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Review

# Effects of reactive nitrogen deposition on terrestrial and aquatic ecosystems

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ABSTRACT

Globally, acute increases in anthropogenic emissions of reactive nitrogen (Nr) have led to change of N process in terrestrial and aquatic ecosystem. Although excessive Nr deposition is known to drastically alter global N cycling, the consequences of excessive Nr deposition on N processes occurring in terrestrial and aquatic ecosystems have not been well depicted. Owing to the unique influencing effects Nr deposition have on different ecosystems, different N demands will result in different N critical loads and dynamic equilibration point. Sharp increases in anthropogenic Nr emissions lead to the direct toxicity to plant growth, long-term negative effects on increased $NH_3$ and $NH_4^+$ availability, and soil and water acidification, so the study proposes the critical value of Nr deposition health threshold for terrestrial and aquatic ecosystems. In present study, we summarize the health effect thresholds to different ecosystem type under threat of progressively increasing Nr deposition, while effective emission-control strategies can be developed for Nr deposition detrimental effects control in the near future.



## 1. Introduction

The N cycling in ecosystem is mainly derived from biological N fixation, atmospheric deposition, and mineralization. Globally, acute increases in anthropogenic emissions of reactive nitrogen (Nr) have led to enhanced terrestrial and aquatic ecosystem Nr deposition. By 1860, anthropogenic N inputs were only 16 Tg N $yr^{-1}$ (Galloway et al., 2004), while by 2005, anthropogenic N processes had reached to 210 Tg N $yr^{-1}$ (Galloway et al., 2008). The Nr includes inorganic reduced forms of N ($NH_3$ and $NH_4^+$), inorganic oxidized forms ($NO_x$, $N_2O$, $NO_3^-$ and $HNO_3$), and organic compounds. Anthropogenic Nr emissions mostly derived from agricultural and the industrial and transportation sectors have been proven to be dominant Nr deposition contributors (Galloway et al., 2008; Schlesinger, 2009; Liu et al., 2013). Human activity is greatly increasing the amount of Nr cycling that takes place between life on the planet and the soil, water bodies, and the atmosphere, and has drastically altered global ecosystem N cycling through biotic and abiotic N fixation (Vitousek et al., 1997; Clark and Tilman, 2008).

N is recognized as the preeminent limiting nutrient in plant growth for both terrestrial and aquatic ecosystems (Xia and Wan, 2008; Gao et al., 2014), and it has been found that increased emissions of atmospheric Nr deposition have led to enhanced Nr deposition on such ecosystems. Although excessive Nr deposition will generally yield negative impacts on ecosystems, Nr deposition can also be beneficial for N-limited terrestrial and aquatic ecosystems (Law, 2013). This is because Nr deposition increases atmospheric $CO_2$ uptake via photosynthesis due to the close coupled relationship between carbon (C) and N (Luo et al., 2006; Gao et al., 2012, 2013). However, excessive Nr deposition has aroused concerns related to its negative impacts on ecosystem health and services, such as loss of biodiversity, eutrophication and N saturation, soil acidification, and increased susceptibility to secondary stresses. Increased concentrations of $N_2O$, which along with NO is a potent atmospheric greenhouse gas, will drive the formation of photochemical smog (Vitousek et al., 1997). Galloway et al. (2008) reported that anthropogenic Nr emissions that lead to atmospheric Nr deposition would have an impact on the climate and the composition and function of terrestrial and aquatic ecosystems.

Because Nr deposition directly impact on ecosystem heath, such as direct toxicity to plant, long-term negative effects accompanied

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with increased $NH_3$ and $NH_4^+$ availability, acidification, and eutrophication. Nevertheless, the consequence of excessive Nr deposition on N processes that takes place in terrestrial and aquatic ecosystems still has not been well depicted. In this study, we think the critical load for Nr deposition existing in terrestrial and aquatic ecosystems is similar to a health threshold. As a result, this study depicts a health threshold value for terrestrial and aquatic ecosystems undergoing sharply increasing anthropogenic Nr deposition, and then summarizes the difference of different N process in both terrestrial and aquatic ecosystems due to excess Nr deposition.

## 2. N health threshold existing in ecosystem

Much of the anthropogenic Nr produced is deposited on the planet's surface as the dissociation byproduct of $HNO_3$. Owing to the relatively short lifespan of atmospheric Nr, the bulk of acid deposition is deposited on terrestrial ecosystems. The subsequent acidification of terrestrial and freshwater ecosystems by dry deposition and increased acidic rainfall is a well-established environmental problem. Anthropogenic Nr deposition on the surface of the oceans alters surface seawater chemistry, leading to acidification and reduced alkalinity. As a result of these factors, researchers have begun to pay considerable attention to anthropogenic Nr emissions in the atmosphere (Liu et al., 2011a,b; Sutton and Bleeker, 2013). N accumulation in both terrestrial and aquatic ecosystems is the main driver for changes of ecosystem species composition for different ecosystem types by driving the competitive interactions (Bobbink et al., 2010). The Nr gas and aerosols has direct toxicity to aboveground plant growth and physiology (Pearson and Stewart, 1993). Because increased $NH_3$ and $NH_4^+$ availability would be toxic to sensitive plant species in habitats with $NO_3^-$ as the dominant N form and cause poor root and shoot growth (Kleijn et al., 2008).

As research intensified, people are gradually concerned on the effect thresholds for Nr deposition (Umweltbundesamt, 2004; Bobbink et al., 2010; Law, 2013). For example, when forests exceed such a threshold where N saturation limits have been reached, N availability will then exceed microbial and plant demands, leading to N leaching. Fleischer et al. (2013) also reported that under conditions of increased atmospheric N deposition, a photosynthetic threshold value of 8 kgN $ha^{-1}$ $yr^{-1}$ for boreal and temperate evergreen forests will be attained. Luo et al. (2006) thought there would be an equilibration point for N cycle in ecosystem due to C and N coupling relationship. Nilsson and Grennfelt (1988) introduced critical load concept for Nr deposition, which is the effect threshold for Nr deposition and would be helpful for governments to make progress toward reducing N loads on sensitive ecosystems.

Three key N processes occur when Nr enters into terrestrial and aquatic ecosystems and concentrations increase: fixation, uptake, and loss. According to the N mass balance theory, a point of equilibrium will be reached between these N processes for the health threshold to be initiated, sustaining continued healthy N cycling processes. However, the N demands for terrestrial and aquatic ecosystems differ. It therefore stands to the reason that Nr deposition gives rise to different health thresholds for N equilibration processes to occur, depending on ecosystem type.

## 3. N processes and associated health threshold in terrestrial ecosystems

The magnitude of N fixation driven by Nr deposition is proportional to plant growth and N uptake. When Nr is deposited into terrestrial ecosystems, the performance of N fixation will decrease while N-fixing plant uptake will remain unchanged (Fig. 1). This will result in higher residue C or soil organic C mineralization. N fixation will decrease with an increase in the quantity of available N. A lower Nr deposition rate will increase plant growth and N absorption more than it will diminish N fixation processes. Enhanced mineralization brought on by Nr deposition preferentially impacts terrestrial ecosystem N processes, including primary production and nitrate leaching (Castellano et al., 2012). Accelerated Nr deposition will increase inorganic N as well as net N mineralization and nitrification rates in soils but it will reduce soil microbial C biomass (Liu et al., 2011a). As Nr deposition increases, C productivity will increase the potential for N loss. McLauchlan et al. (2013) pointed out that the buffer capacity of terrestrial ecosystems in retaining additional Nr as N inputs increase operates without the evidence of adverse effects, but the N availability may decline nevertheless. As more N is stored in organic matter, its subsequent turnover rate will also contribute to plant available N, promoting an increase in plant productivity (Gao et al., 2011; Wang et al., 2013; Wu et al., 2013).

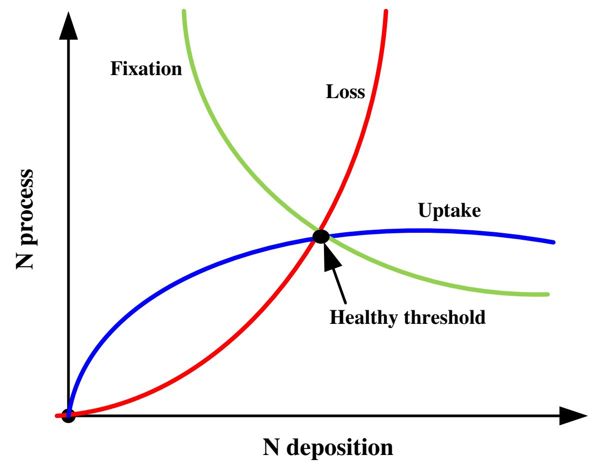


**Fig. 1.** The terrestrial ecosystem N health threshold.

When ecosystem constituents (such as soils, plants, and microbes) can no longer respond to further increases in Nr deposition, we think that the tendency in N limitation of plant primary production and ecosystem biological fixation is toward the equilibration of the health threshold. As N enrichment results in the removal of biological N limitation and the N retention capacity of the system is exceeded, the ecosystem is considered being in N saturated status (Fenn et al., 2005). It is not yet known whether an ecosystem must reach N saturation for this to occur, but any additional Nr deposits will be lost to streams, groundwater, and eventually, the atmosphere. It is clear that a number of damaging consequences related to the health and function of ecosystems will take place when the N health threshold is exceeded. In such a case, a substantial fraction of atmospheric nitrate deposits will be transported from land to streams without ever being taken up by organisms or playing a role in biological cycling.

The tendency of N dynamics toward equilibrium in terrestrial ecosystems often results in decreases in N uptake and fractionating losses if increasing N supplies produce additional fixed N (Högberg, 1997). However, if accumulating C and N uptake surpasses the equilibrium point in terrestrial ecosystems because of excessive N input deposition, N biological fixation will decline and N loss will abruptly increase. Furthermore, the increasing of anthropogenic atmospheric $CO_2$ emissions can result in a progressive increase in N limitation in plants. This is due to the demand of plants for N under the conditions of higher levels of productivity as well as the N and C sequestered in plant biomass and soil organic matter pools