The exposure of British peatlands to nitrogen deposition, 1900–2030

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SUMMARY

Nitrogen (N) pollution from industry and intensive agriculture is one of the greatest threats to ecosystems globally. Peatland ecosystems are particularly sensitive to atmospheric pollution and Great Britain has both extensive peatlands and high levels of nitrogen deposition. This study combines data from national pollutant deposition models, hind-casting factors and projections of future deposition with survey-based mire vegetation data to quantify the nitrogen deposition exposure of different vegetation communities and how this has changed over time. By sub-dividing a wide range of diverse peatland habitats the results give a more nuanced picture of N deposition to peatlands than has previously been possible. Grid cells containing mire vegetation receive an average of 14.1 kg N ha^{-1} yr^{-1} (decade to 2010) and have received an average cumulative deposition of 1312 kg N ha^{-1} since 1900. The lower limit of the critical load range is exceeded for 69.6 % of cells, but deposition levels and potential for consequent harm vary widely across Britain and between vegetation types. Nitrogen deposition to peatlands is currently falling and is projected to continue to fall until 2020 but with relatively little further change by 2030. N is likely to continue to accumulate in British peats for at least the first three decades of the 21st Century. It is clear that N deposition is currently a serious threat to British peatlands and is likely to remain so for some time to come.

KEY WORDS: air pollution; bog; fen; mire; vegetation

INTRODUCTION

While di-nitrogen (N_2) is an inert gas which forms most of earth's atmosphere, other forms of nitrogen are important air pollutants which can lead to eutrophication and acidification of terrestrial ecosystems. Oxides of nitrogen (NO_x) are primarily produced by fossil fuel combustion, and reduced forms of nitrogen (NH_y) are mostly products of intensive agriculture. Anthropic production of these reactive forms of nitrogen is now more than double natural N fixation and the global nitrogen cycle is increasingly dominated by human activity (Dentener *et al.* 2006, RoTAP 2012). N deposition is implicated in widespread loss of biodiversity and ecosystem services and is ranked among the top five drivers of global biodiversity loss (Sala *et al.* 2000). In peatlands, N deposition is associated with a reduction in plant species richness (Field *et al.* in press), changed plant (Bobbink *et al.* 2010, Sheppard *et al.* 2014) and microbial communities (Payne *et al.* 2013) and changes in carbon cycling which may enhance C loss (Bragazza *et al.* 2006, Kivimäki *et al.* 2013).

Peatlands cover more than a tenth of the surface area of the United Kingdom (Montanarella *et al.* 2006). N deposition levels are typically high, and believed to be an important threat to British peatlands but there is currently limited information on peatland exposure to N deposition and the potential for consequent harm. While peatlands are included in national critical loads mapping (e.g. Hall *et al.* 2003, 2011) the vegetation datasets used are based on remote sensing (the UK Land Cover Maps) with just a single 'bog' vegetation type considered. This has prevented any attempt to understand the differences in exposure and potential impact on different peatland vegetation communities. Furthermore, the results of critical loads mapping have been published in grey literature where they have generally been overlooked by land managers and peatland scientists not working directly on air pollution impacts.

The aim of this study is to use the results of national nitrogen deposition modelling, hind-casting factors and forward projections combined with survey-based vegetation data to assess the exposure of different British peatland habitats to N deposition, how this has changed over time, and how it will change in the future.

MATERIAL AND METHODS

Vegetation data

The vegetation distribution data are taken from the JNCC 10 × 10 km gridded National Vegetation Classification (NVC) dataset, which includes both the original data used to produce the classification system (Rodwell 1991) and more recent updates by Averis *et al.* (2004). The dataset is the result of more than 35,000 individual samples from across Great Britain. Here 32 mire (‘M’ code) vegetation communities are considered, encompassing true peatland communities (fens and bogs) and also a variety of floristically-related spring, flush, soakaway and wet heath communities which may occur on both peat and non-peat soils. It is important to note that the dataset records the *presence* of communities within grid cells; a record from a cell may refer to a very small fraction of the area of that cell. In opting for this dataset a high level of taxonomic precision is traded off against a lower spatial precision. It is also important to note that the dataset does not allow the consideration of changes in vegetation cover over time; all results are based upon an assumption of constant vegetation distribution.

Nitrogen deposition data

Nitrogen deposition is quantified using output from the UK’s national pollutant deposition models and historical scaling factors. Current deposition data are from the CEH (Centre for Ecology and Hydrology) C-BED model (Smith *et al.* 2000), which models N deposition on the basis of interpolated national atmospheric concentration and climate data. C-BED results are presented on a 5 × 5 km grid but this was reduced to a 10 × 10 km grid by averaging four adjacent cells to match the resolution of the NVC data. At the time of research, annual model runs from 2004 to 2011 were available. To predict peatland exposure to N deposition into the future, projections for 2020 and 2030 produced for the UK Department of Environment, Food and Rural Affairs (DEFRA) were used. These predictions were derived using the FRAME (Fine Resolution Atmospheric Multi-pollutant Exchange) model based on expected trends in industrial and agricultural activity (Fournier *et al.* 2004, Fournier *et al.* 2005, Dore *et al.* 2007). While all such models have errors, both FRAME and C-BED have been extensively tested and are widely used in a variety of scientific and policy contexts. Because FRAME is calibrated against C-BED, results for future projection should be comparable to modelled past and present deposition. To assess N deposition through the 20th Century the C-BED model is hind-casted using the scaling factors of Fowler *et al*. (2004). These data are based on simple re-scaling of current N deposition patterns using reconstructed national emissions trajectories and do not take account of the changing spatial distribution of pollutants, which means that results are likely to over-estimate deposition in remote regions and under-estimate it downwind of conurbations. Thus, the deposition chronologies show parallel trends in all grid cells up to 2000 but then diverge with different trends in individual cells.

An increasingly used alternative metric to annual N deposition is total cumulative deposition over an extended period of time during the era of direct anthropic N fixation (Fowler *et al*. 2004, Duprè *et al*. 2010, Phoenix *et al*. 2012). Cumulative N deposition values have been found to provide useful ‘common currency’ for integrating experiments with differing treatment regimes and monitoring datasets produced at different times (Duprè *et al*. 2010, De Schrijver *et al.* 2011, Phoenix *et al*. 2012). The amount of N which is actually available to organisms will depend on a complex variety of factors, with some N being lost from the system and some retained, and these are difficult to model on a national basis. Current and long-term cumulative N deposition values provide the constraints between which the amount of available N must lie. Here cumulative N deposition is calculated by summing combined deposition chronologies from hind-casted, current and projected deposition data. A starting point of 1900 is used throughout to span the period since the implementation of the Haber-Bosch process (1913-) and enhanced footprint of human activities on the global N cycle.

Methods

Annual and cumulative deposition values were identified for each grid square containing mire vegetation at a decadal time step from 1900 through to projected values for 2030. To synthesise results across similar communities, NVC types were assigned to six broad classes: bog (M1–3, M17–20), poor fen (M4–8, M21), wet heath (M15–16), rich fen (M9–12), fen meadows (M23–28) and soakaway, flush and rill (M29–38). Critical loads were used to provide an assessment of the potential for impacts from a certain level of nitrogen deposition in the different communities. Critical loads are defined as ‘a quantitative estimate of the exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge’ (Bobbink & Hettelingh 2011). Critical loads indicate the potential for negative impacts but are not, in themselves, an index of impacts. NVC community types were converted to the EUNIS communities used in critical load setting based on the European Environment Agency EUNIS database. Some critical load values include modifiers for precipitation and water table level (raised and blanket bogs), latitude (rich fens and montane rich fens) and habitat sub-types (valley mires, poor fens and transition mires; Bobbink & Hettelingh 2011). However, as a precautionary approach, and as the evidential basis for such modifiers is generally not particularly strong, here the lower end of the critical load range is used throughout.

RESULTS

N deposition was relatively constant through the first decades of the twentieth century, increasing from the 1950s and peaking around 1990 (Figures 1–3). Deposition is currently falling and is projected to fall further by 2030, but the decline plateaus at values similar to those of the 1960s rather than those found during the first half of the 20th century. The results for total cumulative N deposition (Figure 1) show a continuing rapid increase.

The NVC dataset contains 6083 records of mire vegetation presence in 1108 unique grid cells. These records are more widely distributed than the data used in critical load mapping and include, for instance, the 'valley bogs' of southern England. Grid cells with peatland and mire vegetation receive an average of 14.1 kg N ha^{-1} yr^{-1} (decade to 2010) reflecting an average total cumulative deposition since 1900 of 1312 kg N ha^{-1} (Figure 1). Habitat means show that grid cells containing poor fen and fen pasture vegetation types receive the highest average levels of N deposition, and wet heath the lowest (Figure 2, Figure 3). However, the variability between communities within a broad habitat type is often as large as, or larger than, the difference between habitat types.

Of the more abundant NVC communities, the most exposed to contemporary N deposition is M20 *Eriophorum vaginatum* raised and blanket mire (Table 1). This is a community typical of degraded peatlands found predominantly in the mountains of northern England and Wales. Other communities with high N deposition are M21 *Narthecium ossifragum* - *Sphagnum papillosum* valley mire and M4 *Carex rostrata* - *Sphagnum recurvum* mire. The abundant community that is least exposed to N deposition is M28 *Iris pseudacorus* - *Filipendula ulmaria* mire, a community of hollows and flushes found predominantly along the northern and western coasts of Scotland. Other communities with lower average N deposition, such as M1 and M17 blanket bog, are also found particularly in Scotland.

Across all habitats, N deposition exceeds the lower limit of the critical load range in 69.6 % of grid cells; and across all bog communities (EUNIS D1 including NVC M1:M3, M18:M21), 97 % of cells exceed the lower limit of the critical load. For three of the NVC communities (M20, M21, M35) all cells currently (2010) receive N deposition in excess of critical load; and for several relatively abundant

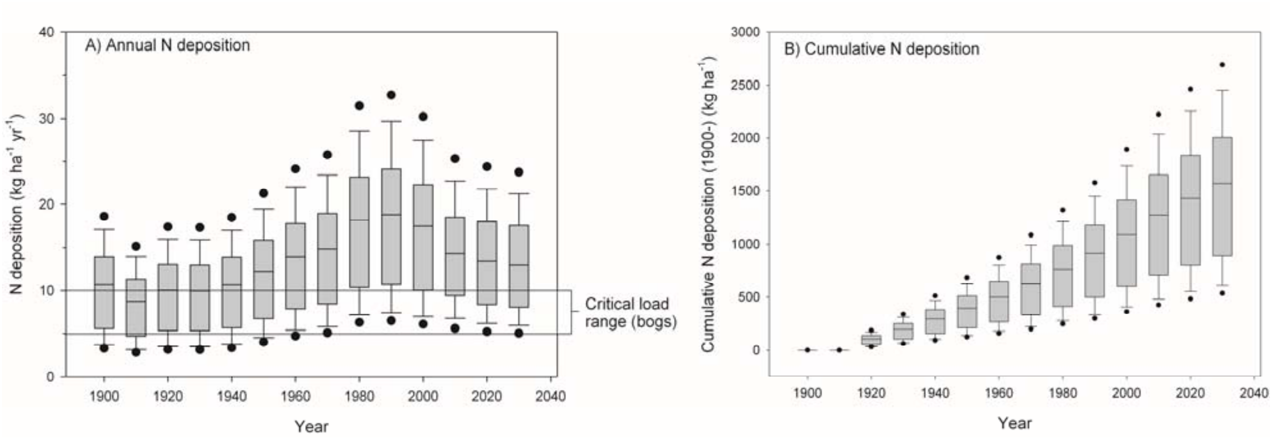


Figure 1. Trends in N deposition for all grid squares containing peatland/mire, 1900–2030. A) average annual deposition; B) total cumulative deposition from 1900. Data are based on historical scaling factors for 1900–2000, annual model runs for 2004–2011 and projections for 2020 and 2030. Box plots show median (horizontal line), first and third quartiles (box), 10th and 90th percentiles (whiskers), and 5th and 95th percentiles (filled circles).

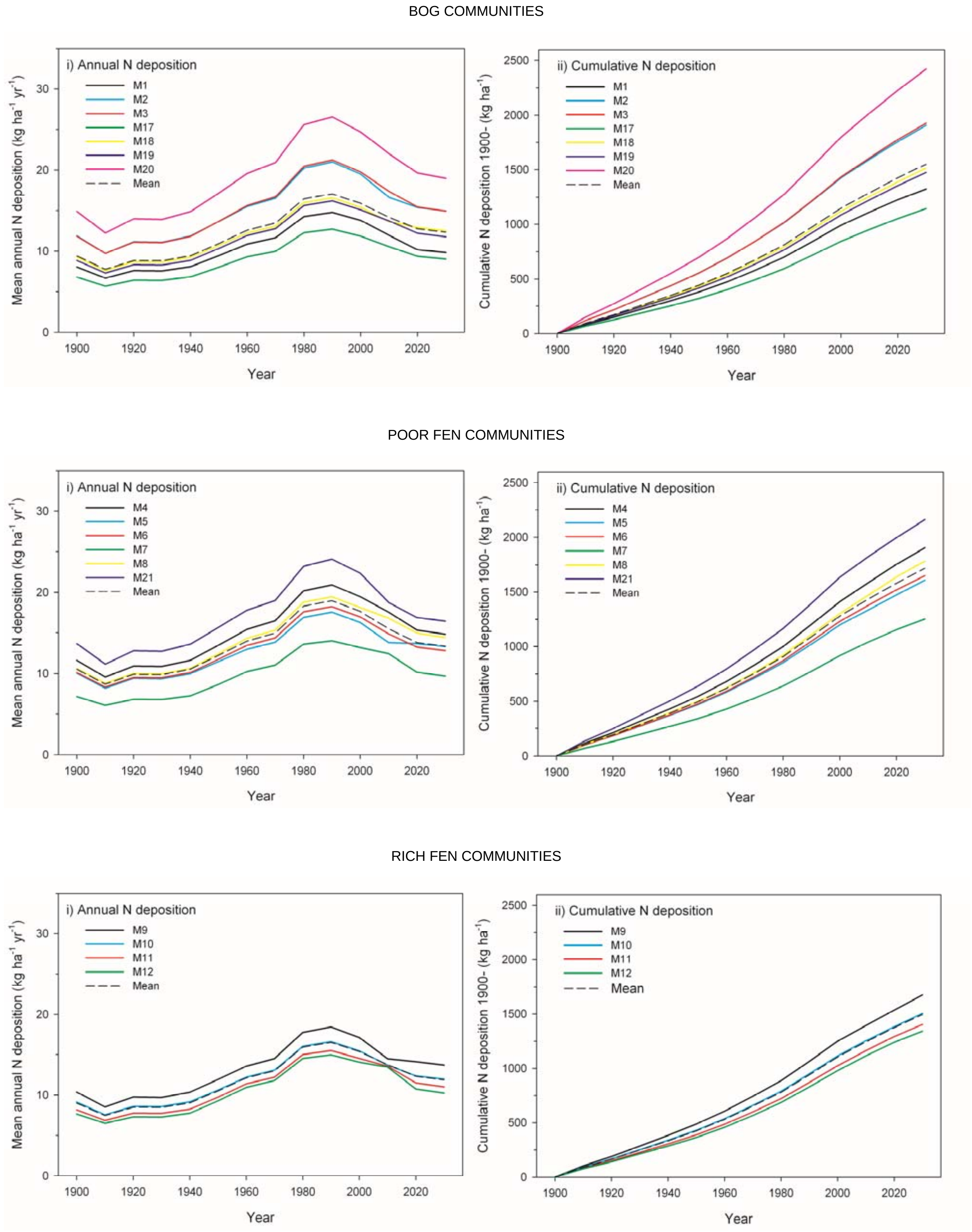
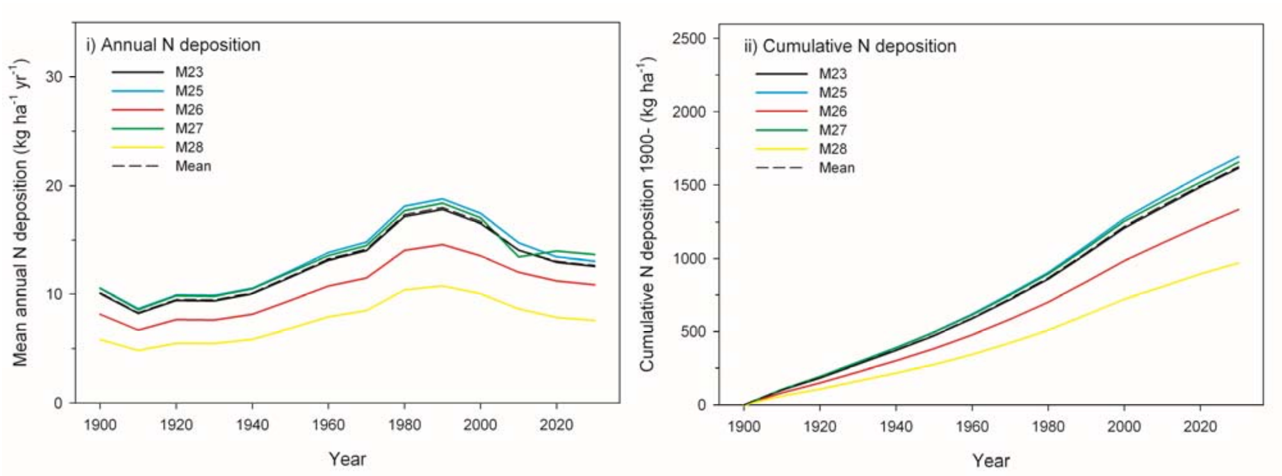
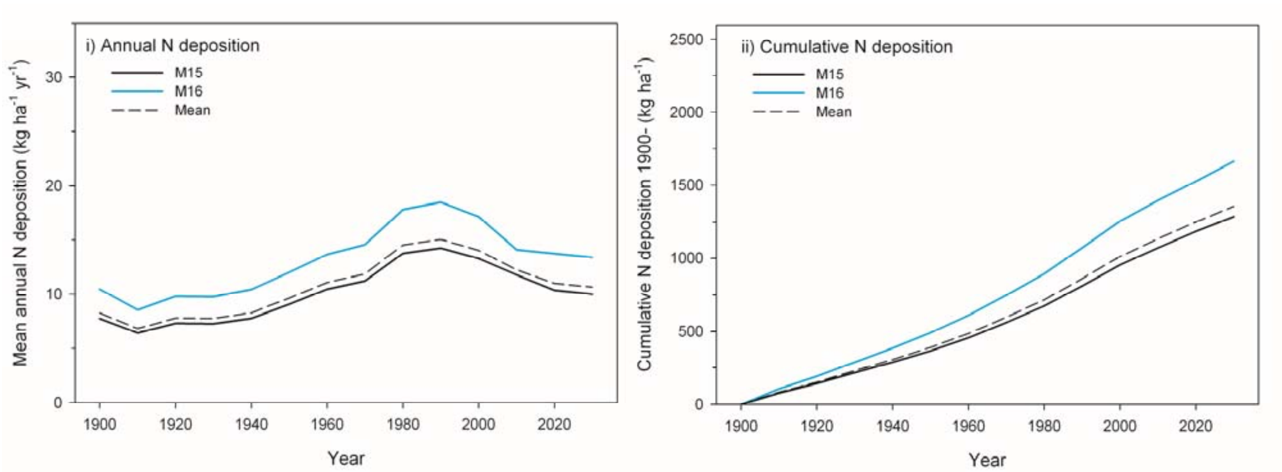


Figure 2. Mean N deposition for three broad NVC community types (bog; poor fen; rich fen), 1900–2030. i) mean annual averages; ii) mean cumulative deposition from 1900. Solid lines show individual community results and dashed lines the mean values for each group of habitat types.

FEN MEADOW COMMUNITIES



WET HEATH COMMUNITIES



SOAKAWAY, FLUSH AND RILL COMMUNITIES

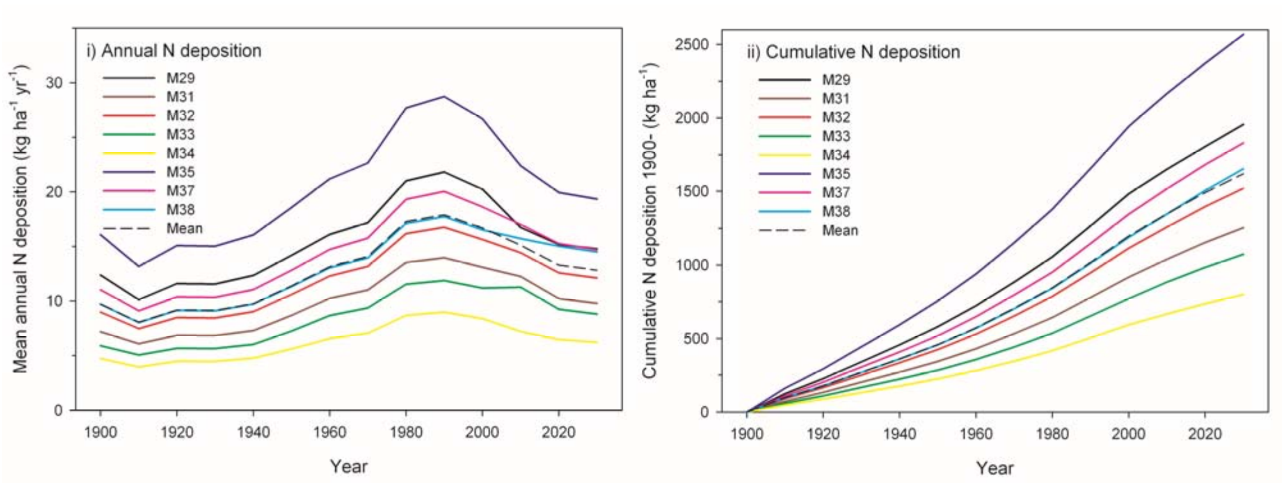


Figure 3. Mean N deposition for three broad NVC community types (fen meadow; wet heath; soakaway, flush and rill), 1900–2030. i) mean annual averages; ii) mean cumulative deposition from 1900. Solid lines show individual community results and dashed lines the mean values for each group of habitat types.

Table 1. N deposition for British mire communities showing National Vegetation Classification (NVC) community, corresponding EUNIS community, number of grid squares the community is present in (n), mean N deposition for three selected years and percentage of grid squares exceeding critical load for these years.

NVC code	NVC community*	EUNIS code	n	mean N deposition (kg ha^{-1} yr^{-1})			critical load			
							value used†	percentage value exceeded		
				1950	2010	2030		1950	2010	2030
M1	*Sphagnum auriculatum* bog pool community	D1.112	72	9.44	11.95	9.84	5	76.39	93.06	88.89
M2	*Sphagnum cuspidatum/recurvum* bog pool community	D1.112	115	13.65	16.63	14.94	5	97.39	99.13	96.52
M3	*Eriophorum angustifolium* bog pool community	D1.112	90	13.68	17.38	14.94	5	87.78	94.44	94.44
M4	*Carex rostrata - Sphagnum recurvum* mire	D2.33	152	13.46	17.55	14.81	10	72.37	84.87	73.68
M5	*Carex rostrata - Sphagnum squarrosum* mire	D2.33	44	11.46	13.80	13.31	10	61.36	75.00	68.18
M6	*Carex echinata - Sphagnum recurvum/auriculatum* mire	D2.223	696	11.74	14.86	12.80	10	57.04	68.82	56.75
M7	*Carex curta - Sphagnum russowii* mire	D2(?)	32	8.66	12.42	9.68	10	34.38	53.13	40.63
M8	*Carex rostrata - Sphagnum warnstorfii* mire	D2.33	19	12.41	16.80	14.40	10	57.89	73.68	68.42
M9	*Carex rostrata - Calligeron cuspidatum/giganteum* mire	D2.33	56	11.94	14.51	13.74	10	62.50	64.29	67.86
M10	*Carex dioica - Pinguicula vulgaris* mire	D4.15	354	10.64	13.73	11.97	15	19.77	37.85	24.86
M11	*Carex demissa - Saxifraga aizoides* mire	D4.19	117	9.73	13.58	11.01	15	17.09	32.48	13.68
M12	*Carex saxatilis* mire	D4.17	23	9.26	13.47	10.25	15	8.70	43.48	0.00
M15	*Scirpus cespitosus - Erica tetralix* wet heath	F4.11	648	9.08	11.77	10.00	10	34.72	49.23	35.34
M16	*Erica tetralix - Sphagnum compactum* wet heath	F4.11	151	12.01	14.09	13.38	10	66.89	74.17	72.19
M17	*Scirpus cespitosus - Eriophorum vaginatum* blanket mire	D1.21	423	8.03	10.56	9.03	5	71.87	95.27	89.83
M18	*Erica tetralix - Sphagnum papillosum* raised and blanket mire	D1.111	267	10.69	13.63	12.49	5	82.77	99.63	98.13
M19	*Calluna vulgaris - Eriophorum vaginatum* blanket mire	D1.221	515	10.34	13.70	11.77	5	79.61	97.28	93.98
M20	*Eriophorum vaginatum* raised and blanket mire	D1.222	186	17.18	21.99	18.97	5	100.00	100.00	100.00
M21	*Narthecium ossifragum - Sphagnum papillosum* valley mire	D1.113	82	15.65	18.73	16.44	5	100.00	100.00	100.00
M23	*Juncus subnodulosus - Cirsium palustre* fen-meadow	E3.42	524	11.56	14.08	12.59	Critical load values not available			
M25	*Molinia caerulea - Potentilla erecta* mire	E3.51	833	12.18	14.75	13.07	15	29.53	50.06	36.61
M26	*Molinia caerulea - Crepis paludosa* mire	E3.51	29	9.42	12.03	10.88	15	13.79	27.59	20.69
M27	*Filipendula ulmaria - Angelica sylvestris* mire	E3.45, E5.42	141	12.03	13.46	13.68	Critical load values not available			
M28	*Iris pseudacorus - Filipendula ulmaria* mire	E3.45, E5.42, E3.418	73	6.85	8.65	7.59				
M29	*Hypericum elodes - Potamogeton polygonifolius* soakway	C3.41	57	14.20	16.74	14.80				
M31	*Anthelia judacea - Sphagnum auriculatum* spring	D2.2C	57	8.69	12.26	9.79	10	29.82	49.12	33.33
M32	*Philonotis fontana - Saxifraga stellaris* spring	D2.2C	176	10.60	14.45	12.12	10	48.86	64.77	53.41
M33	*Pohlia wahlenbergii var. glacialis* spring	D2.2C	24	7.27	11.27	8.80	10	16.67	58.33	25.00
M34	*Carex demissa - Koenigia islandica* flush	D2.2C	4	5.63	7.23	6.24	10	0.00	0.00	0.00
M35	*Ranunculus omiophyllus - Montia fontana* rill	D2.2C	17	18.56	22.38	19.33	10	100.00	100.00	100.00
M37	*Cratoneuron commutatum - Festuca rubra* spring	D4.1N	94	12.84	17.03	14.72	15	27.66	56.38	44.68
M38	*Cratoneuron commutatum - Carex nigra* spring	D4.1N	11	11.33	15.73	14.51	15	9.09	54.55	36.36

*Note that some NVC community names refer to out-dated taxonomy but these are retained for consistency. †Units: kg ha^{-1} yr^{-1}.

communities with low critical loads (M1, M2, M3, M17, M18, M19), over 95 % of cells have critical load exceeded. The communities with the lowest proportion of exceedance tend to be sedge fen and flush communities with higher critical load values and distributions predominantly in the Scottish mountains (e.g. M10, M11, M12). For one very rare community (M34 *Carex demissa - Koenigia islandica* flush, *n*=4), no cells have deposition above critical load.

DISCUSSION AND CONCLUSIONS

There are important uncertainties in the datasets which should be borne in mind when interpreting the results. The recording of vegetation community presence in a grid cell is dependent on whether specific areas were visited by a surveyor in one of the component surveys, and it is likely that the distribution of many habitats is under-represented, particularly in more remote regions. Furthermore, the data take no account of changes over time and it is probable that there has been considerable change in vegetation distribution both before and since the surveys were conducted (mostly in the 1980s) (e.g. Ross *et al*. 2012). Deposition models inevitably have errors due to the limitations of both the underlying datasets and the models themselves. The deposition data are particularly limited for the period 1900–2000, when values are based on re-scaling of national trends. There are further uncertainties associated with critical load values. Nevertheless, given the spatial resolution, the data are adequate to determine relative patterns of national N deposition exposure and critical load exceedance.

Although the most extensive British peatlands are remote from local sources of air pollution it is clear that, due to the combination of long-distance dispersal of N and the preferential occurrence of peatlands in high-precipitation areas, N deposition on British peatlands is substantial. Temporal trends in N deposition for peatland habitats reflect the national picture (Fowler *et al*. 2004). Most of the decline since the 1990s has been due to reductions in oxidised N emissions derived from industry with reduced N emissions from agriculture proving much more difficult to tackle (RoTAP 2012). Projected emission reductions this century will slow the rate of increase in cumulative deposition values only very slightly (Figure 1). Thus, although some deposited N is certain to be lost through both aquatic (DON, DIN) and gaseous (NO, N_2O) pathways, it appears likely that N will continue to accumulate in many British peatlands through the first three decades of the 21st century. The national picture also hides local variability. For instance, in the heart of the Britain's most extensive peatland area at Forsinard Flows National Nature Reserve in northern Scotland, annual deposition is predicted to be almost 50 % greater in 2030 than it was in 2010 (6.3 kg N ha^{-1} yr^{-1} to 9 kg N ha^{-1} yr^{-1}).

The percentage of grid cells containing bog communities for which the critical load is exceeded (97 %) is considerably higher than the 56 % of total area reported for bogs in the latest national critical load mapping (Hall *et al.* 2011), which uses critical load figures towards the higher end of the range and different habitat data. It is also important to recognise that the relationship between the proportion of grid cells with critical load exceeded and the area of habitat with critical load exceeded is not linear. The fraction of a grid cell containing mire habitat is likely to be higher in less polluted northern regions, where peatlands are more extensive, than in southern regions where peatlands are relatively scattered and air pollution higher. The fraction of a cell covered by a particular vegetation community is also likely to differ systematically, with certain communities restricted to relatively small features (e.g. flushes) and others much more widespread (e.g. blanket bog communities).

The results of this study provide a more nuanced picture of the exposure of British peatlands to nitrogen deposition than has been possible with previous datasets. High deposition values for M20 *Eriophorum vaginatum* raised and blanket mire are unsurprising as air pollution, along with high levels of grazing and burning, is an important reason for the occurrence of this degraded vegetation type which would be replaced by other communities (notably M19) in cleaner areas. M21 valley mires are particularly abundant in high-deposition southern England and, therefore, high deposition values are again relatively unsurprising. It is perhaps more surprising that M4, a community of pools and seepage areas in topogeneous and soligeneous mires, also receives high deposition as this community is relatively widespread across the mountains of northern Britain.

Such data are important for the prioritisation of nature conservation efforts. For instance the results highlight that M35 (*Ranunculus omiophyllus - Montia fontana* rills), a community of relatively oligotrophic conditions often found amongst blanket mire and wet heath particularly in south-west England, is both nationally rare and likely to be affected by nitrogen deposition with average grid cell deposition of 22.38 kg N ha^{-1} yr^{-1} and critical load exceeded for all grid square records in the NVC dataset. Nationally, blanket bog communities are likely to be most impacted as they cover large areas, are widely present in high-deposition locations, and have a low critical load (5–10 kg N ha^{-1} yr^{-1}). It is clear that the exposure of peatlands to N deposition is considerable with at least the potential for ecosystem degradation due to nitrogen deposition in much of the national resource. Peatland scientists and conservation managers should be aware of this threat.

ACKNOWLEDGEMENTS

This paper is based on the extensive deposition modelling carried out by the Centre for Ecology and Hydrology (CEH) and vegetation survey and compilation co-ordinated by JNCC and its predecessor organisations. The author would like to thank all involved in producing the datasets used here and particularly Tony Dore of CEH for providing the DEFRA projection data.

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Submitted 22 Feb 2014, revision 16 May 2014
Editor: Olivia Bragg

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