Science of the Total Environment 541 (2016) 319–328

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Critical loads and nitrogen availability under deposition and harvest scenarios for conifer forests in Ireland

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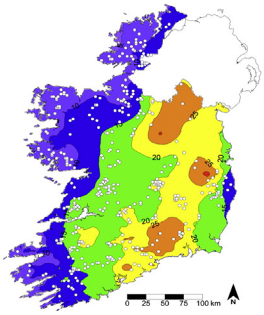
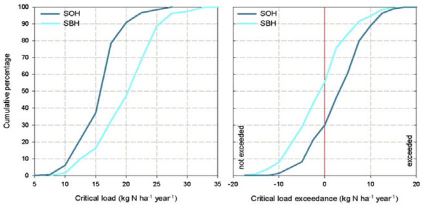
HIGHLIGHTS

- Critical loads were calculated for stem-only (SOH) and stem branch harvest (SBH)
- Critical loads were 15.3 and 19.5 kg N ha^{-1} year^{-1} under SOH and SBH respectively
- Critical loads were exceeded at 67% of sites under SOH and 40% under SBH
- Most forest monitoring sites had low to intermediate nitrogen (N) status
- N availability depends on harvest intensity, deposition and soil characteristics

GRAPHICAL ABSTRACT





Mapped nitrogen deposition at forest plots (left) and cumulative frequency distributions of critical loads and exceedance (above) under stem only (SOH) and stem branch harvest (SBH).

ARTICLE INFO

Article history:
Received 18 May 2015
Received in revised form 28 August 2015
Accepted 28 August 2015
Available online xxxx

Editor: J.P. Bennett

Keywords:
Sitka spruce
Soil
Nutrients
Forest floor C:N
Harvest residue
Monitoring
Ammonia
Air pollution

ABSTRACT

In this study we calculated the critical load of nutrient nitrogen (N) for Irish forest plots (n = 380) under two harvesting scenarios: conventional stem-only harvest (SOH) and stem plus branch harvest (SBH) and two deposition scenarios: current and with a 10% increase in reduced-N. In addition, current N status was assessed using the following data from forest monitoring plots: forest floor C:N, foliar N and plant root simulation (PRS™) probe N supply rate. Average critical loads were 15.3 kg N ha^{-1} year^{-1} under SOH and 19.5 kg N ha^{-1} year^{-1} under SBH. Average total (wet + dry) N deposition was 18 kg N ha^{-1} year^{-1}, ranging from 8.6 to 26 kg N ha^{-1} year^{-1}. As a result, critical loads were exceeded at 67% of sites under SOH and 40% of sites under SBH. However, there was little evidence of exceedance at monitored plots. Foliar and forest floor C:N data indicated that most of these sites had low to intermediate N status. There were considerable differences in N cycling between soil types. Plant root simulation (PRS™) probe data indicated that this was likely due to differences in net N-mineralization and nitrification. Our results indicate that many sites are currently N limited but critical load exceedance suggests that these systems will accumulate N over time. The findings have implications for forest management, allowing for the assessment of nutrient management under different harvest scenarios.

1. Introduction

Since the mid-19th century human activities such as animal production, nitrogen (N) fertilizer application and fossil fuel combustion have greatly increased emissions of trace N gases including nitric oxides (NO), and ammonia (NH_3) to the atmosphere (Galloway et al., 2004) such that deposition of bioavailable N has increased threefold globally during the period 1860 to early 1990s (Vitousek et al., 1997). In many areas, N deposition is not only an important source of bioavailable N but is the dominant source (Gruber and Galloway, 2008) and is projected to increase in many regions by 2100 (Lamarque et al., 2005).

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http://dx.doi.org/10.1016/j.scitotenv.2015.08.140

The deposition of reactive N can have a number of important ecological effects on terrestrial ecosystems including changes to plant communities (Fenn et al., 2003; Bobbink et al., 2010); tree nutrition (Crowley et al., 2012; Ferretti et al., 2014; Jonard et al., 2015); growth and carbon sequestration (de Vries et al., 2006; Thomas et al., 2010; Ferretti et al., 2014) and decomposition (Janssens et al., 2010). Forests generally retain the majority of N deposition; however, in areas with continued high (>10 kg N ha^{-1} $year^{-1}$) deposition the occurrence of nitrate (NO_3^-) leaching suggests that the retention capacity of these ecosystems has been exceeded—or saturated (Aber et al., 2003; Gundersen et al., 2006; van der Salm et al., 2007; Dise et al., 2009).

The critical load is an effects-based measure, which has been widely adopted to protect ecosystems from the effects of atmospheric deposition (Hettelingh et al., 2001). It is defined as the level of deposition, below which sensitive elements of the ecosystem are not impacted according to present knowledge (Nilsson and Greenfelt, 1988). The critical load can be calculated empirically, through observed changes in ecosystems e.g. plant diversity (Bobbink and Hettelingh, 2011), or using a steady state approach, by defining a chemical criterion e.g. N concentration in soil solution, and calculating the deposition for which that criterion is not exceeded (Posch, 2004).

In Ireland, total N (wet + dry) deposition in the range 2–20 kg N ha^{-1} $year^{-1}$ has been estimated for semi-natural grasslands, exceeding critical loads in many areas (Henry and Aherne, 2014). Deposition is primarily driven by emissions of ammonia (NH_3); reduced-N (NH_3 and NH_4^+) make up 55–90% of total N deposition (EPA, 2014; Henry and Aherne, 2014). These emissions are driven by agricultural sources and have remained virtually unchanged during the period 1990 to 2012 (EPA, 2012). Furthermore, NH_3 emissions are expected to increase by 5 to 10% from current levels with increases in agricultural output (EPA, 2012). In contrast, deposition of oxidized N has also remained unchanged over the period 1991 to 2010 (Henry and Aherne, 2014), although domestic NO_x emissions have declined since 2008 (EPA, 2014).

The area of forest cover in Ireland has expanded rapidly in recent decades; currently forests cover 11% of the land area, up from 1% at the start of the twentieth century (Forest Service, 2013). This has been achieved through rapid expansion of state-supported forest plantations since the 1950's. Initially government policy was to afforest areas considered unsuitable for agriculture and as a result, large areas of planting occurred on wet, nutrient poor soils in areas exposed to wind, including peatlands in the west of the country. With the introduction of subsidies to landowners in the 1980's and 1990's planting expanded to include a wider range of sites including more fertile mineral soils (Farrelly et al., 2009). Plantations consist primarily of fast-growing conifers (>70%). Sitka spruce (*Picea sitchensis* (Bong.) Carr) is the main species, accounting for more than 50% of forest area, followed by provenances of lodgepole pine (*Pinus contorta*) (almost 10%) (Forest Service, 2007). These species grow rapidly in Ireland's mild temperate climate and as a result, rotation lengths in plantations are generally less than 50 years (Forest Service, 2013). In addition inputs of base cations, mainly through deposition, are sufficient to support uptake (Johnson et al., 2015). To date, forest harvesting has consisted of stem-only removal with logging residues left on site; however, this material is being examined as a potential source of biomass for energy production and may be removed in future (Anon, 2007).

Monitoring of N deposition and soil water indicates a contrasting picture of the magnitude and impact of N deposition on forests in Ireland. In the west of Ireland, N deposition is low and forests located on blanket peats in this area are commonly P-, and sometimes N-limited with very low N availability (Farrell, 1990; Byrne and Farrell, 1998). In contrast, incidences of NO_3^- leaching have been observed at forest plots in the east and south of the country receiving high deposition (Farrell et al., 2001; Huber et al., 2010).

The objective of this paper was to determine, whether N deposition to conifer forests in Ireland exceeds their N sinks such that elevated NO_3^- leaching may occur. Critical loads were calculated for two harvest scenarios: stem-only harvest (SOH) and stem plus branch harvest (SBH), and two scenarios of N deposition: current deposition and a future scenario with a 10% increase in reduced-N deposition. In addition we used monitoring data to assess the current N status of forests plots and to determine how quickly they are likely to respond to excess N deposition in future. The results provide an assessment of the potential impacts of N deposition, factors influencing N availability in these systems and implications of harvest intensity on N availability under current and projected deposition scenarios.

2. Methods

2.1. Critical load calculation

Critical loads of nutrient N, ($CL_{nut}N$), were calculated for 380 forest plots that were part of the 2012 National Forest Inventory (Forest Service, 2013) (Fig. 1). The NFI network consisted of 1827 inventory plots randomly selected from a systematic grid sample design based on a 2 km × 2 km grid across the country. We included plots only containing Sitka spruce (*P. sitchensis* (Bong.) Carr) or lodgepole pine (*P. contorta* (Dougl. var. *latifolia*)), as these are the most important commercial tree species in Ireland and limited the study to pure stands of these species, to facilitate calculation of volume increment.

The critical load calculation is based on the steady-state mass balance of input and output N fluxes as follows (Hettelingh et al., 1995; Posch, 2004):

$$N_{dep} + N_{fix} = N_{upt} + N_{imm} + N_{ads} + N_{denit} + N_{vol} + N_{fire} + N_{le} \quad (1)$$

where:

N_{dep} total N deposition
N_{fix} biological N fixation

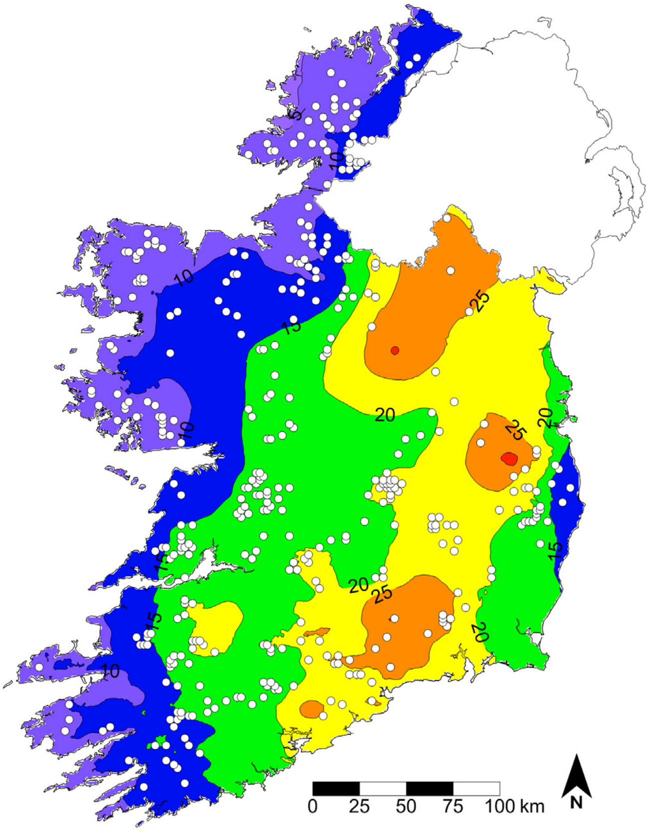

Fig. 1. Location of national forest inventory (NFI) plots in Ireland at which critical loads were calculated. Contours indicate total (wet + dry) nitrogen deposition (kg N ha^{-1} $year^{-1}$).