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Metrics for evaluating the ecological benefits of decreased nitrogen deposition

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ABSTRACT

Atmospheric pollution by reactive nitrogen (N) can have profound effects on ecosystem functioning and biodiversity. Numerous mechanisms are involved, and response times vary among habitats and species. This complex picture can make it difficult to convey the benefits of controlling N pollution to policy developers and the public. In this study we evaluate pressure, midpoint, and endpoint metrics for N pollution, considering those currently in use and proposing some improved metrics. Pressure metrics that use the concept of a critical load (CL) are useful, and we propose a new integrated measure of cumulative exposure above the CL that allows for different response times in different habitats. Biodiversity endpoint metrics depend greatly on societal values and priorities and so are inevitably somewhat subjective. Species richness is readily understood, but biodiversity metrics based on habitat suitability for particular taxa may better reflect the priorities of nature conservation specialists. Midpoint metrics indicate progress towards desired endpoints – the most promising are those based on empirical evidence. Moss tissue N enrichment is responsive to lower N deposition rates, and we propose a new Moss Enrichment Index (MEI) based on species-specific ranges of tissue N content. At higher N deposition rates, mineral N leaching is an appropriate midpoint indicator. Biogeochemical models can also be used to derive midpoint metrics which illustrate the large variation in potential response times among ecosystem components. Metrics have an important role in encouraging progress towards reducing pollution, and need to be chosen accordingly.

1. Introduction

Atmospheric pollution by reactive nitrogen (N) is a global threat to biodiversity (Bobbink et al., 2010; Pardo et al., 2011; Phoenix et al., 2006; Sala et al., 2000) and is driving major changes in semi-natural habitats (e.g. Clark et al., 2013; Hauck et al., 2013; Song et al., 2012; Stevens et al., 2011a). Nitrogen availability often constrains plant growth (Elser et al., 2007), and although alleviating N limitation is of critical importance in agricultural systems (Ladha et al., 2005; Vanlauwe and Giller, 2006), the consequences of increased N deposition in more natural systems can be profound. Impacts can also be long-lasting because of N retention and recycling within the ecosystem, and because of depletion of seed banks (Basto et al., 2015) and delayed recolonisation. Efforts to decrease atmospheric N pollution need to be supported by an understanding among scientists and policymakers of the effects of present-day and historic emissions on ecosystems. Metrics have an important role in communicating the effects of policy decisions. We assessed current metrics used to represent benefits of decreases in N deposition, and propose new metrics to better represent nitrogen pressure and responses.

Many types of observations have been proposed as indicators of N pollution, such as plant tissue N concentration, litter C/N ratio, or plant species richness, but these are sometimes difficult to measure, not consistently related to the degree of pollution by N, or affected not only by N pollution but by management change and other drivers. A complicating factor is that N pollution is beneficial in some respects, not only as 'free' fertiliser for farmers and foresters but by increasing the fixation and storage of carbon (C) in woodlands, at rates estimated at 15–40 kg C kg^{-1} N (de Vries and Posch, 2011). However, untargeted applications of N are inefficient and have unintended consequences. Overall assessments also need to take into account the major impacts of atmospheric

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N pollution on human health and on tropospheric ozone formation, but here we focus on metrics suitable for assessing the direct impacts of N on ecosystems. Metrics can:

a) represent the *pressure*, defined as "physical expression of human activities that could change the status of the environment in space and time" (EEA, 2015), on the ecosystem;
b) illustrate achievement of a desired *endpoint*, i.e. an aspect of the environment that is directly important and relevant to people. Examples are metrics that can be directly related to favourable conservation status, or that indicate attainment or failure of a water quality target; and
c) be seen as *midpoints* or "links in the cause-effect chain" (Bare et al., 2000) that represent progress towards or away from a desired endpoint, e.g. chemical conditions that make it likely that this endpoint will be achieved in future, or reductions in the abundance of a species that point to eventual local extinction.

The terms do not necessarily relate to the timescale of change, and 'midpoint' does not mean progress half-way towards a goal. The same metric may have a different role in relation to different targets – for example, the concentration of nitrate (NO_3^-) in soil leachate is an endpoint metric for water quality since it is "of direct relevance to society's understanding of the final effect" (Bare et al., 2000), but a midpoint indicator for biodiversity since it indicates progress towards changes in biological diversity.

Nitrogen affects terrestrial vegetation through direct toxic effects (especially on lichens and bryophytes), by increasing the growth of tall, fast-growing plants at the expense of shorter-growing and stress-tolerant species, and by the acidifying effect of nitrate leaching (Jones et al., 2014). Most evidence for biodiversity impacts is from studies on plants, although other taxa are affected via impacts on plants (Feest et al., 2014), in particular animals that require open microsites that may be shaded by increased vascular plant growth (Wallis de Vries and Van Swaay, 2006). Changes in plant tissue stoichiometry may also affect invertebrate herbivores directly (Vogels et al., 2013). Sensitive species can decline at very low absolute N deposition rates (Payne et al., 2013; Stevens et al., 2011c), or very low absolute ammonia (NH_3) concentrations (Cape et al., 2009). The form of N pollution can alter impacts on habitats, although whether it is oxidised or reduced N that is more damaging seems to be habitat-specific (van den Berg et al., 2016). Experiments on the effect of N form may have been influenced by effects on soil pH of the added counterion, and in any case the ratio of reduced to oxidised N in the soil environment is mainly determined by soil conditions and may differ greatly from the ratio in deposited N (Stevens et al., 2011b). Given these considerations, it seems adequate to consider total N flux as an indicator of N pollution pressure rather than NO_x and NH_y fluxes separately (RoTAP, 2012). By contrast, gaseous ammonia is phyto-toxic at much lower concentrations than nitrogen oxides and so needs to be considered separately. Nitrogen oxides also have an important role in the formation of ground-level ozone, harmful effects of which are reviewed elsewhere (e.g. Mills et al., 2016).

Air pollution policy makes extensive use of the concept of 'critical load' (CL), 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 Load values for N have been defined on the basis of contribution to the acidity balance or of acceptable loss and immobilisation fluxes (Spranger et al., 2004). Another approach is to determine the CL using experimental and survey evidence regarding the N deposition rates at which biogeochemical or ecological changes begin to occur in different habitats, resulting in 'empirical' values (CL_{empN}) (Bobbink and Hettelingh, 2011). The CL framework has been highly effective in driving reductions in sulphur pollution (Amann et al., 2011; Hordijk, 1991) and remains widely used in policy development.

Effects of N on ecosystems may be delayed by chemical buffering, and by delays in biological responses to the changed environment (Fig. 1). As N deposition rate increases, declines in pH may be buffered by cation exchange or mineral weathering; and available N concentrations in soil solution may be buffered by increased immobilisation or by plant uptake. Plant nutrient uptake is a critical process in ecosystems, and biological responses may occur before discernable change in soil solution N concentration. Nevertheless, there are likely to be delays in biological responses to such chemical effects as changes in tissue stoichiometry. Organisms may persist for a time even in unfavourable environments. Conversely, organisms are often unable to immediately colonise a site where the environment has become more favourable, particularly where the species has become extinct in the locality. Limited or no recovery from N pollution has been observed in several studies

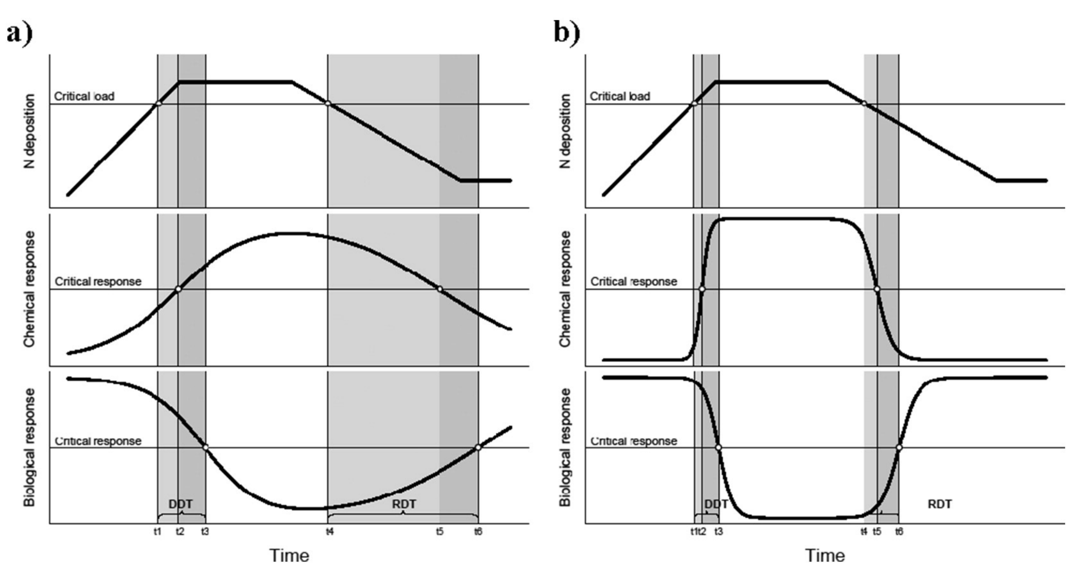

Fig. 1. Delayed effects of changes in N deposition on a chemical indicator and a biological indicator in: a) a strongly-buffered ecosystem, and b) an ecosystem with limited buffering capacity. Deposition above the critical load causes a chemical response, for example in conditions in the soil solution, to exceed a critical level after time ($t_2 - t_1$). The biological response to these conditions is further delayed, and only becomes critical after time ($t_3 - t_1$), called the Damage Delay Time (DDT). Biological recovery after deposition declines below the critical load will similarly be delayed, by the Recovery Delay Time (RDT).
(Adapted from Posch et al., 2004)

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