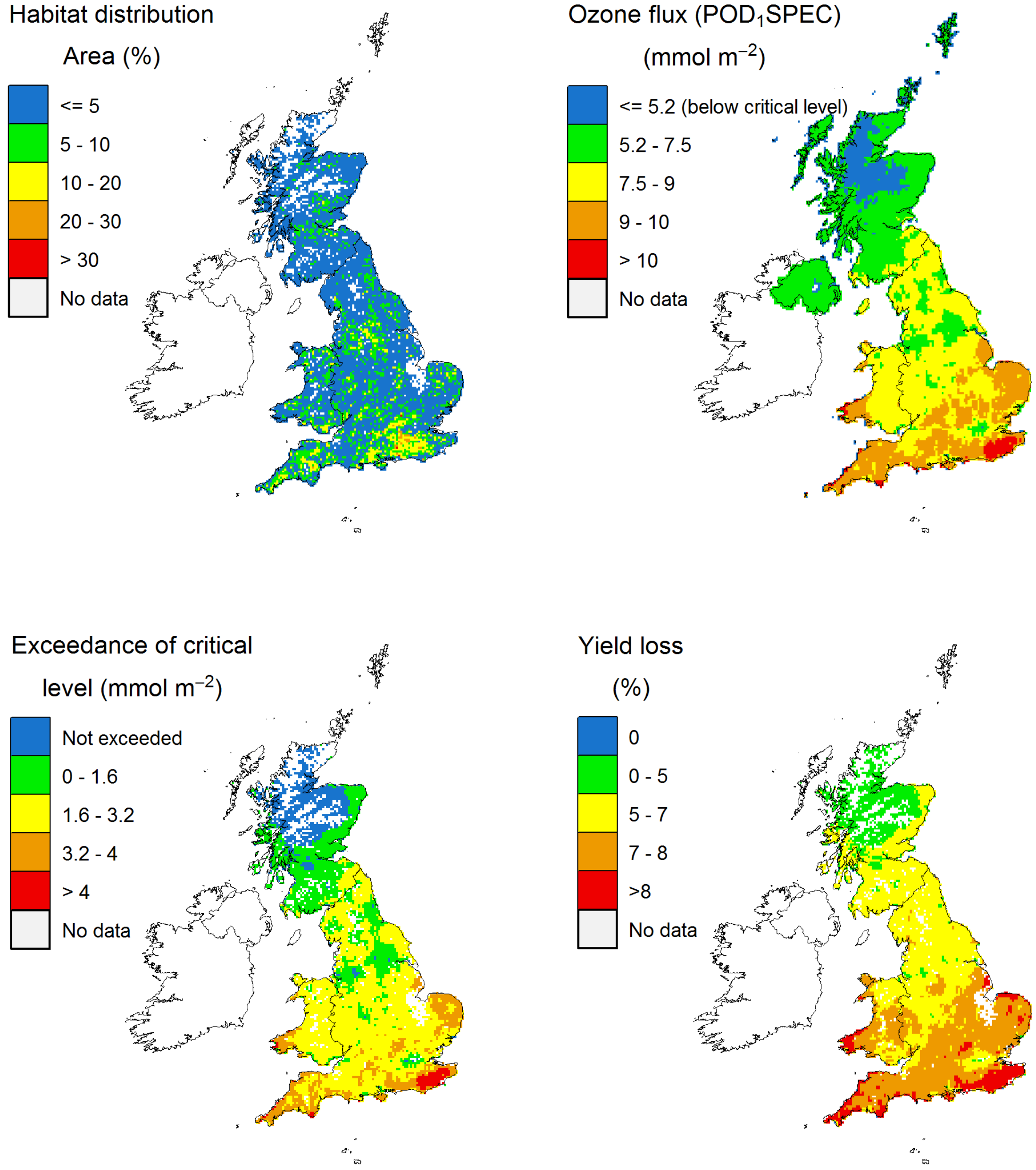

Figure A19: Impacts of ozone on **managed broadleaf woodland** in **2014** calculated using POD_1SPEC. (a) Distribution of managed broadleaf woodland as the percentage area of each 5x5 km grid square; (b) POD_1SPEC (mmol m^{-2}), all squares coloured blue have POD_1SPEC values below the critical level; (c) exceedance of the critical level; (d) Percentage biomass loss (indicative risk only).

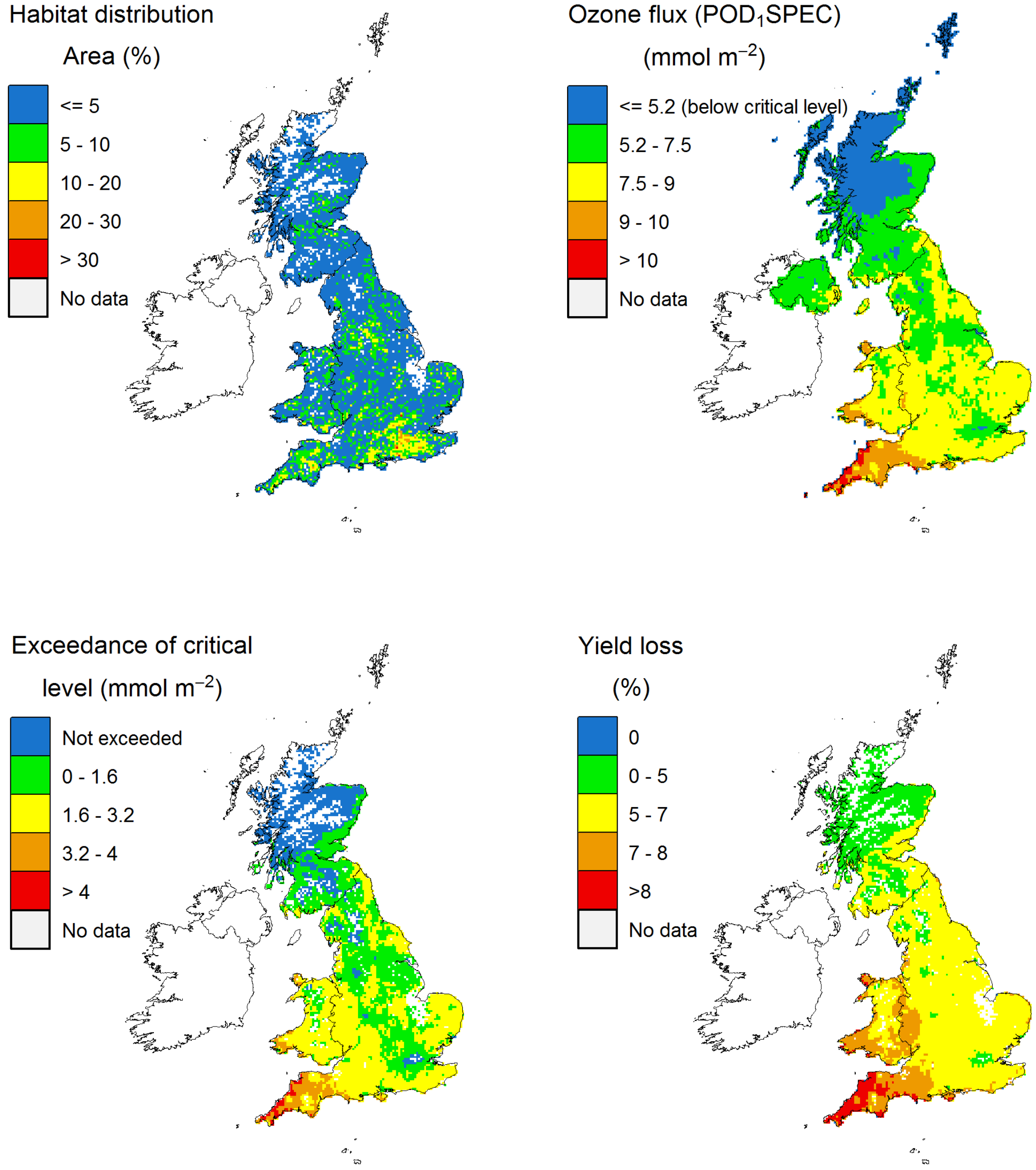

Figure A20: Impacts of ozone on **managed broadleaf woodland** in **2015** calculated using POD_1SPEC. (a) Distribution of managed broadleaf woodland as the percentage area of each 5x5 km grid square; (b) POD_1SPEC (mmol m^{-2}), all squares coloured blue have POD_1SPEC values below the critical level; (c) exceedance of the critical level; (d) Percentage biomass loss (indicative risk only).

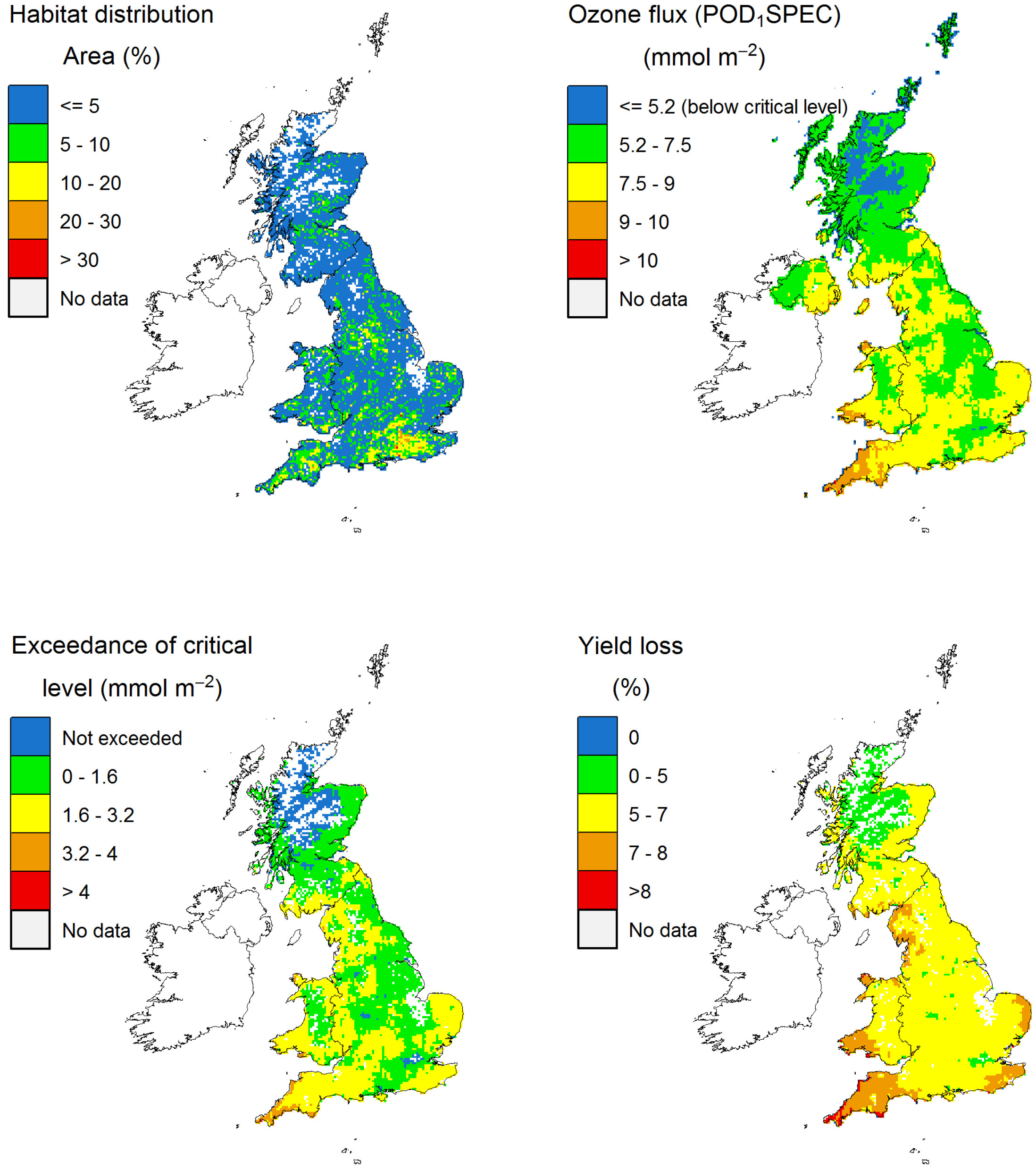

Figure A21: Impacts of ozone on **managed broadleaf woodland** in **2016** calculated using POD_1SPEC. (a) Distribution of managed broadleaf woodland as the percentage area of each 5x5 km grid square; (b) POD_1SPEC (mmol m^{-2}), all squares coloured blue have POD_1SPEC values below the critical level; (c) exceedance of the critical level; (d) Percentage biomass loss (indicative risk only).

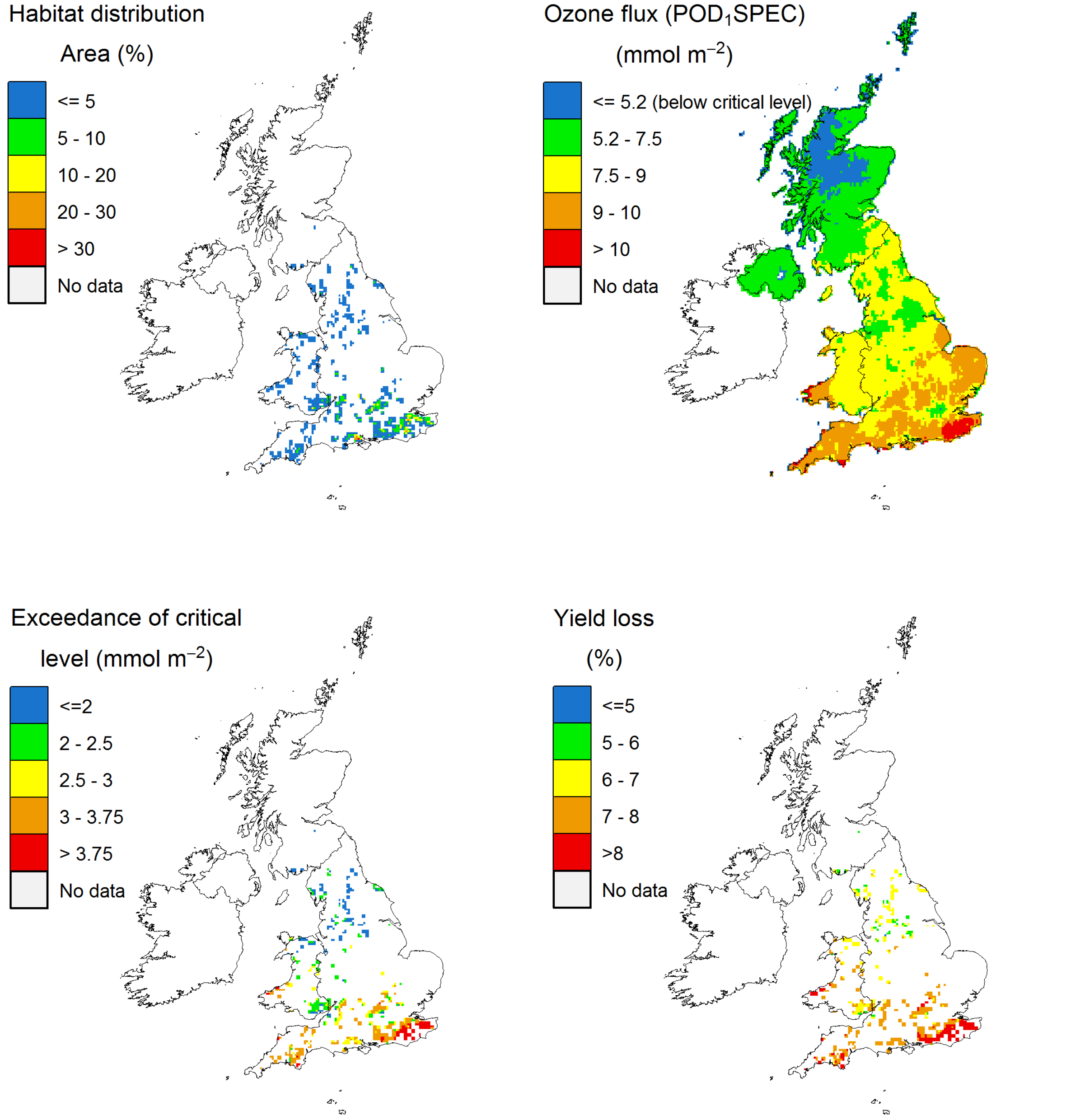

Figure A22: Impacts of ozone on **unmanaged beech woodland** in **2014** calculated using POD_1SPEC. (a) Distribution of unmanaged beech woodland as the percentage area of each 5x5 km grid square; (b) POD_1SPEC (mmol m^{-2}), all squares coloured blue have POD_1SPEC values below the critical level; (c) exceedance of the critical level; (d) Percentage biomass loss (indicative risk only).

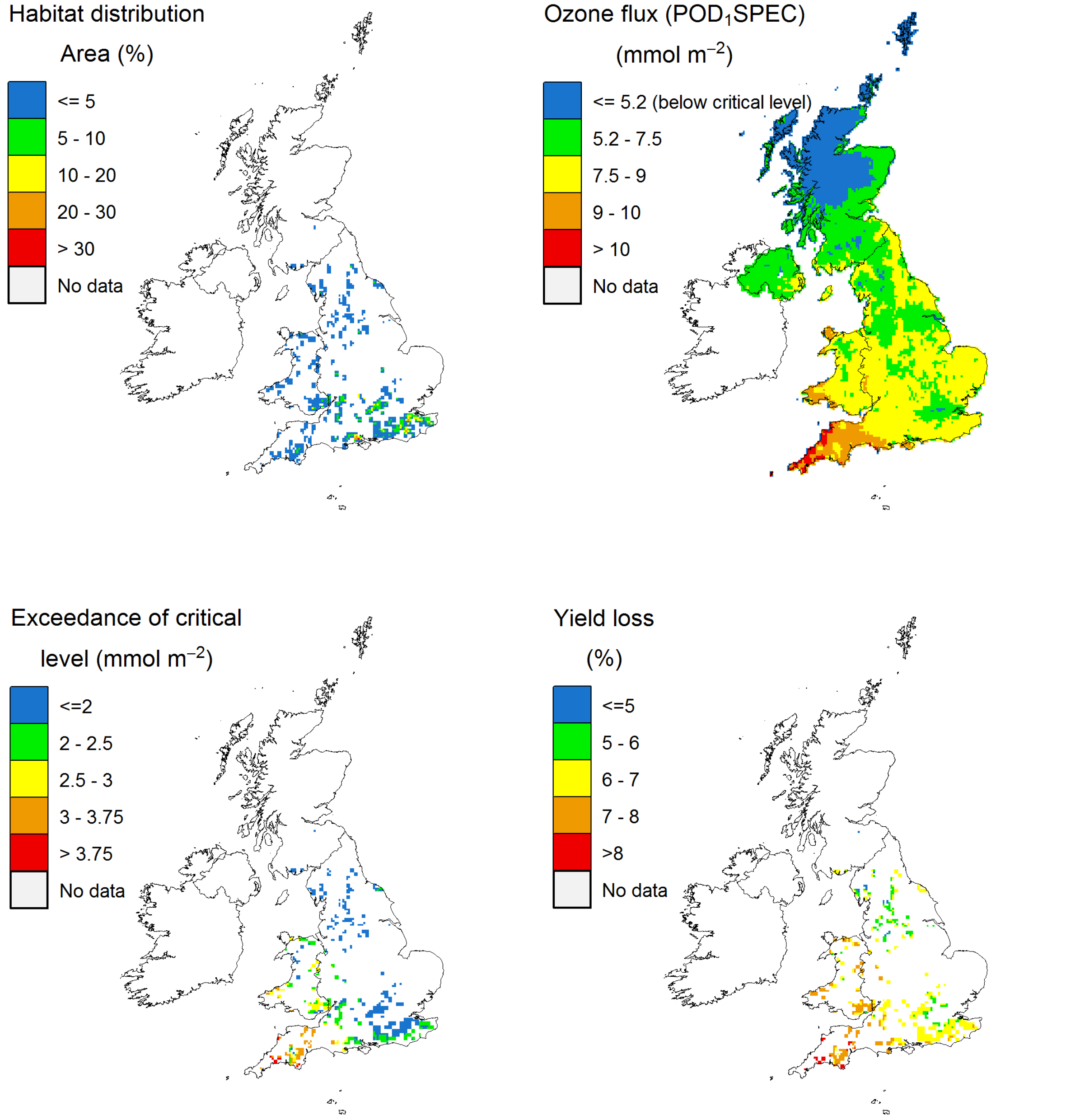

Figure A23: Impacts of ozone on **unmanaged beech woodland** in **2015** calculated using POD_1SPEC. (a) Distribution of unmanaged beech woodland as the percentage area of each 5x5 km grid square; (b) POD_1SPEC (mmol m^{-2}), all squares coloured blue have POD_1SPEC values below the critical level; (c) exceedance of the critical level; (d) Percentage biomass loss (indicative risk only).

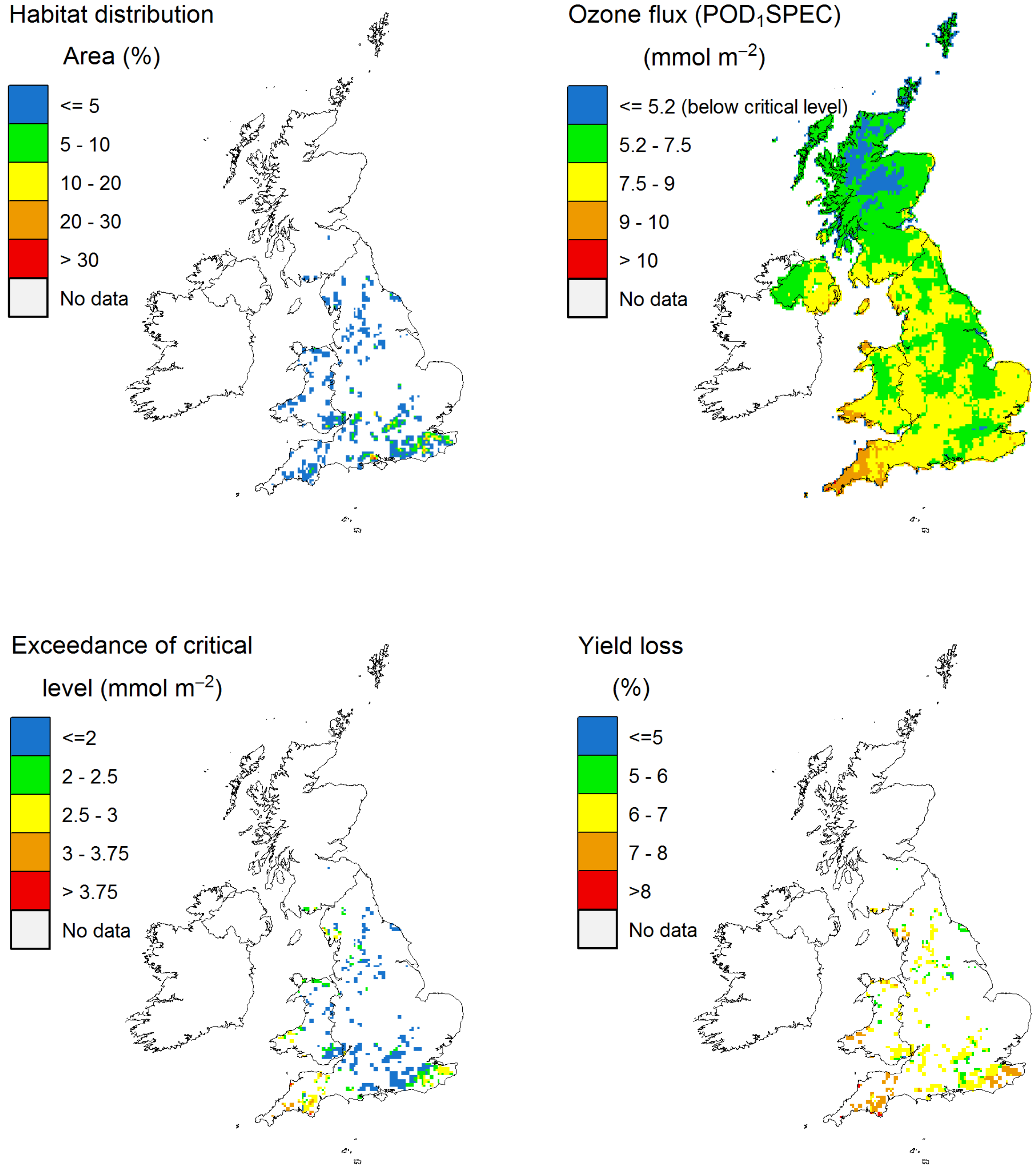

Figure A24: Impacts of ozone on **unmanaged beech woodland** in **2016** calculated using POD_1SPEC. (a) Distribution of unmanaged beech woodland as the percentage area of each 5x5 km grid square; (b) POD_1SPEC (mmol m^{-2}), all squares coloured blue have POD_1SPEC values below the critical level; (c) exceedance of the critical level; (d) Percentage biomass loss (indicative risk only).

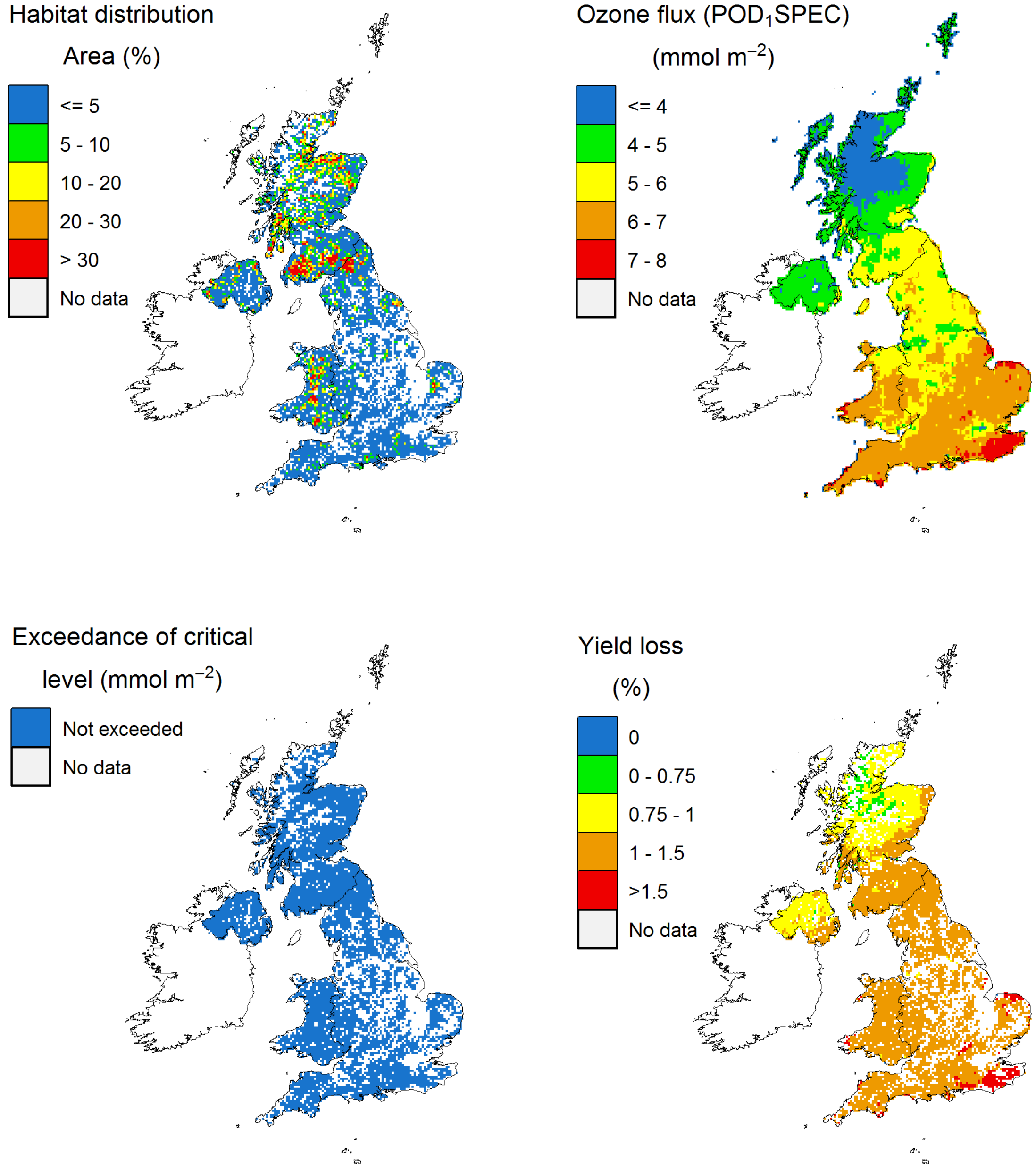

Figure A25: Impacts of ozone on **managed coniferous woodland** in **2014** calculated using POD_1SPEC. (a) Distribution of managed coniferous woodland as the percentage area of each 5x5 km grid square; (b) POD_1SPEC (mmol m^{-2}) (**critical level = 9.2**); (c) exceedance of the critical level; (d) Percentage yield loss (indicative risk only).

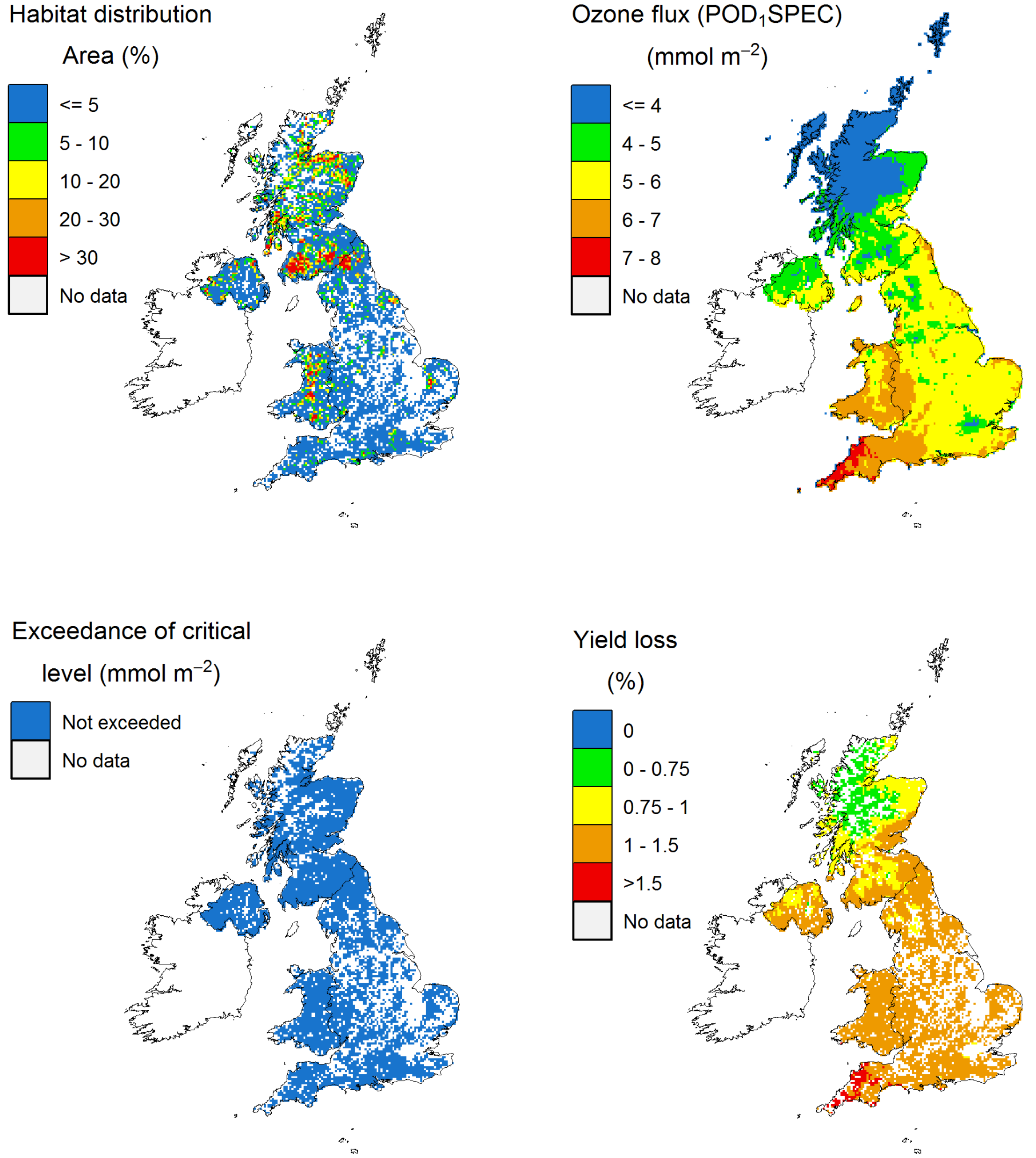

Figure A26: Impacts of ozone on **managed coniferous woodland** in **2015** calculated using POD_1SPEC. (a) Distribution of managed coniferous woodland as the percentage area of each 5x5 km grid square; (b) POD_1SPEC (mmol m^{-2}) (**critical level = 9.2**); (c) exceedance of the critical level; (d) Percentage yield loss (indicative risk only).

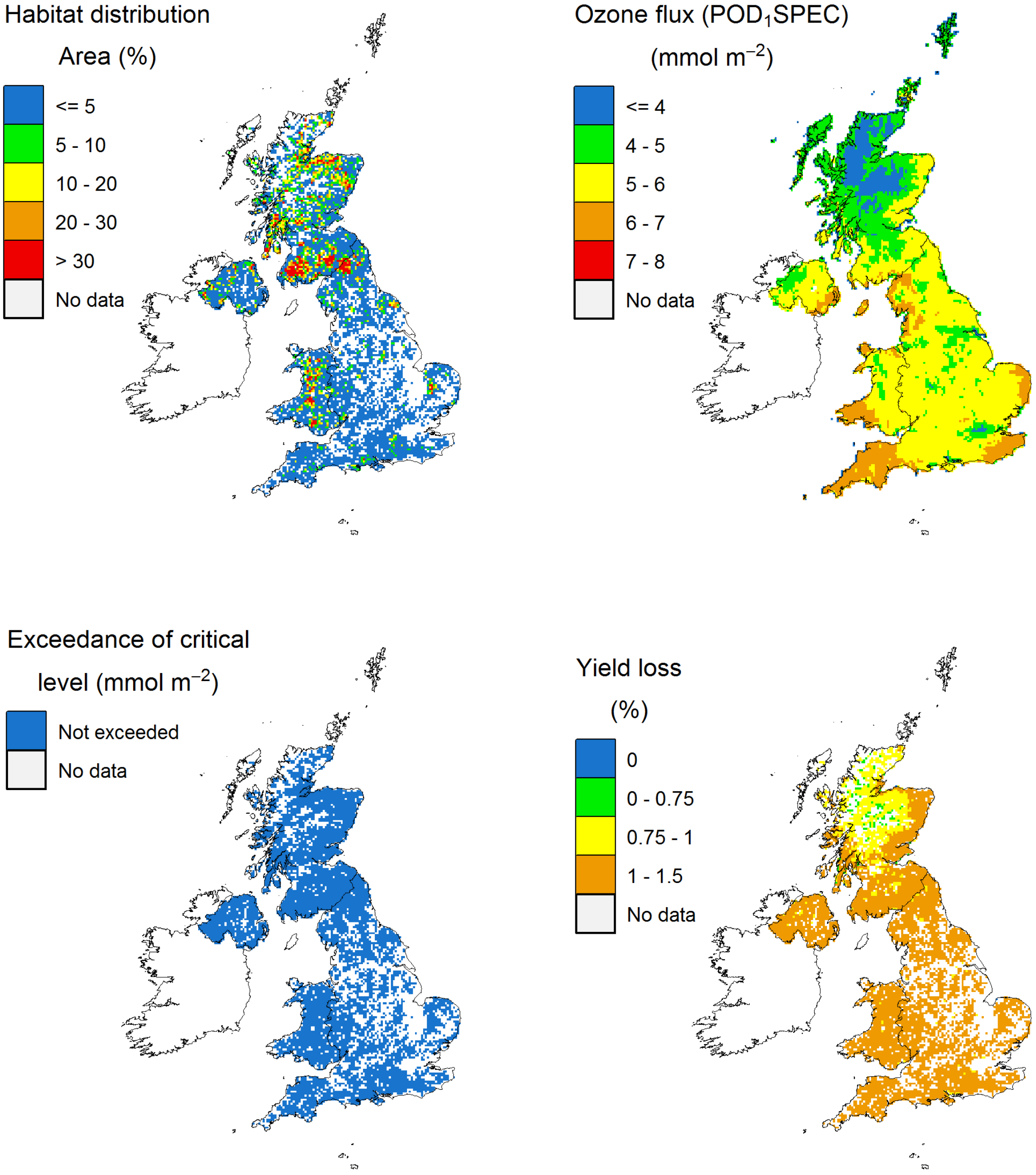

Figure A27: Impacts of ozone on **managed coniferous woodland** in **2016** calculated using POD_1SPEC. (a) Distribution of managed coniferous woodland as the percentage area of each 5x5 km grid square; (b) POD_1SPEC (mmol m^{-2}) (**critical level = 9.2**); (c) exceedance of the critical level; (d) Percentage yield loss (indicative risk only).

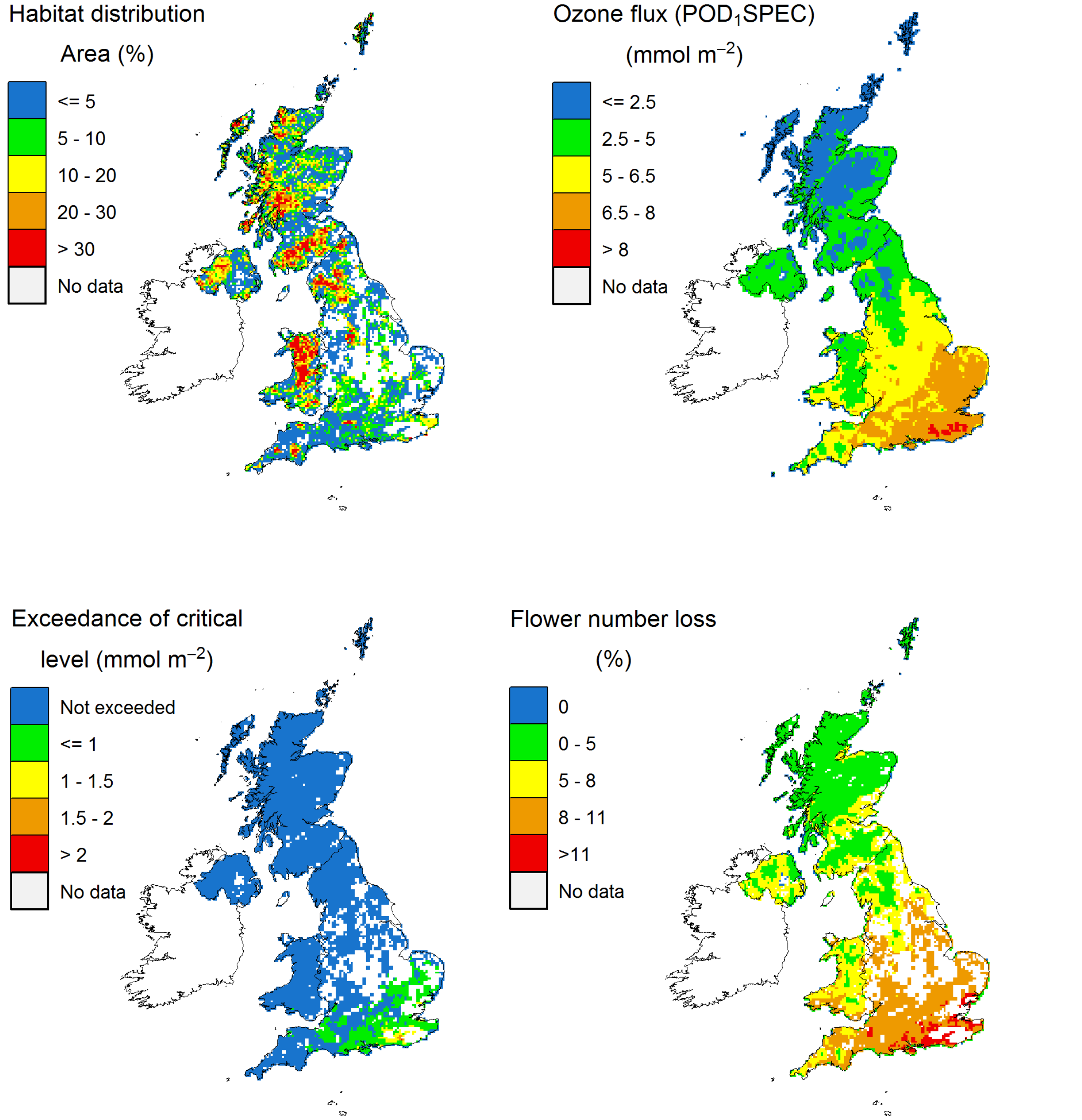

Figure A28: Impacts of ozone on **perennial (semi-natural) grassland** in **2014** calculated using POD_1SPEC. (a) Distribution of grassland as the percentage area of each 5x5 km grid square; (b) POD_1SPEC (mmol m^{-2}) (**critical level = 6.6**); (c) Exceedance of the critical level for flower number; (d) Percentage flower number loss (indicative risk only).

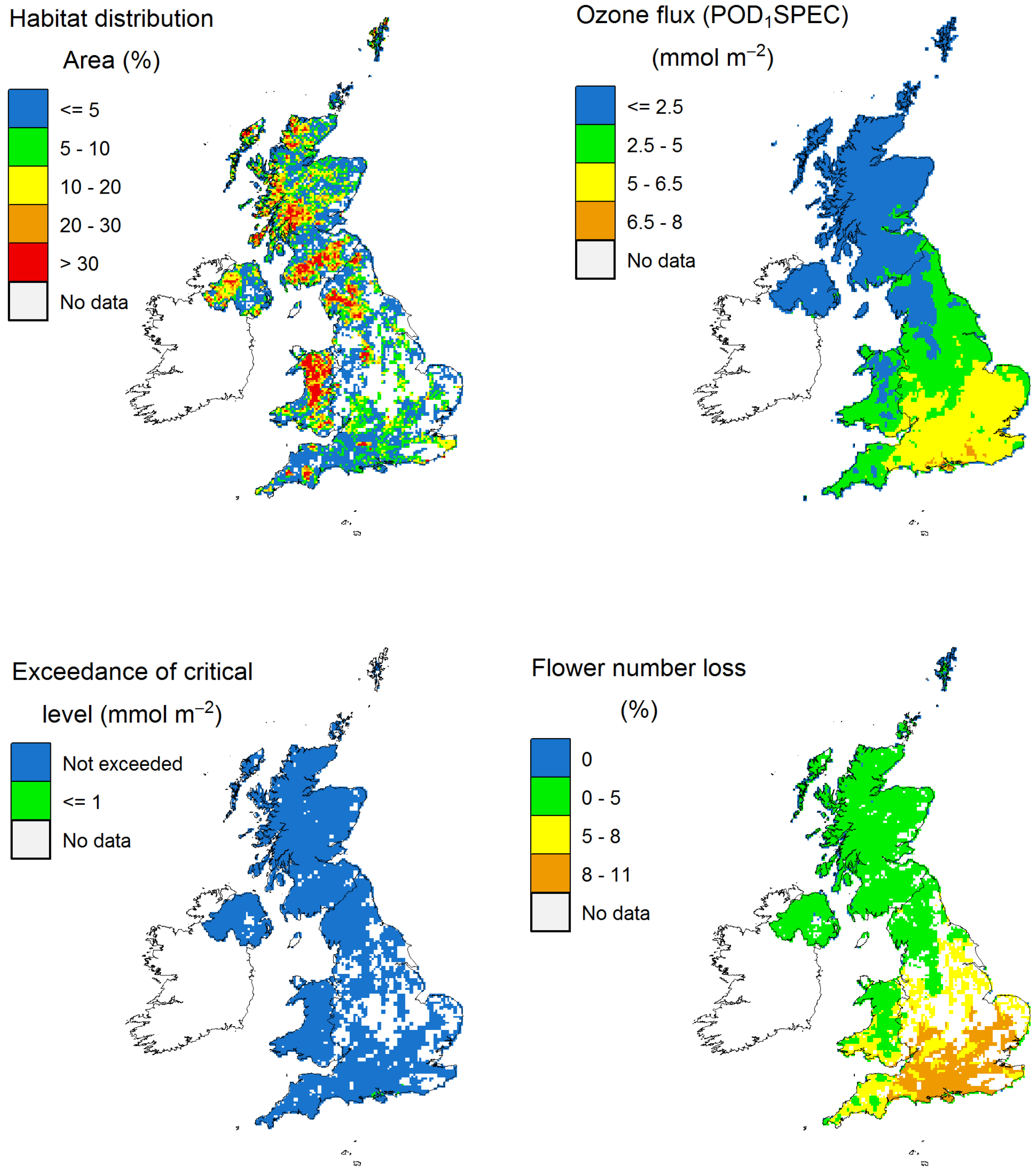

Figure A29: Impacts of ozone on **perennial (semi-natural) grassland** in **2015** calculated using POD_1SPEC. (a) Distribution of grassland as the percentage area of each 5x5 km grid square; (b) POD_1SPEC (mmol m^{-2}) (**critical level = 6.6**); (c) Exceedance of the critical level; (d) Percentage yield loss (indicative risk only).

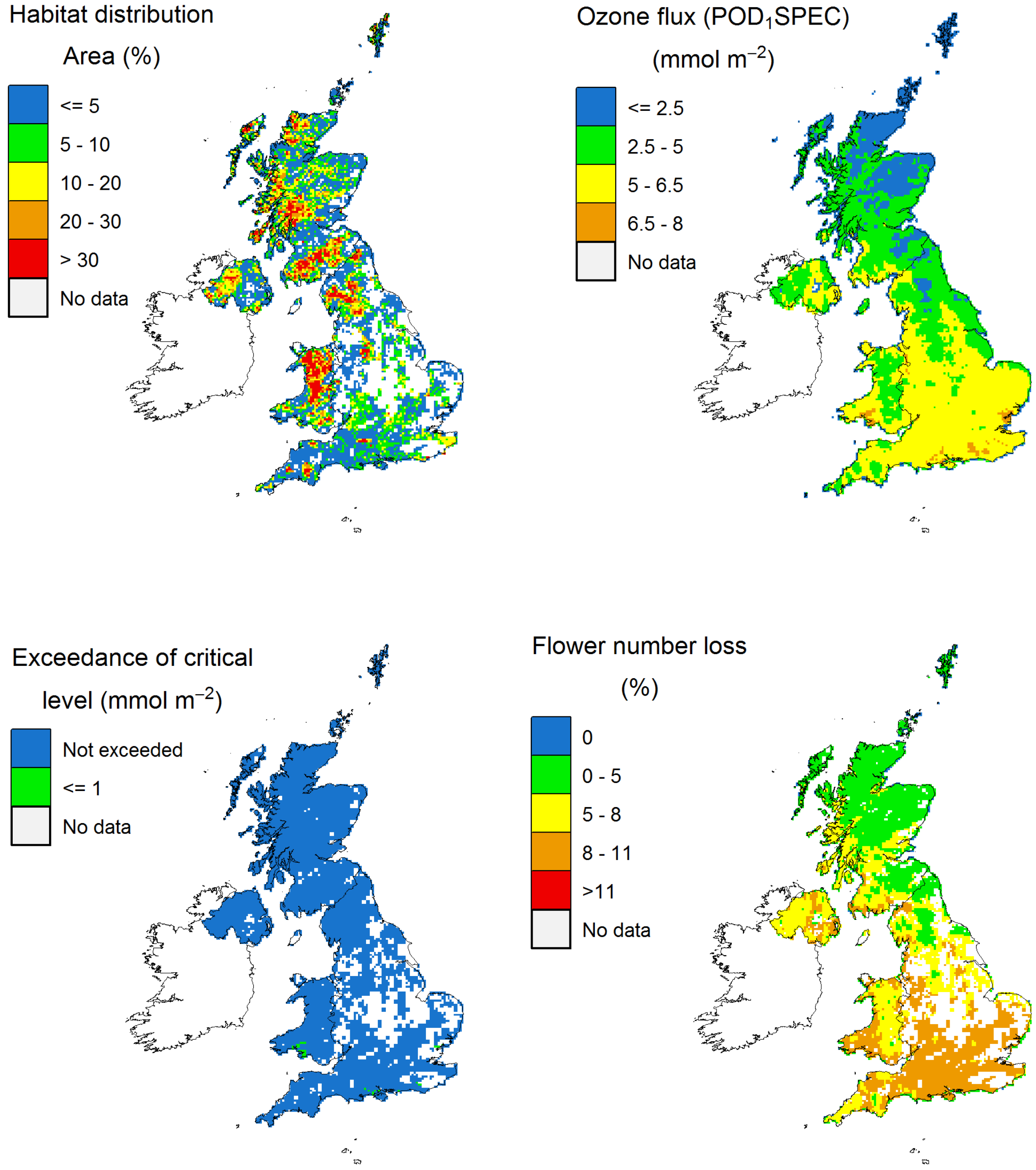

Figure A30: Impacts of ozone **on perennial (semi-natural) grassland** in **2016** calculated using POD_1SPEC. (a) Distribution of grassland as the percentage area of each 5x5 km grid square; (b) POD_1SPEC (mmol m^{-2}) (**critical level = 6.6**); (c) Exceedance of the critical level; (d) Percentage yield loss (indicative risk only).

NERC SCIENCE OF THE ENVIRONMENT

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