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

Asit Mazumder[1]* and Zhanxue Zhu[2]

Water and Aquatic Sciences Research Program, Department of Biology, University of Victoria, P.O. Box 3020, STN CSC, Victoria, British Columbia, Canada V8W 3N5

ABSTRACT

Nitrogen is one of the critical nutrients regulating terrestrial and aquatic productivity, and is linked to degradation of water quality of freshwater and marine ecosystems worldwide. The landscape patterns of stream nitrogen components, concentrations and loadings and their relationships with climate variability and landuse, were analyzed and quantified in this study. We used stream nitrogen concentration data collected at 2,125 sites and climate data at 301 weather stations during 1976 to 2005 in 30 eco-regions across British Columbia, Canada. While the patterns of stream nitrogen component, concentration, and loading distributions were found to be related to landscape patterns of climate variability, human activities, landuse, natural vegetation, and relief across British Columbia, the climate variability on both temporal a d spatial scales were found to be the dominant driver of variability in loading and concentrations of nitrogen. Elevated air temperature gradient across the landscape of British Columbia resulted in a significant increase in stream nitrogen loading from terrestrial into aquatic ecosystems. Precipitation, nitrogen deposition, population density and urban area also significantly affected the stream nitrogen components, concentrations and loadings. We suggest that climate change, especially shifts in temperature and precipitation, along with increased human activities tend to have important implications for loading of nitrogen from terrestrial to aquatic ecosystems and associated water quality in aquatic ecosystems.

***Corresponding author**

Asit Mazumder, Water and Aquatic Sciences Research Program, Department of Biology, University of Victoria, P.O. Box 3020, STN CSC, Victoria, British Columbia, Canada V8W 3N5. Tel: (250) 472-4833; E-mail: mazumder@uvic.ca

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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]. Although many studies describing water chemistry and quality were carried out in British Columbia, most of them were single watershed-based studies and focused on the impacts of forest operations on stream water chemistry [14]. 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.

Here, we present the results collected from 1976 to 2005 across different ecosystems of British Columbia to (1) analyze large landscape patterns of stream nitrogen components, concentrations, and loadings in the provincial scale; (2) quantify the relationships of these patterns with landscape variation in landuse and other human activities, and climatic climate variability; and (3) evaluate the potential impacts of vegetation, relief and future climate variability on stream nitrogen components, concentrations and loadings in British Columbia.

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. According to ecosystem classification system of British Columbia, the land of British Columbia is stratified into following ecosystem hierarchy: Ecodomain (an area of broad climatic uniformity) → Ecodivision (an area of broad climatic, physiographic and plant uniformity) → Ecoprovince (an area with consistent climate or oceanography, relief, plate tectonics, and vegetation types) → Ecoregion (an area with major physiographic and minor macroclimatic or oceanographic variation) [15]. Here, the Ecoregions were used as basic spatial units to analyze the landscape variations of stream nitrogen components, concentrations, and loadings and their responses to land uses, human activities and climatic conditions and then summarized these results at the Ecoprovince level. 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].

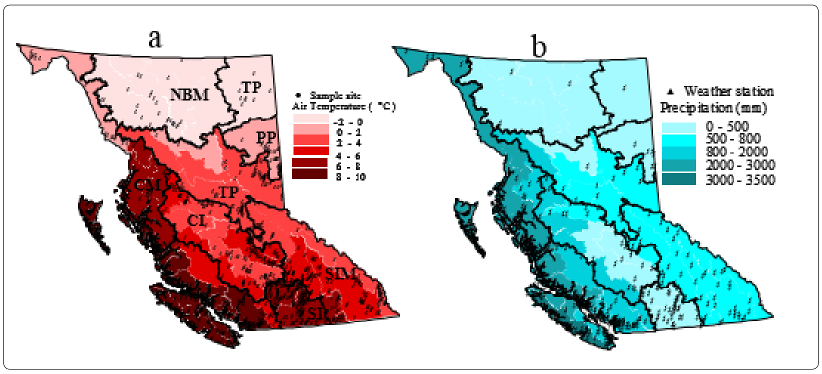

Figure 1: Maps show the landscape patterns of air temperatures and precipitations in British Columbia: Panel 1a represents mean annual air temperatures (°C), sample sites and boundaries of Ecoprovinces (see Table 1 for description); Panel 1b shows the annual precipitation (mm) and climate data collection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

Table 1: Characteristics of each Ecoregion in British Columbia*

Ecoprovince	Ecoregion	Area (10^3 ha)	Sample number	Sample site number	MAT (°C)	MJaT (°C)	MJuT (°C)	Precip. (°C)	Elevation (m)
Central Interior (CI)		**10,711**	**7044**	**268**	**4.54**	**-9.7**	**15.45**	**647**	**671**
	Bulkley Basin (BB)	1200	470	34	4.05	-7.9	14.8	629	528
	Central Interior Plateau (CIP)	3433	1263	67	2.83	-8.8	13.6	388	984
	Chilcotin Ranges (ChR)	1517	179	19	9.45	-2.7	21.2	424	221
	Lower Nechako (LN)	1439	935	24	3.87	-23.0	14.9	765	601
	Nechako Plateau (NP)	1400	678	21	2.55	-8.0	12.4	1208	863
	Pothole Lakes (PL)	1721	3519	103	4.51	-8.0	15.8	465	831
Coastal Mountains (CM)		**27,553**	**17100**	**528**	**7.13**	**-1.9**	**15.9**	**1647**	**236**
	Eastern Pacific Ranges (EPR)	613	323	17	8.00	-0.8	16.6	1609	357
	Exposed Fjords (EF)	4035	603	27	7.48	-0.8	15.4	2612	54
	Nass Ranges (NR)	1381	1280	19	5.10	-5.2	16.4	995	146
	North Coastal Mountains (NCM)	4444	1273	60	1.60	-12.0	13.7	882	474
	Windward Island Mountains (WIM)	3240	1259	127	9.54	4.9	14.9	3007	21
	Queen Charlotte Island (QCI)	1185	-	-	-	-	-	-	-

	Northern Pacific Ranges (NPC)	9850	6273	59	6.06	-6.0	15.4	521	649
	South Pacific Ranges (SPC)	501	3113	54	9.55	2.8	17.5	1681	38
	Southern Pacific Ranges (SPR)	2034	2975	217	9.74	2.3	17.1	1866	145
Northern Boreal Mountains (NBM)		**10,830**	**401**	**61**	**-1.33**	**-15.0**	**11.9**	**586**	**966**
	Cassiar Ranges (CaR)	4869	200	36	-2.10	-14.6	11.5	750	1078
	Stikine Plateau (SP)	5961	201	25	-0.55	-15.4	12.2	422	853
Peace Plains (PP)		**3756**	**1267**	**59**	**1.46**	**-13.8**	**14.6**	**498**	**690**
	Peace Plains (PP)	3756	1267	59	1.46	-13.8	14.6	498	690
Southern Interior (SI)		**3,819**	**11360**	**604**	**7.49**	**-4.2**	**18.9**	**431**	**578**
	Okanagan Plateau (OP)	1450	976	380	7.31	-4.6	18.8	411	576
	Southern Interior (SI)	2370	10384	224	7.68	-3.7	18.9	451	579
Southern Interior Mountains (SIM)		**11,238**	**13391**	**436**	**5.15**	**-6.9**	**16.4**	**711**	**761**
	Columbia Mountains (CoM)	4181	5575	96	4.56	-7.4	16.0	781	995
	Quesnel Highlands (OH)	2169	1153	59	3.73	-8.5	14.8	628	872
	Shuswap Highlands (SH)	2413	5194	143	5.99	-6.5	17.6	673	574
	Upper Fraser Trench (UFR)	1484	987	69	4.00	-8.5	15.2	686	753
	Southern Selkirk Mountains (SSM)	990	482	69	7.49	-3.4	18.5	788	610
Sub-Boreal Interior (SBI)		**9,943**	**4469**	**148**	**2.6**	**11.2**	**14.50**	**590**	**734**
	Babine Upland (BU)	1404	966	5	3.13	-10.3	13.9	504	707
	Central Rocky Mountains (CRM)	4258	419	85	2.72	-10.0	14.8	670	770
	Omineca Mountains (OM)	2249	583	2	1.00	-15.1	14.1	538	763
	Upper Fraser (UF)	2005	2501	56	3.57	-9.5	15.3	647	696
Taiga Plains (TP)		**6198**	**56**	**9**	**-0.70**	**-21.2**	**16.8**	**452**	**319**
	Taiga Plains (TP)	6198	56	9	-0.70	-21.2	16.8	452	319

* MAT, mean annual temperature; MJaT, mean January temperature; MJuT, mean July temperature.

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. 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.

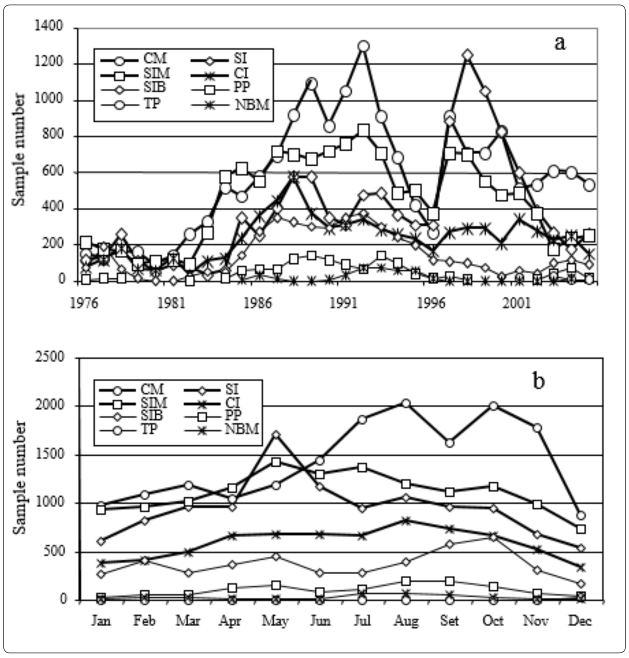

Figure 2: Yearly (Panel a) and monthly (Panel b) distributions of stream water samples

The water samples were filtered by 0.45µ membrane for analyzing nitrogen concentrations. The ammonia (NH_3-N) was analyzed by ion selective electrode or automated berthelot colorimetric method; nitrite (NO_2-N) by automated colorimetric diazotization method; nitrate (NO_3-N) by ion chromatography method; nitrogen (NO_3-N + NO_2-N) by automated (or manual) cadmium reduction and colorimetric method; total dissolved nitrogen (TN) by alkaline persulphate oxidation followed by colourimetry or oxidation of bound nitrogen components by thermal combustion with quantification of nitrogen by chemiluminescence detection; and total Kjeldahl nitrogen by automated digestion and colorimetric or $HgSO_4$ digestion and auto colorimetric method.

The climate record database was compiled using climate data from 301 weather stations managed by Environment Canada during the same period in the 30 Ecoregions across British Columbia (Figure 1b). The following Ministries of BC provincial government provided the land use data: the Ministry of Agriculture, Fisheries and Food provided the data for agriculture landuse, cattle density, fertilizer (chemical) and manure application information; the Ministry of Forestry and Ranges for forest landuse, shrubs and grasses as well as water area information; and the Ministry of Municipal Affaires, Recreation and Culture for urban area and population information. Precipitation nitrogen deposition was from the Canadian National Atmospheric Chemistry (NatChem) Database and Analysis System (http://www.msc.ec.gc.ca/natchem/index_e.html) maintained by Environment Canada. 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:

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

where [*N*] is stream nitrogen concentration for an Ecoregion weighted by monthly stream flows and the sampling site catchment areas (mg L^{-1}), [N_{sym}] is stream nitrogen concentration sampled in the month *m* of the year *y* at site *s*, Q_{sy} is yearly stream flow at site s during year *y*, Q_{sym} is monthly stream flow in month *m* of year *y* at site *s*, *Y*s 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 (Q_N) of each Ecoprovince was calculated using monthly stream water nitrogen concentrations and discharges and weighted by sample site catchment areas. The equation is

$$Q_N = \sum_{s=1}^{n} \left\{ \frac{A_s}{A} \left(\frac{1}{Y_s} \sum_{y=1}^{Y_s} \sum_{m=Jan}^{Dec} Q_{sym} [N_{sym}] \right) \right\} \quad (2)$$

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].

$$Q_s = P - Q_i - Q_e - S \quad (3)$$

where Q_s is monthly stream water yield (equal to Q_{sym} in Equation (1)); *P* is precipitation; Q_i, is interception; Q_e 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 NO_3-N, NH_4^+-N, and NO_2^-_N accounted for 23.16%, 10.45%, and 6.16%, respectively. DON consistently made up the majority of stream 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. Components and concentrations of stream water nitrogen varied greatly among the different ecosystems within each Ecoprovince (Figure 3c). The stream nitrogen concentrations generally decreased from south to north within each Ecorpovince.

Table 2: Stream nitrogen concentration (mg/l)/load (kg/ha/yr)/total load(Mt/Eco-region) in of British Columbia

Ecoprovince	Ecoregion	NO_3—N	NH_4+-N	NO_2^--N	IN	DON	TN	IN/DON
CI)		**0.0943/0.28/3.04***	**0.0723 /0.22/2.39**	**0.0451/0.13/1.43**	**0.2118/0.72/6.86**	**0.2118/0.72/6.86**	**0.5166/1.48/15.90**	**1.1548**
	BB	0.0168/0.07/0.08	0.0665/0.26/0.31	0.0070/0.03/0.03	0.0903/0.35/0.43	0.0900//0.35/0.42	0.1803/0.71/0.85	1.0029
	CIP	0.0912/0.22/0.76	0.0665/0.26/0.31	0.0380/0.09/0.32	0.1679/0.41/1.40	0.4808/1.16/4.00	0.6487/1.57/5.39	0.3491
	ChR	0.3030/0.80/1.22	0.1892/0.76/1.16	0.0380/0.09/0.32	0.7594/2.01/3.05	0.3000/0.79/1.20	1.0594/2.80/4.25	2.5312
	LN	0.0207/0.10/0.14	0.0137/0.07/0.09	0.0086/0.04/0.06	0.0430/0.21/0.30	0.0214/0.10/0.15	0.0644/0.31/0.44	2.0075
	NP	0.0460/0.35/0.49	0.0306/0.23/0.32	0.0192/0.14/0.20	0.0958/0.72/1.01	0.0214/0.10/0.15	0.1435/1.08/1.51	2.0075
	PL	0.0718/0.21/0.36	0.0353/0.10/0.18	0.0300/0.09/0.15	0.1371/0.40/0.68	0.5536/1.61/2.76	0.6909/2.00/3.45	0.2476
CM		**0.0338/0.41/11.25**	**"0.0276/0.27/7.40**	**"0.0101/0.13/3.54**	**0.0716/0.86/22.19**	**0.1890/1.05/28.99**	**0.2606/2.35/51.18**	**1.1753**
	EPR	0.0660/ 0.78/0.48	0.0400/0.47/0.29	0.0098/0.12/0.07	0.1157/1.36/0.83	0.0953/1.12/0.69	0.2110/2.48/1.52	1.2151
	EF	0.0505/ 0.96/4.15	0.0405/0.77/3.33	0.0053/0.10/0.43	0.0963/1.84/7.91	0.0475/0.91/3.91	0.0475/0.91/3.91	2.0267
	NR	0.0650/ 0.47/0.65	0.0632/0.46/0.63	0.0082/0.06/0.08	0.1364/0.99/1.37	0.1170/0.85/1.18	0.2534/1.84/2.54	1.1656
	NCM	0.1347/ 0.09/0.42	0.0171/0.11/0.49	0.0200/0.03/0.12	0.0362/0.23/1.04	0.2287/1.47/6.55	0.2649/1.71/7.59	0.1583
	WIM	0.0670/ 1.48/4.79	0.0760/1.66/5.38	0.0100/0.22/0.71	0.1530/3.43/1.09	0.0482/1.06/3.43	0.2010/4.43/14.32	3.1701
	NPC	0.0200/0.08/0.75	0.0300/0.11/1.13	0.0030/0.01/0.11	0.0305/0.20/1.99	0.3400/1.30/12.77	0.3930/1.50/14.76	0.1558
	SPC	0.2163/2.66/1.33	0.0092/0.11/0.06	0.0321/0.39/0.20	0.2576/3.17/1.59	0.1353/1.66/0.83	0.3929/4.83/2.42	1.9034
	SPR	0.0745/1.02/2.07	0.0205/0.28/0.57	0.0785/1.07/2.18	0.1735/2.37/4.81	0.0547/0.75/1.52	0.2282/3.11/6.33	3.1701
NBM		**0.0593/0.27/2.89**	**0.0205/0.09/1.02**	**0.0188/0.08/0.92**	**0.0987/0.61/4.83**	**0.1253/0.57/6.13**	**0.2240/1.01/10.96**	**0.7873**
	CaR	0.0748/ 0.41/2.02	0.0273/0.15/0.74	0.0237/0.13/0.64	0.1258/0.70/3.40	0.1597/0.89/4.32	0.2855/1.58/7.71	0.7873
	SP	0.0467/ 0.15/0.87	0.0150/0.05/0.28	0.0148/0.05/0.28	0.0765/0.24/1.43	0.0972/0.30/1.81	0.1738/0.54/3.24	0.7873
PP		**0.1434/0.35/1.31**	**0.0050/0.01/0.05**	**0.0455/0.11/0.41**	**0.1939/0.47/1.77**	**0.2463/0.60/2.24**	**0.4403/1.07/4.01**	**0.7873**
	PP	0.1434/0.35/1.31	0.0050/0.01/0.05	0.0455/0.11/0.41	0.1939/0.47/1.77	0.2463/0.60/2.24	0.4403/1.07/4.01	0.7873
SI		**0.1506/ 0.31/1.19**	**0.0890/0.17/0.66**	**0.0299/0.06/0.24**	**0.2695/0.75/2.08**	**0.6305/1.30/4.96**	**0.9000/1.85/7.05**	**0.472**
	OP	0.1087/0.21/0.30	0.2043/0.39/0.57	0.0215/0.04/0.06	0.3346/0.64/0.93	0.4557/0.88/1.27	0.7903/1.52/2.21	0.7343
	SI	0.1763/0.37/0.88	0.0185/0.04/0.09	0.0215/0.04/0.06	0.3346/0.64/0.93	0.7373/1.56/3.69	0.9669/2.04/4.84	0.3115
SIM		**0.1466/0.596.63**	**0.0632/0.26/2.94**	**0.0191/0.08/0.86**	**0.2290/1.11/10.43**	**0.2023/0.79/8.89**	**0.4312/1.72/19.32**	**1.1649**
	CoM	0.2059/ 0.87/3.65	0.0853/0.36/1.51	0.0289/0.12/0.51	0.3201/1.36/5.68	0.2080/0.88/3.69	0.5281/2.24/9.37	1.5394
	OH	0.0649/0.22/0.48	0.0165/0.06/0.12	0.0091/0.03/0.07	0.0905/0.31/0.67	0.0091/0.03/0.07	0.0905/0.31/0.67	0.4111
	SH	0.1315/0.48/1.16	0.0280/0.10/0.25	0.0184/0.07/0.16	0.1780/0.65/1.57	0.2200/0.80/1.94	0.3980/1.45/3.51	0.8091
	UFR	0.0806/0.30/0.45	0.0150/0.06/0.08	0.0113/0.04/0.06	0.1069/0.40/0.59	0.0694/0.26/0.38	0.1763/0.66/0.97	1.5394
	SSM	0.2110/0.90/0.89	0.2110/0.90/0.89	0.0135/0.06/0.06	0.4545/1.94/1.92	0.2950/1.26/1.25	0.7495/3.20/3.17	1.5408
SBI		**0.0732/ 0.37/3.69**	**0.0336/0.17/1.73**	**0.0102/0.05/0.47**	**0.0172/0.74 /5.89**	**0.2219/1.08/10.72**	**0.3388/1.67/16.61**	**0.5543**
	BU	0.0141/ 0.06/0.08	0.0064/0.03/0.04	0.0052/0.020.03	0.0257/0.10/0.14	0.0926/0.37/0.52	0.1183/0.47/0.66	0.2773
	CRM	0.1220/ 0.65/2.77	0.0600/0.32/1.36	0.0020/0.01/0.05	0.1840/0.97/4.18	0.2000/1.06/4.54	0.3840/2.03/8.72	0.92
	OM	0.0553/ 0.23/0.53	0.0060/0.03/0.06	0.0203/0.09/0.19	0.0816/0.35/0.78	0.2943/1.25/2.81	0.3759/1.60/3.59	0.2773
	UF	0.0302/ 0.15/0.31	0.0271/0.14/0.28	0.0198/0.10/0.20	0.0771/0.39/0.79	0.2779/1.42/2.85	0.3550/1.82/3.64	0.2773
TP		**0.1056/0.02/1.22**	**0.0665/0.12/0.77**	**0.0336/0.06/0.39**	**0.2057/0.38/2.3**	**0.2613/0.49/3.02**	**0.4670/0.87/5.40**	**0.7872**
	TP	0.1056/0.20/1.22	0.0665/0.12/0.77	0.0336/0.06/0.39	0.2057/0.38/2.38	0.2613/0.49/3.02	0.4670/0.87/5.40	0.7872
Provincial average		0.0807/0.42/34.61	0.0427/0.26/21.43	0.0213/0.10/8.63	0.1447/0.78/64.46	0.2297/0.92/75.88	0.3745/1.70/140.53	0.9976

* Average of Ecoprovince was calculated by area weight of each Ecoregion.

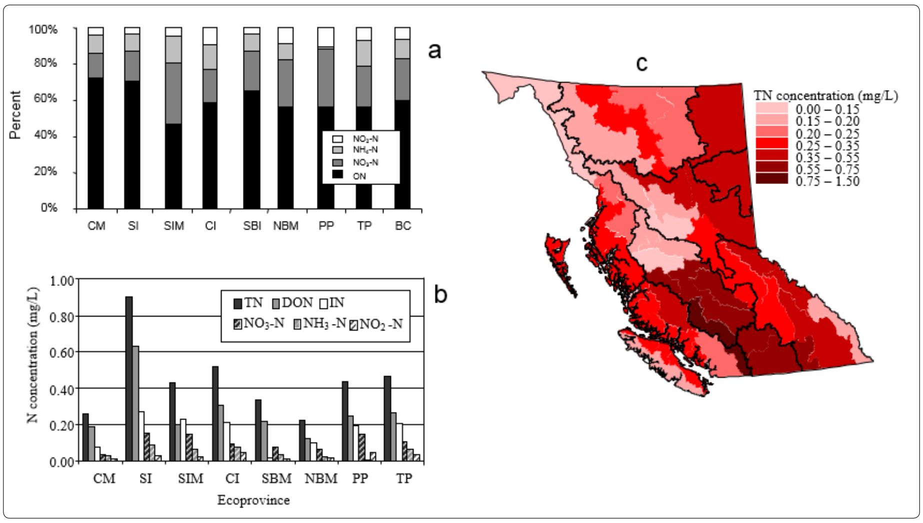

Figure 3

Landscape patterns of stream nitrogen loadings

The mean stream total nitrogen loading was 1.70 kg ha^{-1}yr^{-1} for the entire British Columbia, consisting of 0.42 kg ha^{-1}yr^{-1} of NO_3-N, 0.26 kg ha^{-1}yr^{-1} of NH_3-N, 0.10 kg ha^{-1}yr^{-1} of NO_2-N and 0.92 kg ha^{-1}yr^{-1} of DON. The highest rate of stream nitrogen loading (2.35 kg ha^{-1}yr^{-1}) appeared in Coastal Mountains and the lowest (0.87 kg ha^{-1}yr^{-1}) in Taiga Plain (Table 2; Figure 4). The stream total nitrogen loadings across British Columbia showed the following landscape patterns: (1) decrease from the Coastal Mountains to the Central Interior and further decrease from the Central Interior to the eastern boundary of British Columbia; (2) decrease from south to north except the Sub-Boreal Mountains; and (3) decrease from south to north in the Peace and Taiga Plains (Figure 4a, 4b). Stream organic nitrogen loadings showed the similar landscape patterns as the stream total nitrogen loading did. Inorganic nitrogen loadings showed following spatial patterns: (1) South Interior had the lower inorganic nitrogen loading and increased from the South Interior west to Costal Mountains and east to South Interior Mountains in the south of British Columbia, and (2) decrease from South Interior Mountains (SIM) to North Boreal Mountains (NBM) except Sub-Boreal Mountains (Figure 4a). The stream nitrogen loading varied greatly within each Ecoprovince, generally decreased from south to north (Figure 4b).

Overall, total annual nitrogen transfer from terrestrial to aquatic ecosystems was 140.54 Mt yr^{-1} for the entire British Columbia, consisting of 8.63 Mt of NO_2--N, 34.61 Mt of NO_3--N, 21.43 Mt of NH^{4+}-N, and 75.88 Mt of DON (Table 3).

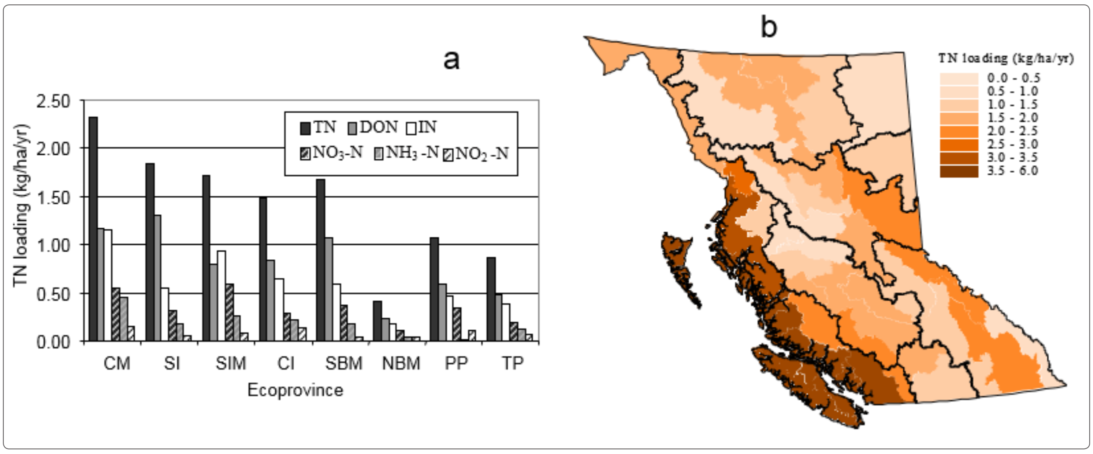

Figure 4

Nitrogen budgets for the ecosystems of British Columbia

Nitrogen budgets for each Ecoregion and Ecoprovince of British Columbia were summarized in Table 3. Some biogeochemical processes of nitrogen cycle such as nitrogen biological fixation, atmospheric nitrogen dry deposition, and denitrification were not included in this study because there were not enough data to quantify their landscape variations accurately. Also point sources of nitrogen from industries were not included because they were minimal according to the information from the Ministry of Environment, British Columbia (http://www.env.gov.bc.ca).

Precipitation nitrogen deposition was one of the most important nitrogen sources for the ecosystems of British Columbia. Provincial average of precipitation nitrogen deposition was 1.78 kg ha^{-1} yr^{-1} with the lowest, 0.40 kg h^{a-1} yr^{-1}, in the Northern Boreal Mountains and the highest, 2.69 kg ha^{-1} yr^{-1}, in the Central Interior (Table 3). Average of nitrogen fertilizer application was 0.18 kg ha^{-1} yr^{-1} with the lowest, 0.01 kg ha^{-1} yr^{-1}, in the Taiga Plains and the highest, 0.35 kg ha^{-1} yr^{-1}, in the Southern Interior. The average of nitrogen input from manure application was 0.01 kg ha^{-1} yr^{-1}, the lowest in the Northern Boreal Mountains and the highest in the Southern Interior Mountains. Annually total input of nitrogen for entire British Columbia was 162.76Mt including 147.33 Mt from precipitation deposition, 14.46 Mt from fertilizers, and 0.97 Mt from manure.

Total stream nitrogen loading for entire British Columbia was140.54 Mt yr^{-1} that accounted for 86.35% of total nitrogen inputs (Table 3). The average rate of annual nitrogen removal by logging was 1.07 kg ha^{-1} yr^{-1} for the entire ecosystems of British Columbia, with the lowest, 0.24 kg ha^{-1} yr^{-1}, in the Taiga Plains and the highest, 2.06 kg ha^{-1} yr^{-1}, in the Sub-Boreal Interior. Annual nitrogen removal due to forest logging for entire British Columbia was 88.38Mt that accounted for 54.30% of total nitrogen inputs form atmospheric precipitation deposition, fertilizer and manure applications. Stream nitrogen loss from the terrestrial ecosystems in the Coastal Mountains and the Northern Boreal Mountains were more than nitrogen inputs to these ecosystems from atmospheric precipitation deposition, fertilizer and manure application. Overall, total nitrogen losses through stream loading and forest logging were more than the inputs from precipitation deposition, fertilizer and manure application for the terrestrial ecosystems of British Columbia.

Table 3. Nitrogen budget for each Ecoregions and Ecoprovince of British Columbia

Ecoprovince	Ecoregion	Deposition (kg ha-yr-)/ (Mt)	Fertilizer (kg ha-yr-)/ (Mt)	Manure (kg ha-yr-)/(Mt)	Total-input (kg ha-yr-)/ (Mt)	Stream load (kg ha-yr-)/ (Mt)	Logging removal (kg ha-yr-)/ (Mt)	% of stream export to total input	% of logging to total input	Total input minus total output (Mt)
CI		2.69*/28.84* 0.26/2.84		0.0041/0.0439	2.96/31.72	1.48/15.89	1.90/20.01	50.11	46.33	-4.18
	BP	1.50/1.80	0.06/0.07	0.0013/ 0.0016	1.56/1.87	0.71/0.85	0.66/0.79	45.32	42.36	0.23
	CIP	3.50/12.02	0.49/1.68	0.0063/ 0.0216	4.00/13.71	1.57/5.39	1.47/5.03	39.32	36.68	3.29
	ChR	3.50/5.31	0.17/0.26	0.0009/ 0.0014	3.67/5.57	2.80/4.25	0.75/1.14	76.28	20.52	0.18
	LN	1.70/2.45	0.42/0.63	0.0030/0.0043	1.76/2.54	0.31/0.44	3.33/4.79	17.44	188.83	-2.7
	NP	1.50/2.10	0.06/0.08	0.0030/0.0042	1.56/2.19	1.08/1.51	2.17/3.04	69.17	139.1	-2.37
	PL	3.00/5.16	0.38/0.65	0.0063/0.0108	3.39/5.83	2.00/3.45	3.02/5.20	59.14	89.28	-2.82
CM		2.06/54.12	0.10/2.59	0.0018//0.0486	2.16/50.07	2.35/61.32	0.77/20.43	107.45	14.48	-31.68
	PER	3.00/1.84	0.49/0.30	0.0235/0.0144	3.51/2.15	2.48/1.52	8.26/5.07	70.64	235.06	-4.43
	EF	0.30/1.29	0.01/0.04	0.0001/0.0004	0.31/1.33	2.74/11.82	0.20/0.87	882.92	65.19	-11.32
	NR	0.30/0.41	0.01/0.01	0.0001/0.0001	0.31/0.43	1.84/2.54	1.13/1.56	593.53	363.51	-3.67
	NCM	0.40/1.78	0.01/0.04	0.0001/0.0004	0.41/1.82	1.71/7.61	0.05/0.23	417.42	12.87	-6.02
	WIM	2.62/8.49	0.38/1.23	0.0033/0.0107	3.00/9.73	4.43/14.34	2.17/7.04	147.36	72.34	-11.65
	NPC	3.00/29.55	0.06/0.59	0.0013/0.0128	3.06/30.15	1.50/14.77	0.12/1.14	49	3.79	14.24
	SPC	2.62/1.30	0.01/0.01	0.0038/0.0019	2.61/1.31	4.83/2.42	4.46/2.23	184.76	170.53	-3.34
	SPR	4.8/9.76	0.18/0.37	0.0038/0.0077	4.98/10.14	3.11/6.33	1.12/2.29	62.45	22.55	-11.65
NBM		0.40/4.33	0.15/1.60	0.0001/0.0011	0.55/5.93	1.01/10.96	0.14/1.51	184.69	3.67	-6.54
	CaR	0.40/1.95	0.01/0.05	0.0001/0.0005	0.41/2.00	1.58/7.71	0.24/1.19	386.36	59.49	-6.91
	SP	0.40/2.38	0.26/1.55	0.0001/0.0006	0.66/3.93	0.54/3.24	0.05/0.32	82.35	8.01	0.38
PP		2.00/7.51	0.34/1.28	0.0029/0.0109	2.34/8.80	1.85/4.01	1.01/3.90	45.55	24.23	0.89
	PP	2.00/7.51	0.34/1.28	0.0029/0.0109	2.34/8.80	1.07/4.01	1.01/3.81	45.55	43.26	0.89
SI		2.00/7.64	0.35/1.35	0.0076/0.0289	2.36/9.02	1.78/7.05	1.17/3.90	78.15	30.66	-1.93
	OP	2.00/2.90	0.13/0.19	0.0080/0.0116	2.14/3.10	1.52/2.21	1.82/2.64	71.17	85.09	-1.74
	SI	2.00/4.74	0.49/1.16	0.0073/0.0173	2.50/5.92	2.04/4.84	0.53/1.26	81.8	21.29	-0.18
SIM		1.54/17.30	0.25/2.86	0.0505/0.5681	1.84/20.73	1.72/19.32	1.28/12.91	93.18	29.78	-11.5
	CbM	1.00/4.18	0.33/1.38	0.0094/0.0393	1.34/5.60	2.24/9.37	0.42/1.75	167.24	31.3	-5.52
	OH	2.00/4.34	0.13/0.28	0.0080/0.0174	2.14/4.64	1.06/2.30	3.32/7.20	49.54	155.27	-4.86
	UFR	2.00/2.97	0.17/0.25	0.0080/0.0119	2.18/3.23	0.66/0.97	0.77/1.14	30.17	35.37	1.11
	SH	2.00/4.83	0.26/0.63	0.2023/0.4882	2.46/5.94	1.45/3.51	0.66/1.58	59.05	26.66	0.85
	SSM	1.00/0.99	0.32/0.32	0.0114/0.0113	1.33/1.32	3.20/3.17	1.24/1.23	240.35	92.98	-3.08
SBI		2.12/21.08	0.21/2.05	0.0036/0.0361	2.33/16.59	1.67/16.59	2.06/24.32	71.61	17.57	-24.32
	Bu	1.50/ 2.11	0.06/0.08	0.0030/0.0042	1.56/2.19	0.47/0.66	3.41/4.79	30.12	218.42	-3.26
	CRM	2.50/1071	0.18/0.77	0.0038/0.0163	2.68/11.50	2.03/8.70	0.36/1.55	75.64	13.46	1.25
	OM	1.00/2.25	0.38/0.85	0.0013/0.0029	1.38/3.11	1.60/3.59	2.40/5.40	115.61	173.82	-5.88
	UF	3.00/6.02	0.17/0.34	0.0063/0.0126	3.18/6.37	1.82/3.64	6.28/12.58	57.15	197.56	-9.85
TP		1.00/6.02	0.01/0.07	0.0038/0.2355 1.05/6.59	1.05/6.59	0.87/5.40	0.24/1.51	83.05	6.2	-0.41
	TP	1.00/6.02	0.01/0.07	0.00380/0.2355	1.05/6.59	0.87/5.40	0.24/1.51	83.05	23.25	-0.41
Sum of province		1.78/147.33 0.18/14.46		0.0117/ 0.97	1.97/162.76	1.70/140.54	1.07/88.38	86.35	54.3	-66.16

*nitrogen budget for per hectare and ** for Ecoregion and Ecoprovince

Discussions

Impacts of climate conditions on the stream nitrogen components, concentrations and loadings

The data from the 30 Ecoregions were used to analyze the impacts of landuses (forests, agriculture and urban area), human activities (precipitation nitrogen deposition, population, fertilizer and manure application, cattle density, and forest logging) and climate conditions (air temperature and precipitation) on stream nitrogen components, concentratiosn and loadings by Pearson's correlation analysis. The results of Pearson's correlation analysis are summarized in Table 4. The results showed that air temperature had the positive correlations with the stream nitrogen concentrations and loadings in British Columbia, which mean that warm areas had higher stream nitrogen concentrations and loadings than cold area across British Columbia. Air temperature affected stream inorganic nitrogen concentrations and loadings more than DON because high temperature significantly increased the ratio of stream inorganic nitrogen (sum of nitrate, nitrite and ammonia) to organic nitrogen concentration ($P<0.01$), an index to evaluate relative amount of stream inorganic to organic nitrogen content. Stream nitrogen components, concentrations and loadings are affected by temperature because temperature impacts the biotic and abiotic processes that govern nitrogen biogeochemical processes such as nitrogen biological fixation, plant uptake, miniralization, and denitrification [25]. The ecosystems with high temperature have high biomass growth rate that accumulates more organic matter in the soils through litterfall and also high temperature increases mineralization rate that releases nitrogen from soil organic matter to surface water [10,14,15,21]. High temperature resulted in more inorganic nitrogen in stream water (Figure 5d). This may be the result of two ecosystem processes. Firstly, the rate of released inorganic nitrogen from soil organic matter to soil water through mineralization and nitrification is larger than the rate of released dissolved organic nitrogen into soil water through decomposition under the condition of high temperature and secondly increased temperature may enhance the nitrification of dissolved organic nitrogen compounds in surface water [26,27].

Precipitation affected stream nitrogen components, concentrations and loadings because the primary roles of water are transport medium and solvent. Precipitation had negative correlations with the concentrations of all form stream nitrogen, which mean that high precipitation resulted low stream nitrogen concentrations, a result of dilution [25]. Precipitation significantly diluted the stream total nitrogen concentration ($P<0.05$), mainly through diluting stream DON concentration ($P<0.01$). Precipitation had positive correlations with stream nitrogen loadings. High precipitation significantly increased stream NO_3-N, NH_3-N, IN, and TN loading at $P<0.01$. The impacts of precipitation on the stream nitrogen loading might be due to following factors: (1) higher precipitation resulted high stream flow that transferred more nitrogen from soils to streams; and (2) higher precipitation deposited more nitrogen into streams and soils from where nitrogen was exported to streams by runoff, lateral flow and percolation. A significant correlation existed between precipitation and the ratio of stream inorganic to organic nitrogen concentration ($r = 0.37$, $P<0.05$). High precipitation increased stream inorganic nitrogen as precipitation nitrogen consists of mainly inorganic nitrogen. Also precipitation affects nitrogen biogeochemical processes through affecting temperature, soil moisture, vegetation type and growth [25].

Although temperature and precipitation had significantly correlated to stream nitrogen components, concentrations and loadings, how temperature and precipitation affects stream nitrogen components, concentrations and loadings are complicate. Also a correlation exists between temperature and precipitation in British Columbia territory, which makes the impacts of temperature and precipitation on stream nitrogen more complicate. The Coastal Mountain ecosystems are the most productive ecosystems in British Columbia due to high air temperature and precipitation. In these ecosystems, the soil nitrogen content is high due to high accumulation of soil organic matter. The Taiga Plain ecosystems are the least productive ecosystem, presumably due to cold and dry climate conditions, low soil nitrogen content and low soil organic matter accumulation [15].

The temperature and precipitation are closely related to the landscape distributions of vegetation and soils in British Columbia, so the impacts of topography, vegetation and soil on stream nitrogen were indirectly addressed in this study [15]. For example, similar to the impacts of red alder (a nitrogen fixation species, *Alnus rubra* bong.) on stream nitrogen loading in the Oregon Coast Range, the landscape pattern of stream nitrogen loading (Figure 3) well matched the landscape pattern of red alder distribution described by Massie across British Columbia [11,28]. This demonstrated that stream nitrogen was affected by natural vegetation, especially nitrogen fixation species in British Columbia because all the nitrogen cycling processes are biological associated processes.

Impacts of landuse and human activities on the stream nitrogen components, concentrations, and loadings

Increased atmospheric nitrogen deposition mainly resulted from increased industrial nitrogen emission. This study found that precipitation nitrogen deposition increased stream nitrogen concentrations and loadings, but only concentration and loading of stream NO_2-N, inorganic nitrogen and total nitrogen loading increased at significant level ($P<0.05$, Table 4). The impact of precipitation nitrogen deposition on stream nitrogen mainly resulted from its impact on increasing stream inorganic nitrogen concentration and loading, especially increasing stream NO2-N concentration and loading. The population density had significant impacts on stream total nitrogen loading at $P<0.05$, mainly through increasing stream inorganic nitrogen loading. The impacts of landuse and other human activities in terms of urban area, forest, agriculture, cattle density, manure and fertilizer application on stream nitrogen concentrations and loadings did not reach significant level currently in British Columbia.

Landuse change and human activities significantly increased stream nitrogen loadings in eastern United States and Europe Our data showed that stream nitrogen components, concentrations and loadings in British Columbia were determined by both climatic and anthropogenic factors (Table 4) [5,8,29]. Total population of British Columbia was ~4 millions, more than 70% live in Greater Vancouver and Victoria. Population density of British Columbia was ~ 4 people per km2. Forests and other natural vegetations cover more than 95% of British Columbia land. Agriculture land area was less than 2.6%. Although ~14Mt nitrogen fertilizers were applied in agricultural practice per year, they contributed ~2.8Mt nitrogen to aquatic ecosystems, 20% of total fertilizer application transported into streams according to Howarth et al [30]. This only accounted for ~2% of total stream nitrogen loading for entire British Columbia. We concluded that the ecosystems of British Columbia keep relatively natural status except the two Ecoregions of SPR and WIM where Greater Vancouver and Victoria cities are located (Table 1). Pearson's correlation analysis showed that climate dominated the components, concentrations and loadings of stream nitrogen for these relatively natural ecosystems of British

Columbia (Table 4). The climate condition indirectly affects stream nitrogen through its impacts on the distribution of population density across British Columbia because warm areas are high population density and intense agriculture practices.

Table 4: Pearson's correlation coefficients of the stream nitrogen concentration and loading to climate, landuse and anthropogenic impacts

Factors	Loading								Concentration					Climate		
	TN	DON	IN	NO3-N	NO2-N	NH3-N	TN	DON	IN	NO3-N	NO2-N	NH3-N	Ratio	T	PPT	PND
Temperature (T)	0.70**	0.32*	0.72**	0.61**	0.48**	0.55**	0.29	0.05	0.41*	0.40*	0.31	0.40*	0.58**			0.53**
Precipitation (PPT)	0.58**	0.25	0.50**	0.49**	0.28	0.54**	-0.42*	-0.43**	-0.21	-0.24	-0.2	-0.15	0.37	0.42*		-0.01
Forestry	-0.17	0.01	-0.13	-0.15	-0.16	-0.2	0.21	0.19	0.2	0.06	0.14	0.17	-0.07	0.15	-0.44**	0.25
Agriculture	0.25	0.2	0.14	0.3	0.27	-0.09	-0.02	0.03	-0.12	0.04	0.04	-0.19	-0.03	0.11	0	0.29
Urban	0.17	-0.08	0.23	0.18	0.73**	-0.07	0	-0.09	0.07	0.09	0.38	-0.07	0.3	0.27	0.11	0.48**
Population	0.33	-0.03	0.36*	0.24	0.87**	0.15	-0.14	-0.21	-0.02	-0.06	0.3	-0.07	0.44	0.39	0.32	0.56**
Fertilizer	0.07	0.18	-0.01	-0.04	-0.04	0.09	0.31	0.37	0.05	0.19	0.08	-0.01	-0.02	0.16	-0.22	0.33*
Manure	0.01	0.04	-0.05	0.03	-0.11	-0.01	0.17	0.14	0.02	0.21	-0.08	0.08	-0.13	0.14	-0.19	0.17
Cattle	0	-0.01	-0.04	-0.01	0.28	-0.14	-0.09	-0.01	-0.17	-0.12	0.04	-0.21	-0.04	0.04	-0.06	0.42
Logging	0.17	0.21	0.07	0.18	0.03	-0.02	-0.17	-0.11	-0.16	-0.16	-0.12	-0.16	-0.05	0.23	0.04	0.35*
PND	0.32*	0.23	0.32*	0.22	0.58**	0.04	0.27	0.21	0.26	0.18	0.47*	0.08	0.3	0.53**	-0.01	1

* represent significant level at P<0.05, ** P<0.01, PND is precipitation nitrogen deposition.

$$N_T = a * e^{b*T} \quad (4)$$

where NT is total stream nitrogen loading (kg ha^{-1} year^{-1}) predicted by air temperature (T, °C), a and b are equation coefficient.

A significant correlation existed between air temperature and precipitation for the Ecoregions of British Columbia, with 0.42 of Pearson's correlation coefficient at the significant level of P<0.05. To reduce the correlation between temperature and precipitation and analyze the impact of individual temperature and precipitation on stream nitrogen loading, we separated the Ecoregions in the Coastal Mountains Ecoprovince from the other Ecoregions in rest of British Columbia (Figure 5a). As a result of the separation, the correlation between temperature and precipitation were not significant for either the ecosystems in Costal Mountains (r=-0.01, P>0.05) or the other ecosystems in the rest of British Columbia (r=-0.08, P>0.05). Then, the impact of landscape temperature gradient on stream total nitrogen loading was quantified by three ways: (1) using data from all the ecosystems in British Columbia, (2) from the ecosystems in Coastal Mountains, and (3) from the ecosystems in the interior of British Columbia (Figure 5b). According to our databases, the parameterized Equation (4) is:

$$\begin{aligned} N_T &= 0.795e^{0.153T} && \text{for all ecosystems} \\ N_T &= 0.563e^{0.214T} && \text{for Coastal ecosystems} \\ N_T &= 0.727e^{0.111T} && \text{for Interior ecosystems} \end{aligned} \quad (5)$$

The r^2 value is 0.89 for all the ecosystems of British Columbia at significant level of P<0.01, 0.96 for the Coastal Mountains ecosystems and 0.86 for the Interior ecosystems at P<0.05. Parameter *a* and *b* value are significant at P<0.05 except *a* value for Coastal Mountains ecosystems.

Figure 5c showed that a logarithmic relationship existed between precipitation and stream total nitrogen loading. Similar to analyzing the impacts of temperature on stream nitrogen loading, the three ways were used to quantify the impacts of precipitation on stream total nitrogen loading. Precipitation had no significant impact on stream nitrogen loading for the ecosystems in either the Coastal Mountains or the interior of British Columbia separately, but it had a significantly impacts on stream total nitrogen loading for all the ecosystems of British Columbia (Figure 5c). The relationship between precipitation and stream total nitrogen loading was expressed as

$$N_P = a + b * \log(P) \quad (6)$$

where N_p is total stream nitrogen loading predicted by precipitation (kg ha^{-1} year^{-1}) and P is precipitation (mm year^{-1}). The parameterized Equation 6 is:

$$N_p = -2.916 + 0.698\log(P) \quad (7)$$

The Equation has 0.80 of r2 value with significant level at P<0.05. Parameter b has significance at P<0.05 and *b* has no significance.

The ratio of stream inorganic nitrogen to organic nitrogen was used as an indicator of the change of stream nitrogen components. The ratio is relatively less affected by precipitation because precipitation simultaneously dilutes stream inorganic and organic nitrogen concentrations. The ratio of inorganic nitrogen to organic nitrogen concentration increased exponentially as air temperature increases (Figure 5d). The relationship was mathematically expressed as

$$R_{io} = a * e^{b*T} \quad (8)$$

where R_{io} is the ratio of inorganic nitrogen to organic nitrogen concentration in stream water and *T* is air temperature. The parameterized Equation (8) is:

$$\begin{aligned} R_{io} &= 0.553e^{0.119T} && \text{for all ecosystems} \\ R_{io} &= 0.239e^{0.223T} && \text{for Coastal ecosystems} \\ R_{io} &= 0.645e^{0.095T} && \text{for Interior ecosystems} \end{aligned} \quad (9)$$

The r^2 value was 0.75 for all ecosystems, 0.87 for the Coastal ecosystems, and 0.72 for Interior ecosystems. These parameterized Equations are all significant at P<0.05.

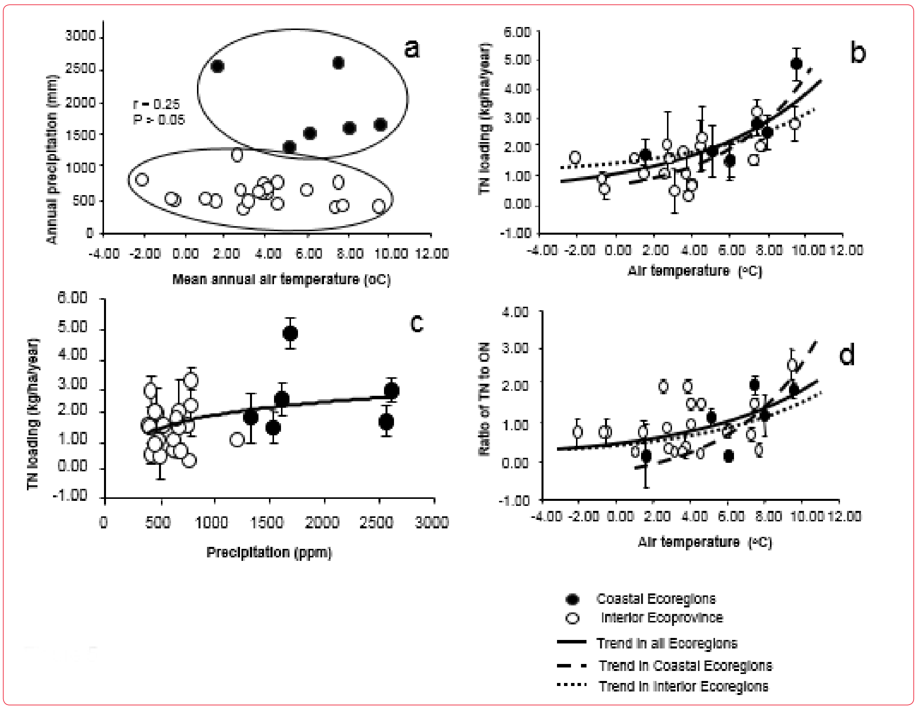

Figure 5

The r^2 value was 0.75 for all ecosystems, 0.87 for the Coastal ecosystems, and 0.72 for Interior ecosystems. These parameterized Equations are all significant at $P<0.05$.

Even though climate conditions were dominant factors that controlled stream nitrogen loading in the ecosystems of British Columbia, it is important to know how the stream total nitrogen loading responded to per °C increment of landscape temperature gradient across British Columbia. The impact of landscape gradient of temperature on stream total nitrogen loading was quantified by

$$N_{Ti} = N_{To} e^{b(T_i - T_o)} \qquad (10)$$

where NTi is stream nitrogen loading when air temperature increases from current (To) to future temperature (Ti) and NTo is current stream total nitrogen loading. The model development was based on Equation 4 with form, , using air temperature and stream total nitrogen loading as variables (Figure 5b). We calculated the unit increase ( ) in stream total nitrogen loading by

$$\delta_T = \frac{N_{Ti} - N_{To}}{N_{To}} = e^{b(Ti - To)} - 1 \qquad (11)$$

when temperature increases from To to Ti. We also assumed that

$$N_{Ti} = N_{To} + N_{To}\delta_T = N_{To}(1 + \delta_T) \qquad (12)$$

Combining Equation 11 with Equation 12, we derived Equation 10. The parameterized
Equation 10 is:

$$N_{Ti} = N_{To} e^{0.153(T_i - T_o)} \quad \text{for all ecosystems}$$

$$N_{Ti} = N_{To} e^{0.214(T_i - T_o)} \quad \text{for Coastal ecosystems}$$

$$N_{Ti} = N_{To} e^{0.111(T_i - T_o)} \quad \text{for Interior ecosystems}$$

The models, Equation 13, predicts that each °C increment of landscape temperature gradient increased stream total nitrogen loading by an average of 16.54% in entire British Columbia, 23.88% in the Coastal Mountains ecosystems, and 11.75% in the Interior ecosystems according to the data collected during the past 30 years.

Using similar procedures, each oC increment of landscape temperature gradient resulted in 11.90% increase of the ratio of stream inorganic to organic nitrogen concentrations for the entire British Columbia, 9.50% for the Interior ecosystems and 22.30% for the Coastal Mountain ecosystems.

These results of landscape temperature gradient impacts on stream nitrogen may have meaningful implications for the impacts of climate change and global warming on stream nitrogen components, concentrations and loadings [31]. For the different Ecoregions of British Columbia, total stream nitrogen loading in response to per °C increments of landscape temperature gradient increased from 0.10 kg ha^{-1} yr^{-1} in the Central Interior to 0.56 kg ha yr^{-1} in the Coastal Mountains according to Equation (13) using current air temperature and stream nitrogen loading regimes. In total, one °C increment of air temperature across British Columbia resulted in an extra 23.24 Mt of nitrogen loading from terrestrial to aquatic ecosystems. These models would suggest that the Coastal marine ecosystems might be more sensitive to climate change and global warming than the Interior ecosystems according to Equation (9) and (13). The further studies are needed to address the actual responses of the stream nitrogen components, concentrations and loadings to climate change and global warming because the responses of many ecosystem processes that affect nitrogen cycling were not quantified such as vegetation components, nitrogen fixation, plant uptake, and denitrification in this study.

Stream nitrogen from all of the ecosystems except the Taiga and Peace Plains (Arctic drainage) flows into the coastal regions of British Columbia, suggesting that such increased nitrogen loading to aquatic systems may have an important impact on the coastal marine ecosystems under increased human activities and expected shifts to higher temperature and precipitation due to global climate change [15,32]. Given the stream nitrogen components, concentrations and loadings were affected by both climate conditions and human activities in British Columbia, the increasing patterns of enhanced (e.g., aquaculture and other land-based disturbances) stream nitrogen loadings from anthropogenic sources together with projected climate change may further deteriorate coastal marine and freshwater ecosystems in British Columbia [32].

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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