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Climate Variability Induced Shifts in Nitrogen Loading from Terrestrial to Aquatic Ecosystems

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ABSTRACT

Nitrogen is a critical nutrient linked to degradation of freshwater and marine ecosystems. The nitrogen inputs to terrestrial ecosystems and subsequent loadings to aquatic ecosystems have been doubled and changed the nitrogen cycle as population and human activities increased over the past century. One of the consequences of human alternation of the nitrogen cycle is the eutrophication of marine and freshwater ecosystems. We tested if climate variability can change nitrogen loading from terrestrial to aquatic ecosystems. We used stream nitrogen concentrations from 2,125 sites and climate data from 301 stations from 30 eco-regions across British Columbia, Canada, to test our objective and to compare it with anthropogenic loading of nitrogen in the same regions. We show that elevated air temperature and associated precipitation resulted in increase in nitrogen loading from terrestrial to aquatic ecosystems. Furthermore, inorganic nitrogen (IN) loading increased more rapidly than organic nitrogen (ON) with increasing air temperature. Each oC increment annual air temperature caused a 24% increase in nitrogen loading to aquatic ecosystems and a 22% increase in ratio of IN: ON concentrations in stream water. We also show that the coastal mountains ecosystems seem to be more vulnerable to temperature induced nitrogen loss than the interior ecosystems. We suggest that climate warming and elevated loading of nitrogen from terrestrial to aquatic ecosystems will have major implications for the quality of water in freshwater and coastal marine ecosystems.

Keywords: Climate Conditions, Human Activities, Stream Nitrogen, Aquatic and Terrestrial Ecosystems

INTRODUCTION

The nitrogen inputs to terrestrial ecosystems and subsequent loadings to aquatic ecosystems have been doubled and changed the nitrogen cycle as population and human activities increased over the past century [1-5]. These resulted in the changes of species composition, diversity, dynamics, productivity and functioning in many terrestrial and aquatic ecosystems [4]. One of the consequences of human alternation of the nitrogen cycle is the eutrophication of marine and freshwater ecosystems [6, 7].

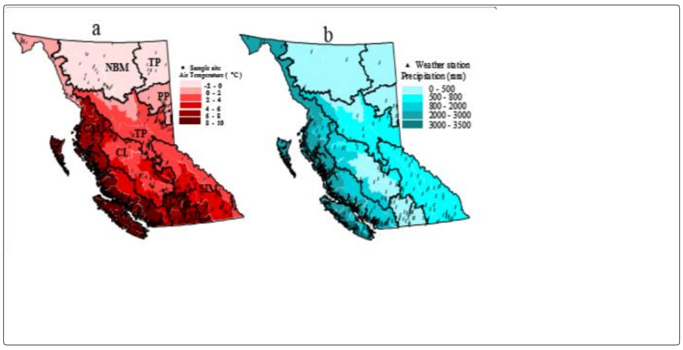
Anthropogenic sources of nitrogen in terrestrial and aquatic ecosystems largely result from (1) manure and commercial nitrogen fertilizer applications in agriculture lands, (2) increased biological nitrogen fixation from atmosphere due to the increased culture of nitrogen fixing crops, (3) increased atmospheric nitrogen deposition as a result of increased nitrogen emission from industries, and (4) increased human, animal, and industrial waste discharges to surface water [3,4,8,9]. Nitrogen sources to aquatic have been well recorded and analyzed, and linked in terms of their impacts on water quality of aquatic ecosystems in the United Stated and other countries [1,8,10-13]. Understanding the factors and processes regulating large landscape patterns of stream nitrogen components, concentrations, and loadings and the factors is complex and is of fundamental interests to global scientific communities working in the areas of environmental quality under changing climate.

MATERIALS AND METHODS

British Columbia ecosystem characteristics and stratification

British Columbia (BC) is Canada's westernmost province and one of North America's most mountainous regions. Its 94.78 million hectares of land span 11 degrees of latitude and 25 degrees of longitude, and offer remarkable topographic, climate, and vegetation contrasts, with coastal mountains and islands in the west, plateaus in the central region, rocky mountains in the east, and an extension of prairie plains in the north-east corner (Table 1, Figure 1a). About 59.63 % of British Columbia land is covered by natural forests. Natural grasses and other non-wood plants (alpine, open range, and wetland) occupy 35.47%, agriculture 2.6%, urban and rural settlement 0.3%, water 1.9%, and mining 0.1%. Crop and pasture lands are mainly distributed in Central and Southern Interior and Vancouver Island. Total population is 4,039,198 based on the census by the Government of British Columbia in 2005. About 70% of the population lives in the cities of Vancouver and Victoria and surrounding areas. Furthermore, Ecoregion and Ecoprovince also represent the impacts of vegetation type, topography and soil variations as they are represented in the classification system of British Columbia ecosystems. Geographical locations and ecological characteristics of each Ecoprovince are shown in Figure 1 and Table 1 [16].

Figure 1: Maps show the landscape patterns of air temperatures and precipitations in British Columbia: Panel 1a represents mean annual air temperatures (°C), sample sites and boundaries of Ecoprovinces (see able 1 for description); Panel 1b shows the annual precipitation (mm) and climate data collection sites.



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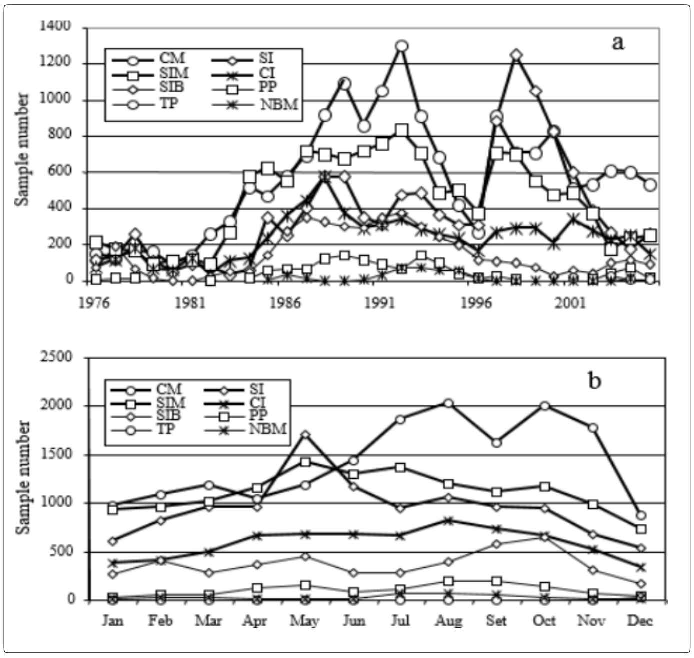
DATA COLLECTIONS

The main databases used in this study included: stream chemistry, climate record, precipitation nitrogen deposition, landuse, urban and municipal community statistics database. The stream chemistry database was compiled based on the data from the BC Water Quality Monitoring Network jointly operated by the BC Ministry of Environment and Environment Canada. The database consists of 55,097 stream water samples collected from 2,167 sites in 30 Ecoregions across British Columbia from 1976 to 2005 [15]. The water samples were collected from the creeks and streams. The sampling time, period, and frequency varied from site to site. The most intensive sample sites were sampled at a weekly time interval and the least intensive sample sites were sampled at a seasonal base. The sampling periods varied from the longest for the past 30 years and the shortest only for one year. Seasonal sampling variations depended on the site accessibility. The procedures of water sampling and laboratory analysis followed the British Columbia Field Sampling Manual and the British Columbia Environmental Laboratory Manual [17,18].

The majority of samples collected from creeks and streams were grab samples taken near the surface at one point in the cross section of the flow at the mid-creeks or streams. On rare, special occasions, equal-discharge-increment (EDI) or equal-width-increment (EWI) was used. The EDI method requires first that a complete flow measurement is carried out across the cross-section of the river. The cross-section is equally divided into different sections in vertical and then water is sampled at each section. In the EWI sampling method, a composite sample of water collected across a section of stream with equal spacing between verticals and equal transit rates within each vertical that yields a representative sample of stream conditions. The water samples were collected using multiple samplers or automatic composite samplers and stored in 250ml acid rinsed plastic bottles.

Figure 2: Yearly (Panel a) and monthly (Panel b) distributions of stream water samples.



The water samples were transported to the laboratory and analyzed within 72 hours. The distributions of yearly and monthly water samples for each Eco province are shown in Figure 2a and 2b, respectively. Figure 2 showed that the water sample numbers in all the Ecoprovinces of British Columbia had similar annual and monthly distribution trends from 1976 to 2005. The characteristics of annual water sample distributions for all the Eco provinces were (1) lower sample intensity periods from 1976 to 1980 and from 2002 to 2005, (2) increased sample intensity periods from 1981 to 1993 and from 1996 to 1998, and (3) decreased sample intensity periods from 1993 to 1996 and from 1998 to 2002 (Figure 2a). The Characteristics of monthly water sample distributions for all the Ecoprovinces were (1) high sampling intensity periods during summer, (2) lower sampling intensity periods during winter, and (3) intermediate sampling intensity periods during spring and fall (Figure 2b). The similarities of annual and monthly water sample distributions in the different Ecoprovinces ensured the comparability of stream water nitrogen components, concentrations and loadings across the ecosystems of British Columbia. Nitrogen inputs from manure application was calculated based on the amount of manure application and 0.4% of nitrogen concentration according to Vegetation Production Guide of British Columbia [19]. Nitrogen removals due to forest logging were calculated by using 535kgm-3 of wood density (http://woodsgood.ca) and 0.21% of wood nitrogen content [20].

CALCULATIONS OF STREAM NITROGEN CONCENTRATIONS FOR EACH ECOREGION

The concentrations of stream water nitrogen for each Ecoregion were weighted average of dtream water nitrogen concentrations by monthly stream flows and sample site catchment areas and calculated using following equation:

(1) $$[N]=\sum_{s=1}^{n}\left\{\frac{A_s}{A}\left(\frac{1}{Y_s}\sum_{y=1}^{Y_s}\sum_{m=Jan}^{Dec}\frac{Q_{sym}}{Q_{sy}}\left[N_{sym}\right]\right)\right\}$$

where [N] is stream nitrogen concentration for an Ecoregion weighted by monthly stream flows and the sampling site catchment areas (mg L-1), [Nsym] is stream nitrogen concentration sampled in the month m of the year y at site s, Qsy is yearly stream flow at site s during year y, Qsym is monthly stream flow in month m of year y at site s, Ys is sampling year number at site s, A is the sum of catchment areas for all the sampling sites in the Ecoregion, and As is the catchment area of sampling site s.

The annual stream nitrogen loading (QN) of each Ecoprovince was calculated using monthly stream water nitrogen concentrations and discharges and weighted by sample site catchment areas. The equation is (2)

$$Q_N=\sum_{s=1}^{n}\left\{\frac{A_s}{A}\left(\frac{1}{Y_s}\sum_{y=1}^{Y_s}\sum_{m=Jan}^{Dec}Q_{sym}\left[N_{sym}\right]\right)\right\}$$

We assumed that stream water nitrogen was mainly from terrestrial ecosystem soils and was transferred by soil surface runoff, lateral flow and percolation. The exchange of nitrogen between streams and groundwater is minimal and negligible [21].

Monthly stream water discharge for the catchment of each sampling site was estimated using the hydrology balance equation [22].

$$Qs = P - Qi - Qe - S \qquad (3)$$

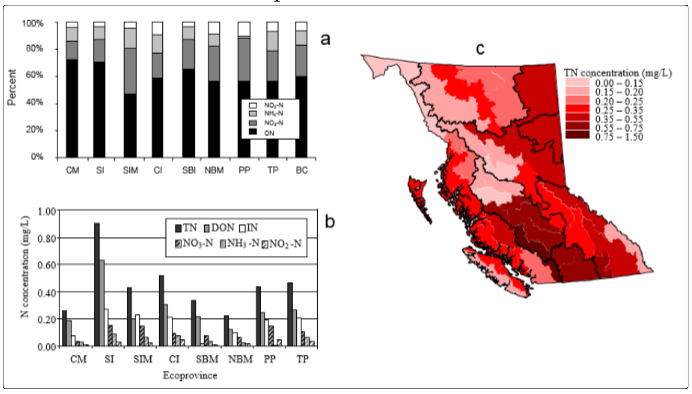
where Qs is monthly stream water yield (equal to Qsym in Equation (1)); P is precipitation; Qi, is interception; Qe is evapotranspiration; and S is soil water storage change. Monthly stream flows for each sample site were estimated using the ForHyM model based on monthly precipitation and temperature data recorded from 1976 to 2005 at the nearest weather in the weather network of British Columbia. The ForHyM is a process-based hydrology model developed and broadly used in Canada [23]. The ForHyM is driven by monthly precipitation and air temperature and calculates precipitation interception by vegetation, soil water storage change, evapotranspiration, and stream flow.

RESULTS

Landscape patterns of stream water nitrogen components and concentrations

The data showed that the mean concentration of stream water total nitrogen in British Columbia was 0.37 mg l-1, with the highest of 0.90 mg l-1 in Southern Interior ecosystems (SI) and the lowest of 0.22 mg l-1 in the Northern Boreal Mountains ecosystems (NBM) (Table 2). On average, dissolved organic nitrogen (DON) accounted for 60.23% of total nitrogen, while the inorganic forms of NO3-N, NH +-N, and NO -_N accounted for 23.16%, 10.45%, and 6.16%, respectively. DON consistently made up the majority of stream 4 2 water nitrogen in all the ecosystems of British Columbia (Figure 3a). Our results showed that British Columbia ecosystems produced the proportions of stream nitrogen components similar to those observed in the ecosystems of South America [24].

The nitrogen concentrations showed strong landscape patterns across British Columbia. The concentrations of different components of nitrogen showed the following landscale patterns: (1) in the south of British Columbia, the concentrations of all components of nitrogen were higher in the South Interior ecosystems and decreased from the South Interior toward to west, the Costal Mountains, and to east, South Mountains Interior (Figure 3b); (2) in the central of BC, the concentrations of all components of nitrogen decreased from the South Interior to North Boreal Mountains through Centre Interior and Southern Boreal Interior; and (3) the Peace and Taiga Plains had medium nitrogen concentrations. The stream nitrogen concentrations generally decreased from south to north within each Ecorpovince.



UNCERTAINTIES OF THIS STUDY

This study was conducted based on available information collected across British Columbia by different organizations. Many important factors that affect nitrogen cycling in terrestrial and aquatic ecosystems such as vegetation, soil, topography, biological nitrogen fixation, and denitrification across the landscape of British Columbia were not quantified in this study. The nitrogen budgets for the terrestrial ecosystems in the different Ecoregions and Ecoprovinces were only based on nitrogen inputs from precipitation nitrogen deposition, fertilizer and manure application in agriculture lands and outputs from stream nitrogen loading and forest logging. The nitrogen inputs from dry deposition and biological fixation, sewage and industry waste and output from denitrification and agricultural products were not taken into accounts due to data limitations. All the aquatic nitrogen processes were also not taken into account in this study.

The Ecoregions were used as the basic analysis unit in this study and indirectly addressed the impacts of vegetation type, topography and soil on stream nitrogen components, concentrations and loadings because the Ecoregions were classified based on the variations of temperature, precipitation, topography and vegetation in British Columbia ecosystem classification system [15]. Each Ecoregion represents a unique combination of climate, topography and vegetation type. Ecoregions also represent the variations of soil types and thire properties such as nitrogen content because soil development is determined by climate, vegetation, topography, time and anthropogenic factors [33]. For example, the dominant vegetations in the Ecoregions of the Coastal Mountains are coastal western hemlock (Tsuga heterophylla) and mountain hemlock (Tsuga mertensiana), whereas Taiga and Peace plains are dominated by boreal white (Picea glauca) and black spruce (Picea mariana).

The sample numbers varied from one Ecoprovince to another (Figure 2). The water samples collected from high population density and intense agriculture areas such as the coastal and south of British Columbia were more than from the areas with less population density and relatively natural land such as the North Boreal Mountains. Also simple sites were more in the coastal and south of British Columbia than in the north. We hope that the large water sample numbers could compensate the uncertainties caused by the variations of sample numbers among the Ecoregions and Ecoprovicnes [34-36].

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