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Coniferous coverage as well as catchment steepness influences local stream nitrate concentrations within a nitrogen-saturated forest in central Japan

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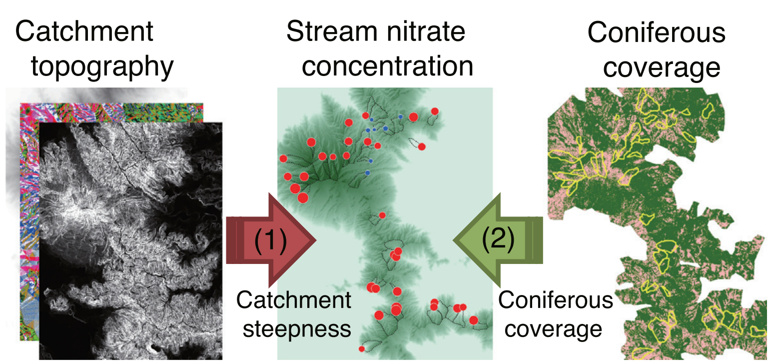
HIGHLIGHTS

- A forest on Mount Tsukuba has experienced nitrogen saturation since the 1980s.
- Stream nitrate concentrations tended to be higher in catchments with steep slopes.
- Coniferous coverage had an additional effect on increasing stream nitrate.
- The appropriate management of coniferous forests could improve streamwater quality.

GRAPHICAL ABSTRACT



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ABSTRACT

High concentrations of nitrate have been detected in streams flowing from nitrogen-saturated forests; however, the spatial variations of nitrate leaching within those forests and its causes remain poorly explored. The aim of this study is to evaluate the influences of catchment topography and coniferous coverage on stream nitrate concentrations in a nitrogen-saturated forest. We measured nitrate concentrations in the baseflow of headwater streams at 40 montane forest catchments on Mount Tsukuba in central Japan, at three-month intervals for 1 year, and investigated their relationship with catchment topography and with coniferous coverage. Although stream nitrate concentrations varied from 0.5 to 3.0 mgN L^{-1}, those in 31 catchments consistently exceeded 1 mgN L^{-1}, indicating that this forest had experienced nitrogen saturation. A classification and regression tree analysis with multiple environmental factors showed that the mean slope gradient and coniferous coverage were the best and second best, respectively, at explaining inter-catchment variance of stream nitrate concentrations. This analysis suggested that the catchments with steep topography and high coniferous coverage tend to have high nitrate concentrations. Moreover, in the three-year observation period for five adjacent catchments, the two catchments with relatively higher coniferous coverage consistently had higher stream nitrate concentrations. Thus, the spatial variations in stream nitrate concentrations were primarily regulated by catchment steepness and, to a lesser extent, coniferous coverage in this nitrogen-saturated forest. Our results suggest that a decrease in coniferous coverage could potentially contribute to a reduction in nitrate leaching from this nitrogen-saturated forest, and consequently reduce the risk of nitrogen overload for the downstream ecosystems.

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This information will allow land managers and researchers to develop improved management plans for this and similar forests in Japan and elsewhere.

1. Introduction

Nitrogen saturation has been reported in forest ecosystems in North America and Europe since the 1980s (Stoddard, 1994; Gundersen et al., 2006; Lovett and Goodale, 2011). Nitrogen saturation describes a phenomenon wherein the "availability of mineral nitrogen exceeds total combined plant and microbial nutritional demands" (Aber et al., 1989). Nitrogen compounds that originate from human activities have accumulated in forests via atmospheric deposition over long periods of time, causing excess levels of mineral nitrogen in soils. Because this excess mineral nitrogen is released into streams as nitrate, nitrate concentrations tend to increase in streams flowing from nitrogen-saturated forests (Peterjohn et al., 1996; Gundersen et al., 2006). This poses a risk of declining quality for water resources and causes eutrophication of downstream lakes or coastal waters (Vitousek et al., 1997; Chiwa et al., 2012).

Atmospheric deposition of mineral nitrogen is generally greater in coniferous forests compared to broadleaved forests, because dry deposition is enhanced in the former (De Schrijver et al., 2007; Watanabe et al., 2008). In addition, the response of nitrate leaching to nitrogen input varies between coniferous and broadleaved forests (Kristensen et al., 2004; Zhang et al., 2008a; Gundersen et al., 2009). Thus, the percent cover of coniferous trees in forested catchments should be an important factor in regulating nitrate concentrations in streamwater.

In Japan, some studies have reported consistently high concentrations of nitrate (>1.0 mgN L^{-1}) with little seasonality in streamwater flowing from forests near large cities (e.g., Ohrui and Mitchell, 1997; Chiwa et al., 2015). This is generally considered to be potential nitrogen saturation in those forests based on the criteria used in North America and Europe (Stoddard, 1994; Dise and Wright, 1995; Aber et al., 2003; Gundersen et al., 2006), although the applicability of this to Japan's forest systems may be arguable and those for Japan's have yet to be established (Mitchell et al., 1997; Zhang et al., 2008b; Ohte et al., 2010). Topography of forests in Japan is generally steeper than that in Europe and North America, considered to be a more important determinant of stream nitrate concentrations compared to forest types (Ohrui and Mitchell, 1998; Hirobe et al., 1998; Fujimaki et al., 2008). Nevertheless, forest types could also alter stream nitrate conditions, with up to 1 mgN L^{-1} higher concentrations observed in coniferous forests compared to those in broadleaved in central Japan (Zhang et al., 2008a). Thus, forest management, for instance via plantation, may allow us to control nitrate concentrations in streams and to improve the water resource quality for the downstream ecosystems (e.g. adhesive agricultural land use). However, relative contribution of forest cover types to nitrate concentrations in streams remains poorly explored (Ogawa et al., 2006; Fukushima and Tokuchi, 2009).

This study evaluated the influences of catchment topography and coniferous coverage on spatial variations of nitrate concentrations in streamwater within a nitrogen-saturated forest. We tested a hypothesis that streamwater nitrate concentrations would be influenced by both topographic characteristics and coniferous coverage. For this purpose, nitrate concentrations in baseflow of headwater streams were measured in 40 catchments located within a forest on Mount Tsukuba in Japan. We evaluated the status of nitrogen saturation in the study site (Mitchell et al., 1997; Takamatsu et al., 2010) from the perspective of stream nitrate concentrations and its potential risk to downstream ecosystems. Then, relationships between stream nitrate concentrations and topographic and vegetative characteristics of the catchments (incl. drainage area, mean elevation, mean slope gradient, percentage of south-facing slopes, and coniferous coverage) were investigated. Moreover, the stream nitrate concentrations were compared for 3 years between five adjacent catchments with similar topography but different coniferous coverage.

2. Materials and methods

2.1. Site description

Forty completely forested catchments were selected within a forest on Mount Tsukuba, Ibaraki Prefecture, Japan (Fig. 1). Mount Tsukuba (elevation: 877 m a.s.l.) is well northeast of the Kanto Plain, approximately 70 km northeast of Tokyo. It is approximately 20 km north of the city of Tsukuba. Although only about 207,000 people live in Tsukuba, there are approximately 134,000 automobiles and 500 facilities that generate soot and smoke in 2007 (City of Tsukuba, 2009, 2010). Although some buildings, roads, and farmland exist at the foot of Mount Tsukuba, no industrial areas there produce NO_X. Whilst the atmospheric concentrations of NO_X at Mount Tsukuba (~5 ppbv) were ca. 80% lower than those in Tsukuba in 2004, gaseous and particulate nitrate (TNO_3) concentrations in the atmosphere did not substantially differ between those two sites (ca. 2 ppbv) (Watanabe et al., 2006). The annual input of mineral nitrogen to the coniferous forest on Mount Tsukuba has been reported as 18–22 kgN ha^{-1} yr^{-1} (Hirata and Muraoka, 1992; Takamatsu et al., 2010; Yoshinaga et al., 2012).

A large part of Mount Tsukuba is covered with a mixed forest of coniferous or broadleaved trees. The dominant evergreen coniferous tree species include *Cryptomeria japonica*, *Chamaecyparis obtusa*, and to a lesser extent *Pinus densiflora*, most of which are plantations distributed from lower to middle area of the mountain. Meanwhile, *Quercus acuta* and *Quercus serrata* are dominant deciduous broadleaved tree species, distributed on the lower–middle and middle–upper areas, respectively. Evergreen broadleaved tree species (*Castanopsis sieboldii* and *Quercus myrsinifolia*) also occur in the lower–middle area. *Fagus crenata* (Deciduous broadleaved) also occur in the upper area but was not found in our studied catchments. No deciduous coniferous tree was found in the studied catchments.

Gabbroic rocks compose the summit of Mount Tsukuba, while the foot is composed of granites and metamorphic rocks. The mean annual temperature and precipitation were 10.3 °C and 1450 mm at the summit during the period from 2007 to 2010, respectively (Hayashi and Research Group for Intramural Project (S), University of Tsukuba, 2006). Temperature and precipitation both peaked during summer from June–September. The streams on Mount Tsukuba flow into Lake Kasumigaura via the Koise or Sakura rivers. Lake Kasumigaura supports the daily water use of 300,000 people and also provides water for irrigation and industrial uses in the surrounding area (Kasumigaura Canal O&M Office, 2009).

2.2. Sampling and analysis of streamwater

To assess the seasonal variation in stream nitrate concentrations, repeated streamwater sampling was conducted at exactly the same locations four times throughout the study (August–September 2007, November 2007, February 2008, and May 2008), at the lowest point of each catchment. Continuous monitoring of the discharge and precipitation rates from July 2007–June 2008 (Masukura et al., 1991) showed no increase in discharge rate and < 5 mm of cumulative precipitation during the 12 h prior to every sampling (Fig. 2). Therefore, all samples were