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Nitrogen deposition and exceedance of critical loads for nutrient nitrogen in Irish grasslands

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HIGHLIGHTS

- Nitrogen deposition in Irish semi-natural grasslands ranged from 2 to 22 kg N ha^{-1}.
- Reduced N (primarily NH_3) represented the dominant form of N deposition.
- ~35% (~2311 km^2) of acid grasslands exceeded the critical load of 15 kg ha^{-1}.
- Only ~9% (~35 km^2) of calcareous grasslands exceeded the critical load of 15 kg ha^{-1}.
- ~15% (~75 km^2) of Natura2000 grasslands exceeded the set critical load of 15 kg ha^{-1}.

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ABSTRACT

High resolution nitrogen (N) deposition maps were developed to assess the exceedance of empirical critical loads of nutrient N for grasslands in Ireland. Nitrogen emissions have remained relatively constant during the past 20 yrs and are projected to remain constant under current legislation. Total N deposition (estimated as wet nitrate [NO_3^-] and ammonium [NH_4^+] plus dry $NO_\times$ and NH_3) ranged from 2 to 22 kg N ha^{-1} yr^{-1} (mean = 12 kg N ha^{-1} yr^{-1}) to grasslands. Empirical critical loads for nutrient N were set at 15 kg N ha^{-1} yr^{-1} for both acid and calcareous grasslands; exceedance was observed for ~35% (~2311 km^2) of mapped acid grasslands. In contrast, only ~9% of calcareous grasslands (~35 km^2) received N deposition in excess of the critical load. Reduced N deposition (primarily dry NH_3) represented the dominant form to grasslands (range 55–90%) owing to significant emissions associated with livestock (primarily cattle). The extent of exceedance in acid grasslands suggests that N deposition to this habitat type may lead to adverse impacts such as a decline in plant species diversity and soil acidification. Further, given that elevated N deposition was dominated by NH_3 associated with agricultural emissions rather than long-range transboundary sources, future improvements in air quality need to be driven by national policies.

1. Introduction

During the last century and a half, intensive agriculture and fossil fuel combustion have drastically changed global emissions of reactive nitrogen (Nr), leading to chronic elevated nitrogen (N) deposition (Dalton and Brand-Hardy, 2003; Galloway et al., 2003, 2008). Global emissions of total oxidised and reduced N (NO_y and $NH_\times$) have increased from ~34 Tg N yr^{-1} in 1860 to ~100 Tg N yr^{-1} in 1995 and are projected to double by 2050 (Galloway et al., 2004, 2008). Under natural conditions, Nr species (i.e., nitrate [NO_3^-], nitric acid [HNO_3], nitrogen oxides [$NO_\times$], ammonia [NH_3]) represent only a small portion of the atmosphere and biosphere (Bobbink et al., 2010; Galloway et al., 2003; Sutton et al., 2009); however, owing to increases in anthropogenic emissions, increases in Nr deposition have been observed (Galloway, 1998) with the highest deposition in agricultural and developed regions of North America, Europe and Asia (Dentener et al., 2006).

Nitrogen is an essential nutrient in terrestrial ecosystems and typically a limiting nutrient for plant growth (Bobbink et al., 1998). Excess Nr from atmospheric deposition to terrestrial ecosystems has led to changes in plant species composition, eutrophication and soil acidification (Bobbink et al., 2010; Horswill et al., 2008; Maskell et al., 2010; Stevens et al., 2004). Critical loads have been developed to protect ecosystems from adverse impacts of atmospheric pollution, defined as “a quantitative estimate of an 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” (Nilsson and Grennfelt, 1988). Two approaches have been predominantly used to determine critical loads: empirical and steady state mass-balance models (Hornung et al., 1995; UBA, Umweltbundesamt, 2004). The empirical approach sets thresholds at which no harmful effects occur across a range of habitats based on observed experimental

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N addition trials and transect studies (Bobbink and Hettelingh, 2011). The approach provides a first stage screening of the potential areas of concern for terrestrial habitats and has been widely applied to determine the spatial distribution and magnitude of critical load exceedance given the modest data requirements, i.e., receptor ecosystem habitat maps and N deposition (Aherne and Farrell, 2000; Bleeker et al., 2011; Fenn et al., 2010; Phoenix et al., 2006).

To protect valuable habitat across the European Union (EU), the Natura2000 directive was developed obliging member countries to protect and restore habitat function/health and to protect species that are threatened (Hicks et al., 2011). The directive established protected habitats by combining areas from the Birds Directive (79/409/EEC; Special Protection Areas [SPAs]) and the Habitat Directive (92/43/EEC; Special Areas of Conservation [SACs]). Although this directive was developed to protect habitat function and biological diversity, it does not specifically include impacts caused from chronic elevated Nr deposition (Hicks et al., 2011).

The objective of this study was to assess the spatial extent of N deposition in Ireland and to determine the extent and magnitude of exceedance of critical load for nutrient N in Irish grasslands and Natura2000 protected grasslands. Despite receiving 'clean rain' from the dominant westerly Atlantic airflow, there are considerable national sources of N emissions, mainly from agriculture, transportation and industrial activities. The long-term trends (1991–2010) in national N emissions ($NO_\times$ and NH_3), and wet deposition (NO_3^- and NH_4^+) at two monitoring stations (Lough Navar and Valentia Observatory) were evaluated using the Mann–Kendall test. Critical load exceedance was evaluated using high resolution total N deposition and mapped receptor ecosystem grassland habitats. Nitrogen deposition was estimated from observed wet, gaseous and modelled N deposition to semi-natural vegetation, and receptor ecosystem habitats were spatially defined using digital databases on land cover, soils and plant species. The ultimate goal of this study was to evaluate if N deposition levels have the potential to impact grassland structure and function.

2. Methods

2.1. Natural and semi-natural grasslands

Grassland habitat represents the dominant ecosystem type in Ireland (>60% coverage), spatially distributed throughout the country; however, the majority is composed of improved grasslands (typically improved using fertiliser O'Neill et al., 2010). In the current study, the spatial extent of natural and semi-natural (unimproved) grassland habitat (i.e., the receptor ecosystem hereafter referred to as 'grassland' excluding improved grassland) was defined using land cover (CORINE 2000 and 2006 [URL: www.eea.europa.eu]), soils and sub-soils (Indicative Soils, Teagasc-EPA [URL: www.teasgasc.ie]) and the 2007 National Forest Inventory (Forest07, Department of Agriculture, Food and the Marine [URL: www.agriculture.gov.ie]) digital databases. All maps were projected in the Irish National Grid coordinate system (OSI, 1996). Grassland habitat was spatially defined using a map overlay procedure; initially unimproved pastures were selected from CORINE 2000 (Level 4 [2312]) and areas not classified as pasture under CORINE 2006 (Level 3 [231]) were removed (note: Level 4 classification was only available for CORINE 2000). Further, natural grassland from CORINE 2006 (Level 3 [321]) was added to the coverage. Grasslands were categorised as basic or acid based on the Teagasc sub-soil map. To ensure consistency between spatial data layers, areas classified as water, urban or forest under all spatial databases were removed. Grasslands overlying subsoils that could not be classified as basic or acid were also removed (Fealy et al., 2009). Finally, the National Biodiversity Network Gateway vascular plant database (URL: www.data.nbn.org.uk) was used to identify regions where plant species indicative of acid (i.e., *Potentilla erecta*, *Rumex acetosella*) and calcareous (i.e., *Plantago lanceolata*, *Carex flacca*) grasslands were recorded on a 10 km × 10 km grid across Ireland (see Supporting Information for complete species list). Areas (grids) with a species richness <40% for acid or calcareous grassland identifier species were removed (resulting in a chess-board appearance).

Protected habitats defined under Natura2000 represent ~13% of the total land cover in Ireland (EC, 2012). In the current study, mapped grasslands associated with protected areas were defined by overlaying the (receptor ecosystem) grassland habitat map with the Natura2000 sites (European Environmental Agency [URL: www.eea.europa.eu]); areas that overlapped were considered protected under the Natura2000 directive (Fig. 1).

2.2. Long-term trends in emissions and deposition of nitrogen

Long-term national emission data for $NO_\times$ and NH_3 during the period 1991–2010 was obtained from the Irish Environmental Protection Agency (EPA, 2011, 2012). Long-term (1991–2009) annual precipitation chemistry data for NH_4^+ and NO_3^- and rainfall volume (based on daily observations) for monitoring stations at Lough Navar (operated by the Department of Agriculture for Northern Ireland [daily observations until 1999, fortnightly since 2001]) and Valentia Observatory (operated by Met Éireann, The Irish Meteorological Service) were obtained from EMEP (Cooperative Programme for Monitoring and Evaluation of Long-range Transmission for Air Pollutants in Europe: Chemical Co-ordinating Centre [URL: www.nilu.no/projects/ccc]). Lough Navar and Valentia Observatory were the only monitoring stations operating continuously during the period 1991–2009. The long-term monotonic trend in emissions ($NO_\times$ and NH_3) and wet deposition (NH_4^+ and NO_3^-) was assessed using the non-parametric Mann–Kendall test (Salmi et al., 2002; MAKESENS), which has been widely used to detect trends in precipitation chemistry (Anttila and Tuovinen, 2010; Fagerli and Aas, 2008; Zbieranowski and Aherne, 2011). The long-term trends in $NO_\times$ and NH_3 air concentrations were not evaluated owing to limited data. However, current average annual concentrations

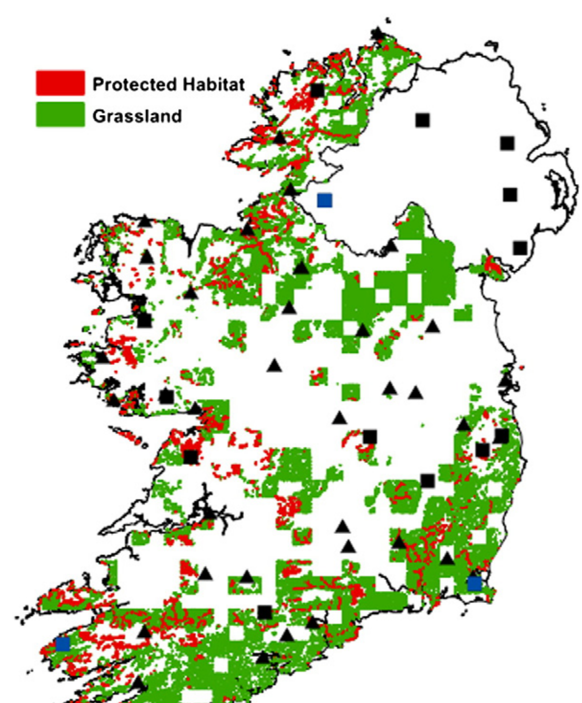

Fig. 1. Spatial distribution of grasslands and protected habitats in Ireland. The location of precipitation-chemistry monitoring stations (filled squares; n = 16) for nitrate and ammonium, and atmospheric ammonia monitoring sites (filled triangle; n = 40) are shown. The monitoring stations, Johnstown Castle, Valentia Observatory and Lough Navar are identified by a filled blue square.