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Impacts of nitrogen deposition on soil nitrogen cycle in forest ecosystems: A review

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ABSTRACT

Atmospheric nitrogen (N) deposition has accelerated in the last several decades due to anthropogenic activities, such as nitrogen fertilization, N-fixing plants cultivation and fossil fuel and biomass combustion. Increasing N deposition has become one of the important factors regulating N cycle in forest ecosystems. Forest ecosystems can retain part of deposited N in soil by biotic and abiotic mechanisms, but when N inputs exceed the capacity of soil retention, N losses will aggravate in terms of N oxide emission and/or nitrate leaching. The excess N input has threatened ecosystem health via acidification and eutrophication, causing declines in terrestrial biodiversity and forest productivity in forest ecosystems of Europe and North America. Recently, China has become one of the three areas that undergo severe N deposition in the world. Impacts of N deposition on soil N cycle in Chinese forest ecosystems have received increasing concern. In this paper, we reviewed the processes of soil N cycle and their responses to atmospheric N deposition based on available literature. The objective is to enhance our understanding on how N deposition affects soil N cycle in forest ecosystems and provide scientific information for sustainable forest management. The review mainly includes the following four aspects: (1) processes of soil N cycle and their controlling factors. These processes include biological N fixation (BNF), decomposition, mineralization, nitrification, denitrification, N oxide emission and NO_3^-—N leaching. The controlling factors of these processes are complicated and interactional. Only one of these factors altered may affect soil N cycle. For example, C/N is the factor that controls BNF, decomposition, mineralization and NO_3^-—N leaching. (2) Research methods and current results about studies are related to the impact of N deposition on soil N cycle in forest ecosystems. In general, the research methods are long-term simulated N deposition experiment, N deposition gradient method, roof clean rain method and ^{15}N tracing method. Effects of N deposition on soil N cycle vary depending on different initial N statuses and lengths of experiment. In "N-limited" forests, N deposition tended to have positive effect on soil N cycling processes, such as accelerating litter decomposition rate and N mineralization rate. However, such result generally showed in short-term fertilization experiments. In some long-term fertilization experiments, it showed that the negative effects would rise when the forests reached N saturation. Compared to "N-limited" forests in temperate region, N deposition tended to have negative or neutral effects in "N-rich" tropical forest. For example, N deposition promoted nitrification process in tropical forests. (3) Possible mechanisms for the effect of N deposition on soil N cycle: N deposition can affect soil N cycle through altering the chemical characteristic of forest substrates, the biomass and community composition of plant and microorganism. (4) Current problems and future research needs for the study about the effect of N deposition on soil N cycle: What role does regional diversity, changes in forest type, and interaction of carbon (C), N and phosphorus (P) play on the effect of N deposition on soil N cycle in forest ecosystems deserve our further study in the future.

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Soil N pool occupies for nearly 90% of total N storage in forest ecosystem. Soil N cycle is an essential component to determine the rate of ecosystem N cycle and effluxes [1,2]. Soil N cycle in forest ecosystems constitutes three processes, such as input, transformation and output. These processes include: biological N fixation (BNF), litter decomposition, N mineralization, nitrification, denitrification, N-oxide emission and N leaching [1]. With less or no human disturbance, soil N in forest ecosystem mainly comes from BNF and decomposition. N element transfers among plant, microorganism, soil organic matter and soil mineral matter, while less N loss occurs in these ecosystems [2,3]. However, N deposition has elevated in the past several decades, due to N fertilization, N-fixing plants cultivation, and fossil fuel and biomass combustion [4]. Galloway et al. [4,5] forecasted global N deposition would reach 200 Tg N $year^{-1}$ in 2050 and it has become the main pattern of N input in forests. Forest ecosystems can retain part of deposited N in soil by biotic and abiotic mechanisms, such as plant uptake, microbial immobilization, soil cation exchange capacity and soil organic matter absorption [6,7]. But when forest ecosystems reach "N saturation", plant and microorganism cannot accumulate excess N any more [8]. At this point, N will loss from ecosystem by leaching and N-oxide emissions, resulting in water pollution and increasing greenhouse gas emissions [9,10]. According to many studies in temperate and tropical forests, excess N input has altered structure and function of forest ecosystems. For examples, N deposition may inhibit plant growth by breaking the balance of elements, reduce biological diversity by soil acidification, and cause forest degeneration in the most serious situation [11,12]. The ecological and environmental issues aroused by N deposition have received increasing concern.

The effect of N deposition on forest ecosystem has been studied in temperate zone early in 1980s, for examples, nitrogen saturation experiments (NITREX) and experimental manipulation of forest ecosystems (EXMAN) programs in Europe [13,14]. In the U.S., study sites were established later in Harvard forest in Massachusetts, the Bear Brook watershed in Maine, and Mt. Ascutney forest in Vermont [15,16]. These studies proposed the response of N-limited forests to N deposition and the related mechanisms. As N deposition has elevated in tropical zones, the effect of N deposition on tropical forest ecosystems has received wide concerns. Currently, long-term study sites were established in many tropical zones, such as Hawaii, Costa Rice, Puerto Rico, Ecuador, and Panama. The findings from these sites enhanced our understandings of the effect of N deposition on structure and function of tropical forest ecosystems [17–22]. In-situ soil core incubation, ion exchange resin and ^{15}N isotopes tracer technique were used to examine the size of soil N pool and soil fluxes in these studies.

Recently, China has become one of the three areas that undergo severe N deposition in the world [4]. In China, average rate of N deposition increased from 13.2 kg N hm^{-2} $year^{-1}$ in 1960s to 21.1 kg N hm^{-2} $year^{-1}$ in 2000s [22]. N deposition rates have reached 30–50 kg N hm^{-2} $year^{-1}$ in Southeast China, and these rates were higher than the peak value of N deposition in Europe and the United State. It means that large amount of N will transport into the forests by deposition [2,23]. However, no attention was paid to assess the effect of N deposition on forest ecosystem in China until the first study site was established in Dinghushan Biosphere Reserve (DHSBR) in southern China in 2003 [9]. After that, study sites were conducted in other subtropical areas (Fujian, Chongqing, Sichuan, etc.) and temperate areas (Changbaishan mountain) in China [23]. However, our understanding of the responses of soil N cycle and N transformation to N deposition in forest ecosystems was still limited. There were two reviews to summarize the effect of N deposition on ecosystem: the former only focused on the processes of soil N transformation (mineralization, nitrification and denitrification) [2]; the latter focused on the different effects of N deposition on N pools and N cycling between agriculture ecosystem and non-agriculture ecosystem, without mentioning the related mechanisms [24]. In this paper, we reviewed the processes of soil N cycle and their responses to atmospheric N deposition in temperate and tropical forests based on available literatures. We also discussed the possible mechanisms for the effect of N deposition on soil N cycle. The objective is to enhance our understanding on how N deposition affects soil N cycle in forest ecosystems and to provide scientific information for sustainable forest management.

1. Processes of soil N cycle

Soil N cycle is one key components of N cycle in forest ecosystems. It is also the most important and active processes in ecosystem N cycle [1,2]. Soil N cycle in forest ecosystem constitutes three processes, such as input, transformation and output. These processes