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Vegetation community change points suggest that critical loads of nutrient nitrogen may be too high

Kayla Wilkins [a,*], Julian Aherne [a], Andy Bleasdale [b]

[a] School of the Environment, Trent University, Peterborough, Ontario, K9J 7B8, Canada
[b] National Park and Wildlife Service, Department of Arts, Heritage and the Gaeltacht, Custom House, Galway, Ireland

HIGHLIGHTS

- Threshold Analysis was used to assess habitat change along a nitrogen deposition gradient.
- Twelve Annex I habitats showed a decrease in species abundance under nitrogen deposition.
- Vegetation community change points were lower than recommended critical load ranges.
- Synergies between the European Union's Habitat and Emissions Directives should be developed.

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ABSTRACT

It is widely accepted that elevated nitrogen deposition can have detrimental effects on semi-natural ecosystems, including changes to plant diversity. Empirical critical loads of nutrient nitrogen have been recommended to protect many sensitive European habitats from significant harmful effects. In this study, we used Threshold Indicator Taxa Analysis (TITAN) to investigate shifts in vegetation communities along an atmospheric nitrogen deposition gradient for twenty-two semi-natural habitat types (as described under Annex I of the European Union Habitats Directive) in Ireland. Significant changes in vegetation community, i.e., change points, were determined for twelve habitats, with seven habitats showing a decrease in the number of positive indicator species. Community-level change points indicated a decrease in species abundance along a nitrogen deposition gradient ranging from 3.9 to 15.3 kg N ha^{-1} yr^{-1}, which were significantly lower than recommended critical loads (Wilcoxon signed-rank test; $V = 6$, $p < 0.05$). These results suggest that lower critical loads of empirical nutrient nitrogen deposition may be required to protect many European habitats. Changes to vegetation communities may mean a loss of sensitive indicator species and potentially rare species in these habitats, highlighting how emission reductions policies set under the National Emissions Ceilings Directive may be directly linked to meeting the goal set out under the European Union's Biodiversity Strategy of "halting the loss of biodiversity" across Europe by 2020.

1. Introduction

Elevated atmospheric nitrogen (N) has progressively gained attention as a prevailing environmental stressor across Europe, with agricultural ammonia (NH_3) emissions identified as the key driver of environmental impacts (EC, 2015a). Nitrogen emissions from anthropogenic sources to the atmosphere, including industrial nitrogen oxide (NO_x) and agricultural NH_3 emissions, have greatly increased during the last century and are predicted to rise further (Galloway et al., 2008). It is now widely acknowledged that elevated atmospheric N deposition can detrimentally impact natural and semi-natural terrestrial ecosystems (Bobbink et al., 1998, 2010; Pereira et al., 2012; Phoenix et al., 2012) and is thought to be one of the leading drivers of global biodiversity loss (Sala et al., 2000).

Elevated N deposition can affect soil-mediated processes in terrestrial ecosystems such as acidification (Bowman et al., 2008;

Abbreviations: EMEP, European Monitoring and Evaluation Programme; EU, European Union; EUNIS, European Nature Information System; N, nitrogen; NPWS, Irish National Parks and Wildlife Service; TITAN, Threshold Indicator Taxa Analysis; UNECE, United Nations Economic Commission for Europe.

* Corresponding author.
E-mail address: kaylawilkins@trentu.ca (K. Wilkins).

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Lieb et al., 2011) and eutrophication (Horswill, 2008; Mansson and Falkengren-Grerup, 2003; Nilsson et al., 2006), which can result in plant community changes. Biodiversity loss related to N deposition has been predominantly observed as a decrease in species richness in both experimental (Clark and Tilman, 2008; Mountford et al., 1993) and gradient (Maskell et al., 2010; Stevens et al., 2010) studies, with more recent studies focusing on changes in the abundance of individual species along a N deposition gradient (Henrys et al., 2011; Payne et al., 2013). In general, most studies to date have focused on the effects of elevated N deposition on one particular habitat type, typically grasslands (Bai et al., 2010; Carroll et al., 2003; Gaudnik, 2011), heathlands (Caporn et al., 2014; Meyer-Grünefeldt et al., 2015; Van den Berg et al., 2008) or forests (Brunet et al., 1998; De Schrijver et al., 1998; Hurd et al., 1998).

The European Commission's commitment to halting biodiversity loss across Europe by 2020, under the European Union's (EU) Biodiversity Strategy, relies heavily on the nature legislation set out in the Habitats Directive, which is aimed at conserving rare animals, plants, and habitats (EC, 2015b). Annex I of the Habitats Directive provides a list of habitats of high conservation importance and community interest, which are in danger of disappearing within their natural range (EU Habitats Directive, 1992). Atmospheric N deposition is a potential threat to many Annex I habitats; nonetheless, the effects of elevated N deposition have not been widely explored at the Annex I habitat level, with some exceptions (Van Dobben et al., 2013). Assessing the risk of elevated N deposition to Annex I habitats, including the determination of N deposition thresholds, is essential for protecting these habitats and meeting the objectives of the Biodiversity Strategy and Habitats Directive.

The critical load approach is widely used across Europe to connect atmospheric environmental stressors with emissions policy development (De Vries et al., 2015). A critical load is 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); critical loads are generally derived from steady-state mass-balance models or based on empirical observations (CLRTAP, 2004). Critical loads have been recommended for nutrient N (i.e., reduced and oxidised N deposition leading to eutrophication) for a number of European Nature Information System (EUNIS) habitat types (Bobbink and Hettelingh, 2011), which can be correlated with Annex I habitats. These critical loads are generally given as a range (e.g., Sub-Atlantic semi-dry calcareous grasslands, EUNIS code E1.26, critical load range: 5–10 kg N ha^{-1} yr^{-1}) to account for variation in environmental properties (e.g., wet to dry soils, or range in precipitation) within a given habitat type, and methodological uncertainty (e.g., use of discrete deposition intervals in addition experiments). Critical loads for nutrient N have been primarily set to protect habitats from loss of biodiversity.

The objective of this study was to compare shifts in vegetation communities along a N deposition gradient to the recommended empirical critical loads of nutrient N for a number of Annex I habitats. Plant species abundance was compared with mapped total N deposition (wet ammonium (NH_4^+) and nitrate (NO_3^-) plus dry NH_3 and NO_x) for twenty-two Annex I habitats using Threshold Indicator Taxa ANalysis (TITAN; Baker and King, 2010). TITAN identifies individual taxa that significantly change in abundance along an environmental gradient, and identifies the point along the gradient at which the most significant change occurs. Further, TITAN estimates the point along the gradient at which the most significant community-level change occurs, i.e., where there is a convergence of individual taxa change points. In the current study, community-level change points for each Annex I habitat were compared to their recommended critical load range to determine whether the critical load protected the habitat from shifts in vegetation community composition. The relationship between community change points and 'significant harmful effects' as defined by critical loads, was evaluated by assessing the ecological importance of species with significant change points; specifically, it was assumed that a decrease in abundance of positive (habitat) indicator species suggested a 'significant harmful effect'. All species abundance data were obtained from plant relevé plots located in Ireland, where recent estimates of reactive N deposition (Henry and Aherne, 2014) suggest that the deposition gradient spanned the current recommended critical load ranges for the study habitats.

2. Methods

2.1. Data sources

Long-term (1991–2010) total N deposition (wet NH_4^+ and NO_3^- plus dry NH_3 and NO_x) was obtained from Henry and Aherne (2014) on a 5 km × 5 km grid. Vegetation with a rough surface has a greater ability to scavenge dry deposition components, as such habitat type influences total deposition, i.e., dry deposition to a native woodland will be higher compared with a peatland under the same atmospheric concentration owing to the greater surface roughness of woodland vegetation. Dry deposition of NH_3 (the largest component of total N deposition in Ireland; Henry and Aherne, 2014) was determined by habitat type using habitat-specific deposition velocities (Table 1); further, vegetation-specific dry deposition for oxidised N was obtained from the EMEP model (URL: www.emep.int). Three deposition velocities for NH_3 were assigned by broad habitat type in this study: 1.0 cm s^{-1} (grasslands and peatlands), 1.5 cm s^{-1} (heathlands), and 2.0 cm s^{-1} (native woodlands) following De Kluizenaar and Farrell (2011), and consistent with Staelens et al. (2012).

Vegetation survey data (species abundances) were obtained from the Irish National Parks and Wildlife Service (NPWS). Relevé data were obtained from several surveys and grouped by Annex I classification. The assigned relevés were further refined to better represent uniform vegetation communities for each habitat, e.g., only relevés with an altitude greater than 150 m were included in habitat 7130 (upland) blanket bog, and similarly only relevés on acid parent material were included in 6230 (non-calcareous) species-rich *Nardus* upland grassland (see Table 1). However, no refinements were applied to habitat 5130 (which is composed of five vegetation communities) owing to the limited number of relevés (per vegetation community). The dominant vegetation community for 5130 was dry siliceous heath and raised bog (*Calluna vulgaris–Erica cinerea*), as such all subsequent analysis assumed all relevés were from this community. The number of relevés per habitat ranged from 12 to 507, and the number of plant species per habitat ranged from 15 to 275 (Table 1). The NPWS also provided a list of positive and negative indicator species for each Annex 1 habitat; for grassland habitats the list of species was further delineated into high quality and general indicator species. In general, the assessment of conservation status includes a presence-absence check list of positive indicator species for each habitat, with the identification (presence) of a specific number of species as one criterion for good status. In contrast, negative indicators for each Annex 1 habitat were provided as a list (group) of species under an areal coverage. As such, the current study focused primary on changes in positive indicator species; a habitat was assumed to show potentially 'significant harmful effects' under N deposition if the number of positive indicator species with a significant decrease in abundance was greater than the number with increasing abundance. However, where available the presence of specific negative