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Impacts of nitrogen and sulphur deposition on forest ecosystem services in Canada

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Canada's forests provide a range of ecosystem services that are vital to human health such as purifying water, stabilizing soil and nutrient cycles, and providing habitat for wildlife rich in biological diversity. The potential impacts of nitrogen and sulphur deposition on ecosystem services provided by Canadian forests were assessed using the concept of critical loads, a well-established scientific effects-based approach for assessing the environmental consequences of air pollution at large regional or national scales. Exceedance of critical load, that is, deposition in excess of critical load, suggests that provisioning, regulating and supporting ecosystem services of Canadian forests (e.g. water quality, soil quality and plant species diversity) are negatively impacted by nitrogen and sulphur deposition. Under modelled 2006 total deposition, widespread exceedance was predicted for critical limits associated with long-term soil quality and plant species diversity. Given both the positive and negative impacts of atmospheric deposition, it is important to employ holistic approaches to assess how future emission reduction policies will affect the quality and quantity of ecosystem services.

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Introduction

Canada's forested and treed land covers 400 million hectares (composed of ~67% coniferous, 16% mixed wood and 11% broadleaf) extending over half of the country's total land surface, and representing 10% of the world's forest cover and 30% of the world's boreal forest (URL: www.cfs.nrcan.gc.ca). In addition to wood production, and recreational and cultural benefits, forest ecosystems provide a range of services that are vital to human health such as purifying water, stabilizing soil and nutrient cycles, moderating climate, and providing habitat for wildlife rich in biological diversity. Further, forests constitute one of the most important elements of the global carbon cycle (e.g. [1]). However, these benefits require that forest ecosystems remain healthy, stable and sustainably managed [2,3].

Since the late 1970s, the ecosystem service concept (benefits people obtain from ecosystems) has gained increasing importance as a scientific approach to sustainable management [4•,5,6]; notably, following the Millennium Ecosystem Assessment report [7], there has been a significant growth in studies and publications on the benefits of natural ecosystems to human society [8]. It is now more or less common to classify ecosystem services into four primary functions: provisioning, regulating, supporting (more recently reclassified as 'habitat' services which support almost all other services [9]), and cultural services [10,7].

Air pollution can have a significant negative impact on ecosystem functioning [11,12]; as such, there is a need to identify and determine ecosystem services that are likely to be affected. The impacts of atmospheric sulphur (S) and nitrogen (N) deposition on terrestrial and aquatic ecosystems have been widely assessed using the critical loads approach (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' [13]). Recently, there have been several studies using the critical load approach to assess the impacts of air pollutions, specifically N deposition (also in interaction with climate change) on European forests [14••,15••].

The objective of this study was to assess the potential impacts of air pollutants on ecosystem services in Canadian forests based on the concept of critical loads following de Vries *et al.* [14••]. Specifically the study assessed the impacts of N and S deposition on soil and water quality, primary production, and plant biodiversity in Canada, with additional focus on southern Ontario. Similar critical load assessments are common in Europe, but few have focused on North American forests.

Critical loads and levels of nitrogen and sulphur

In Europe the critical load approach underpins effects-based emission reduction policies for N and S species (e.g. nitrogen oxides [NO_x], ammonia [NH_3] and sulphur dioxide [SO_2]), and is the key international instrument under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP) and the EU National Emission Ceilings Directive [16]; in Canada critical loads underpin the Canada-Wide Acid Rain Strategy for Post-2000. The approach is based on setting a critical chemical limit to protect a specified (biological) indicator for a chosen receptor ecosystem or ecosystem service (e.g. fish species for surface waters (provisioning)), and via inverse modelling a deposition load (the critical load) is derived to ensure that the limit is not violated at or below that deposition, and thus 'harmful effects' avoided. Similarly critical levels have been derived to protect against the direct adverse effects of air pollutant concentrations on receptors such as plants [17•,18].

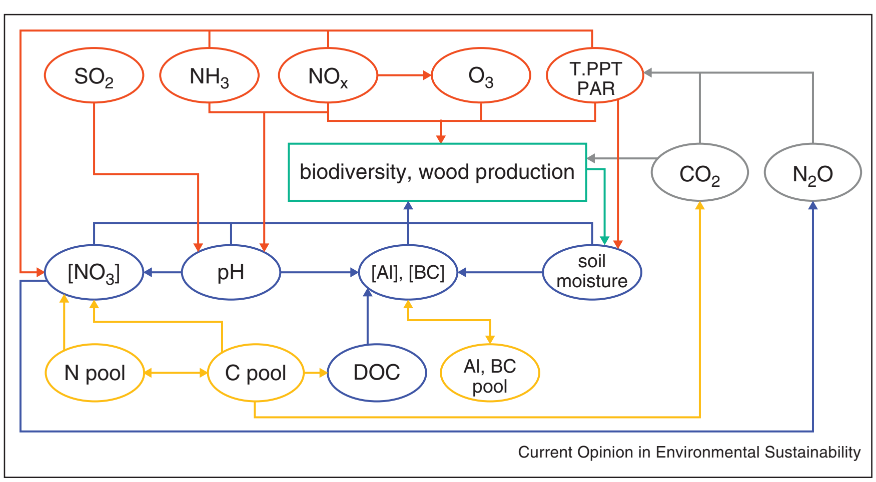
Empirical and steady-state models are predominantly used for calculating effects-based critical loads; empirical approaches set thresholds at which no harmful effects occur across a range of habitats based on observations, addition experiments and transect studies [19•], whereas steady-state models take into account the long-term sources and sinks of acidity and nutrients in deriving a critical load [17•]. Steady-state approaches can also accommodate multiple chemical criteria, for example, linked nutrient N and acidity chemical criteria to determine 'optimal' loads to protect plant species diversity [20]. The methodologies are well-established [17•] and have been widely applied [21–23].

Link between atmospheric pollution and ecosystem services

The interactions between air pollutants and ecosystem services (and also climate) are complex, acting at varying temporal and spatial scales (Figure 1). Elevated N deposition can negatively influence habitat function, reducing biological and genetic diversity for wild plants (provisioning service); in contrast, elevated N deposition can positively influence wood production (provisioning service). Further information on the impacts of atmospheric deposition on ecosystem services, including causal links, is given by de Vries *et al.* [14••,15••]. In this context, critical loads are set to protect a specified ecosystem service (e.g. provisioning, regulating, etc.), and the exceedance of the critical load (i.e. atmospheric deposition in excess of the critical load) is indicative of the magnitude and spatial extent of impacts to that ecosystem service. The level of sustainable management is intrinsically linked to the specified critical limit or threshold [24]; notably, there may still be observable impacts to ecosystem services below the chosen limit [25], especially in cases where the 'damage-function' changes gradually along the impact gradient.

In the current study, exceedance of critical loads for forest ecosystems was determined using a range of indictors (i.e. critical limits and levels) to protect against surface water eutrophication, soil acidification and loss of plant species diversity. The water quality regulating function of forest ecosystems is negatively impacted by elevated nitrate concentrations and soil acidification (leading to elevated leaching of aluminium from soils). The impact of N deposition on surface water eutrophication was assessed using a limit of 2.2 mg N L^{-1} following de Vries *et al.* [14••]. The impact of acidic (N and S) deposition on soil

Figure 1



Relationships between air quality and climate (red), biodiversity and forest growth (green), water quality (blue), soil quality (yellow) and greenhouse gas emissions (grey). Modified from de Vries *et al.* [14••]; Al = aluminium, BC = base cations, PAR = photosynthetically active radiation, PPT = precipitation.