Assessing N inputs and outputs for Canada's forest

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March 2010

Summary

According to the State of the Forest Report 2009 (Natural Resources Canada 2009), total forest coverage in Canada amounts to 403 million ha, and annual tree biomass production across Canada amounts to 410 billion tons. About 0.22 % of this amount would be N (Arp et al. 2008). For this production to be sustainable, forests need a primary N supply amounting to 887,000 N tons per year. This amount is almost met by the estimated annual dry and wet atmospheric deposition rate of 813,000 N tons per year. Under steady–state input-output assumptions, the atmospheric N so captured would be returned to the atmosphere on account of slow and occasional but fast N re-mineralization processes. The slow process refers to litter decay and N cycling, involving litter fall, and gradual organic matter decomposition, N mineralization, nitrification, leaching and denitrification. Soil-based N_2O emissions due to denitrification are the result of excess NO_3-N transfer from uplands to wet areas below through soil leaching and run-off. The fast component refers to recurring fires, which mostly consumes forest canopies, leaving charred stems behind. The amount of N returned so returned amounts to 411,000 tons per year, i.e., 44% of the total amount atmospheric N deposition. Harvesting removes about 150,000 N tons per year from the forested areas, i.e., 19% of the atmospheric N deposition. Denitrification is estimated to return 327,000 N tons per year to the atmosphere (26.3%) owing to anaerobic NO_3-N to N_2O and N_2 transformations. In addition, there are stream-based N exports from forested areas, amounting to (i) 32,500 NO3-N tons per year, and (ii) 159,000 DON-N tons per year. This report also gives an assessment of biomass-related N inputs and outputs by province and territory, and by forest type: hardwoods (HW), mixed woods (MW) and softwoods (SW). The numbers quoted are based on average numbers and calculations by province and territory, as provided by the State of Forest Report (Natural Resources Canada, 2009). A more thorough approach would build these averages from provincial and territorial inventories regarding forestry, hydrology, climate, and topography.

Details

Deciduous versus coniferous forests. Nitrification is an important N cycling process in deciduous forest soils, where a substantial portion of mineralized N is transformed into leachable NO_3-N. Leachable NO_3-N, once transferred from the upland areas to the wet areas below, is converted into volatile N products such as N_2O and N_2. This conversion also applies to the atmospheric NO_3-N component that falls directly into the wet-area component of the forested landscape, regardless of the surrounding forest cover type. In contrast, coniferous forests tend to absorb and transform most of the incoming active N component from the atmosphere into organic N. Coniferous forest soils, are generally too acidic to support the growth and activities of nitrifying soil bacteria. Regardless of forest cover type, very little N is found in forest soil leachates and forest streams and lakes in the form of NH_4-N (Dillon and Molot 1990), in spite of extensive organic matter mineralization.

N_2 fixation. In addition to atmospheric N deposition, and vegetative uptake of recycled N, ecosystems benefit from directed atmospheric N_2 absorption on account of N_2-fixing algae (canopy-dwelling blue-green algae) and bacteriae either free-living or in symbiosis with select herb, shrub, and tree hosts such as sweet fern, black locusts and alder, respectfully. For example, sweet fern thrives under open conditions, occupying recently burnt or harvested well-drained, coarse-textured forest sites for a few years. The net on-site N benefit so accrued, however, would be lost from the site again on account of recurring forest fires or harvesting activities. Alder also grows on open and generally wet-area soils that are not too acidic. On these sites, nitrification of N_2-fixed N tends to limit the extent and intensity of alder growth on account of nitrification-induced soil acidification. As well, some of the N_2 that is fixed on these sites and subsequently converted to NO_3-N is leached and subject to denitrification within the adjacent generally poorly drained soils. Generally, NO_3-N inputs and production in forest soils tend to inhibit, decrease or delay the N_2-fixation process, as would be the case in the more temperate regions of Canada to some extent. In contrast, N_2-fixation exceeds atmospheric N deposition towards alpine and arctic regions where atmospheric N deposition rates are generally low, and lichens, moss-based vegetation in combination with non-symbiotic N_2-fixing bacteriae utilize long daylight hours for the energy-consuming N_2-fixation process. In addition, a steady production and presence of acetylene within the soil-vegetation complex enables the N_2-fixation process while encouraging the denitrification process at the same time. In anaerobic soils, the N_2-fixation comes only into effect once the initially available NO_3-N supply has been depleted (Yoshinara et al. 1976). N_2-fixation rates are typically highest at the soil surface under moist and warm conditions, especially along toe-slopes (Hobara et al. 2006).

Net N immobilization by soil organic matter. Soil organic matter, as it gradually builds up in soils over years, decays and centuries, tends to display a decreasing C/N ratio from initially fairly high values in excess of 100 towards a final value of about 10 or somewhat lower with increasing organic matter humification. Typically, this change can be observed in each forest soil profile, with high C/N ratios on top, and lowest values in the subsoil. Here, C refers to organic C, as opposed to total C which would include calcareous C as well. After more than 10,000 years of post-glacial soil development, rates of further net N immobilization via soil humification within a soil profile would likely be very small or negligible, even under old-growth forest conditions. There are several reasons for this: over the course of time, most forest ecosystems are subject to recurring disturbance regimes, involving fire, storms, soil erosion, and land-use including forest harvesting, deforestation and rapid expansion of industrial, agricultural and recreational activities. Soil disturbances generally lead to higher rates of organic matter and N mineralization with less humified matter remaining on account of greater soil exposure and exposure to the air (oxygen).

Tracking N inputs and outputs. Quantifying the extent of wet areas embedded within the forest landscape is an instructive way to quantify net N inputs and outputs across forest landscapes as affected by the local variations in soil drainage (Murphy et al. 2009). In this way, one can account for (i) upslope N uptake and subsequent litter production by the vegetation, (ii) the extent of upslope nitrification of some of the N mineralized during litter decay, and (iii) the amount of nitrified N from transferred from the uplands to the wet areas below. The resulting N retention efficiency of the forest decreases with

(i) increasing wet-area percentage per basin,
(ii) decreasing upland soil permeability,
(iii) increasing deciduous or decreasing coniferous coverage per basin.

Part of the basin-wide N efficiency assessment also needs to address N loss via stream export in the form of (i) the non-denitrified portion of the incoming NO3-N component, and (ii) dissolved organic nitrogen (DON). The latter amount is directly related to stream-based DOC exports, given by (Murphy et al. 2009)

$$DON\ (N\ kg\ ha^{-1}\ yr^{-1}) = 0.01\ (2.1 + 32\ A_W/A_B)/(40.6+317A_W/A_B)\ Q_{stream}. \quad [1]$$

where A_W/A_B is the wet area ratio for the forested basins, and Q_{stream} is stream discharge. Basin-wide N exports via stream discharge are generally about 5% of atmospheric deposition.

The amount of atmospheric N lost from deciduous and mixed-wood forests can be estimated using the following formula (Murphy et al. 2009)

$$N_{denitrification} = (N_{deposition} + \text{other } NO_3\text{-N inputs}) \text{ x } \max[1, 1.22(A_W/A_B)^{0.22}]. \quad [2]$$

For coniferous forests, it is assumed that all of the incoming N that falls on the uplands is assumed to be taken up by the vegetation. The NO_3-N portion that falls on the SW embedded wetlands is assumed to be denitrified.

Combining the forest biomass balance with the N balance for Canada's forests

Table 1 quantifies the annual rates of N deposition per forested areas by province and totals across Canada. Also shown are the estimates for

(i) N accumulated by the forests in each province,
(ii) N re-emitted to the atmosphere on account of forest fires (assuming that these fires consume foliage, twigs and branches),
(iii) N exported from the forest via harvesting (assuming stem-wood harvesting only),
(iv) The extent of NO3-N denitrification, as specified above,
(v) estimates for net N_2 fixation for provinces and territories with $N_{uptake} > N_{dep}$, so that $N_{2,\ fix} = N_{uptake} - N_{deposition}$. [3]

By province and territories, these calculations lead to positive net N_2 fixation values for British Columbia, Alberta, Yukon, Newfoundland and Labrador, Northwest Territories, and Nunavut because of the artic and alpine conditions within these areas. In turn, the net N_2-fixation estimates were quite small for Manitoba and Quebec, and absent altogether for Saskatchewan, Ontario, New Brunswick, Nova Scotia, and Prince Albert Island. The reduction of net N_2 fixation within the temperate forest regions may in part be due to NO_3-N induced inhibition of the N_2 fixing activities within these ecosystems (Yoshinara et al. 1976). However, reported values for absolute N_2 fixation rates can easily match and even exceed atmospheric N deposition rates within boreal and temperate forests (Boring et al. 1988). As such, these N inputs (i) would definitely be in excess of what is needed to support the documentable tree biomass production in temperate to boreal forests, (ii) do not appear in the reported N loads in the stream discharge from forested basins, (iii) but could be part of the production of the non-tree biomass in forested landscapes, and (iv) could also be part of substantial but less easily quantified and as yet un-documented losses due to herbivory (Hollinger 1988, Chapman 2006).

Across Canada, total N inputs due to atmospheric deposition and net N_2 fixation amount to 1,236,000 tons/year. The combined N loss due to fire, harvesting and wet-area based DON and denitrification (yielding a atmosphere re-entering combination of N_2O and N_2) amounts to 1,080,000 tons/year. The positive difference of 156,000 N tons/year would be an estimate of the N requirements of the net annual non-tree forest biomass production.

Assumptions

The assessment above is based on the following assumptions:

(i) The ratio of NH_4-N to total atmospheric deposition is given by 0.57 everywhere; this assumption needs to be revised, at least by province and territory, especially in areas where agricultural NH_3-N emissions influence the local and regional N deposition pattern.

(ii) For deciduous conditions (mixed woods and hardwoods), N_2-fixed nitrogen gets nitrified, and is then subject leaching and wet-area based N_2O and N_2 losses.

(iii) Softwood forests do not nitrify (too acidic), and do not denitrify incoming NO_3-N on uplands (well aerated); instead, denitrification in softwood forests is limited to direct atmospheric NO_3-N inputs into the embedded wet-area portions of these forests.

(iv) There are no NH_3-N losses from forested areas and associated wet areas and wetlands.

(v) Similarly, NH4-N exports from forests vis streams are assumed to be negligible.

(vi) Atmospheric N deposition that would accumulate within the snow is subject to upland and wet-area retention similar to what can be expected for landscape-wide N retention during the snow free season, according to Eq. 2.

(vii) The delineation of the total wet-area portions within the provinces and territories, as it was derived from the national digital elevation model (DEM) with its 300 m resolution, is more or less the same as the wet-areas portions derived from provincial DEMs with 30 m resolution or better.

(viii) The cartographic depth-to-water index of DTW=0.5 captures the areas within basins in which the denitrification reactions occur for the most part.

(ix) The conversion of standing forest biomass to annual biomass production assumes a 100 year disturbance recurrence cycle everywhere.

(x) The averaging of the forest conditions and the atmospheric deposition rates across each province and territory is adequate to represent the overall N retention and losses by province and territory by way of a first approximation.

(xi) Accounting for differences for climate, hydrology and topography within each province would sharpen the estimates of this report.

Recommendations

(i) The above assumptions should be re-addressed through follow-up examinations and detailed literature reviews.

(ii) The literature on N_2 fixation herbivory-based N losses should be reviewed to confirm the approach taken, and the estimates so generated across Canada.

(iii) The N input-output situation as described above and in Table 1 should also be examined based on data derived from well-studied case study. This may lead to a further refinements and/or re-calibrations of Eqs. 1 to 3.

(iv) Efforts should be made to refine the calculations using provincial or territorial data for forests, climate, hydrology, and topography.

(v) Doing so would generate presentations similar to Table 1, but by climate of forest regions within the provinces and territories.

Acknowledgements

Financial support for compiling the above report was gratefully received from Environment Canada, by way of a research contract (c/o Dr. T. Clair).

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Table 1. Biomass production, N inputs, uptake and outputs (fire, harvesting, streams) for forests in Canada, with wet-area corrections to ascertain the extent of wet-area based N losses.

Province / Territory	Forest type	Forest area	Wet area	Biomass production	Biomass burnt	Biomass harvested	Atm. N deposition	Net N2 fixation	N uptake forest	N fire loss	N harvest export	Denitri-fication	Areas burnt	Areas harvested	Stream flow	DOC production / export	DON export	NO_3-N export
		ha	ha	tons/y	tons/y	tons/y	tons/y	tons/y	tons/y	tons/y	tons/y	tons/y	ha	ha	mm	tons/y	tons/y	tons/y
BC	HW	3,212,500	323,159	8,167,626	151,772	2,137,693	4,318	16,094	18,531	344	4,850	3,328	597	8,408	798	136,331	1,881	990
	MW	8,352,500	840,212	18,101,669	336,367	4,737,707	11,227	35,638	41,975	780	10,986	8,653	1,552	21,861	798	354,462	4,890	2,575
	SW	52,685,000	5,299,800	94,410,452	1,775,981	24,709,824	70,817	156,277	196,250	3,701	51,364	4,061	9,790	137,891	798	2,235,834	30,844	-
	Total	64,250,000	6,463,171	120,679,747	2,264,120	31,585,224	86,362	208,009	256,756	4,826	67,200	16,041	11,939	168,160	798	2,726,627	37,615	3,565
AB	HW	10,917,000	1,408,749	23,080,623	1,309,361	3,487,210	36,567	17,401	52,366	2,971	7,912	29,621	6,193	16,494	192	130,545	1,602	6,946
	MW	6,186,300	798,291	11,148,710	632,465	1,684,439	20,721	6,039	25,852	1,467	3,906	16,785	3,509	9,347	192	73,976	908	3,936
	SW	16,739,400	2,160,082	24,943,908	1,432,517	3,768,730	56,069	-	51,851	2,986	7,834	4,124	9,496	25,291	192	200,170	2,456	-
	Total	36,390,000	4,695,831	59,173,241	3,374,343	8,940,379	113,357	21,677	130,069	7,423	19,652	50,530	19,199	51,132	192	435,151	4,965	10,883
SK	HW	3,881,600	802,367	4,081,055	19,012,045	218,688	9,546	194	9,259	43,135	496	8,497	180,829	2,080	151	51,067	481	1,049
	MW	8,976,200	1,855,473	8,044,584	37,476,585	431,078	22,076	-	18,654	86,903	1,000	19,649	418,166	4,810	151	118,092	1,113	2,426
	SW	11,402,200	2,356,952	8,449,493	39,848,377	452,776	28,042	-	17,564	83,049	941	3,304	531,184	6,110	151	150,009	1,413	-
	Total	24,260,000	5,014,792	20,575,132	96,337,007	1,102,542	59,664	-	45,477	213,087	2,437	31,450	1,130,179	13,000	151	319,168	3,007	3,476
MB	HW	5,452,500	1,971,921	4,527,770	1,876,789	170,000	8,557	2,898	10,273	4,258	386	8,518	22,601	2,047	246	183,597	1,183	39
	MW	3,998,500	1,446,075	2,830,318	1,173,184	106,267	6,275	1,155	6,563	2,720	246	6,247	16,574	1,501	246	134,638	867	29
	SW	26,899,000	9,728,143	15,743,641	6,606,322	591,112	42,214	-	32,726	13,768	1,229	8,702	111,498	10,100	246	905,745	5,834	-
	Total	36,350,000	13,146,139	23,101,728	9,656,295	867,379	57,046	400	49,562	20,747	1,861	23,467	150,673	13,648	246	1,223,979	7,884	68
ON	HW	10,926,400	3,425,066	4,955,388	9,535	1,335,067	39,545	-	11,243	22	3,029	38,255	210	29,438	478	633,577	4,527	1,290
	MW	17,755,400	5,565,732	6,864,050	13,207	1,849,293	64,261	-	15,917	31	4,288	62,165	342	47,836	478	1,029,563	7,356	2,096
	SW	39,608,200	12,415,863	12,660,943	24,662	3,411,076	143,351	-	26,318	51	7,091	25,613	762	106,711	478	2,296,718	16,409	-
	Total	68,290,000	21,406,661	24,480,381	47,404	6,595,435	247,157	-	53,478	104	14,408	126,033	1,314	183,985	478	3,959,858	28,291	3,386
QC	HW	9,303,800	1,549,959	9,405,065	16,468	1,830,418	19,256	7,871	21,339	37	4,153	16,416	163	18,107	782	540,649	5,788	2,840
	MW	13,532,800	2,254,486	11,661,074	20,419	2,269,484	28,009	7,451	27,041	47	5,263	23,877	237	26,338	782	786,398	8,419	4,131
	SW	61,743,400	10,286,093	43,991,867	77,980	8,561,718	127,789	2,067	91,445	163	17,797	12,135	1,081	120,165	782	3,587,942	38,411	-
	Total	84,580,000	14,090,538	65,058,006	114,867	12,661,620	175,054	17,388	139,824	247	27,213	52,427	1,481	164,610	782	4,914,989	52,617	6,972
NB	HW	1,552,500	174,170	1,089,094	2,508	1,267,067	4,706	-	2,471	5.7	2,875	3,707	36	18,062	656	57,949	761	999
	MW	1,925,100	215,970	1,151,162	2,651	1,339,278	5,836	-	2,669	6.1	3,106	4,597	44	22,397	656	71,857	943	1,239
	SW	2,732,400	306,538	1,351,009	3,149	1,571,783	8,283	-	2,808	6.6	3,267	530	63	31,789	656	101,990	1,339	-
	Total	6,210,000	696,678	3,591,265	8,308	4,178,127	18,824	-	7,949	18.4	9,248	8,833	143	72,248	656	231,796	3,043	2,238
NS	HW	565,500	102,979	384,396	24,036	386,676	1,739	-	872	55	877	1,510	354	5,689	904	40,525	412	230
	MW	1,261,500	229,722	730,943	45,705	735,278	3,880	-	1,695	106	1,705	3,367	789	12,690	904	90,402	919	513
	SW	2,523,000	459,443	1,208,772	76,515	1,215,941	7,761	-	2,513	159	2,528	806	1,578	25,380	904	180,804	1,839	-
	Total	4,350,000	792,143	2,324,111	146,256	2,337,896	13,381	-	5,080	320	5,110	5,683	2,720	43,758	904	311,732	3,170	743
PE	HW	78,300	19,547	119,862	355	93,670	188	127	272	0.8	213	174	2	612	650	5,135	43	14
	MW	126,900	31,680	165,589	491	129,405	305	148	384	1.1	300	282	4	992	650	8,322	69	23
	SW	64,800	16,177	69,916	210	54,638	156	25	145	0.4	114	22	2	506	650	4,249	35	-
	Total	270,000	67,403	355,367	1,055	277,713	649	300	801	2.4	626	478	8	2,110	650	17,705	148	37
NF	HW	200,700	37,409	137,153	3,513	11,617	156	293	311	8.0	26	136	51	170	853	13,806	138	20
	MW	1,204,200	224,453	701,465	17,965	59,413	938	1,519	1,627	42	138	818	308	1,020	853	82,838	831	120
	SW	18,665,100	3,479,024	8,990,190	233,082	761,456	14,544	17,024	18,688	486	1,583	1,545	4,780	15,809	853	1,283,982	12,880	-
	Total	20,070,000	3,740,886	9,828,808	254,559	832,486	15,639	18,837	20,626	535	1,747	2,500	5,140	16,999	853	1,380,626	13,850	140
YK	HW	455,800	29,795	270,586	22,376	249	205	439	614	51	0.6	145	377	4	95	1,822	30	60
	MW	4,330,100	283,051	2,191,182	181,198	2,019	1,943	3,420	5,081	420	4.7	1,374	3,581	40	95	17,312	282	569
	SW	18,004,100	1,176,895	7,533,258	630,640	6,942	8,080	8,753	15,659	1,314	14.4	301	14,888	166	95	71,981	1,174	-
	Total	22,790,000	1,489,740	9,995,026	834,213	9,210	10,228	12,612	21,354	1,785	19.7	1,820	18,846	210	95	91,115	1,486	629
NT	HW							-					-	-	113			-
	MW	15,674,500	4,416,027	35,629,675	37,803,994	5,449	7,035	77,098	82,621	87,663	12.6	6,662	166,310	24	113	196,451	1,512	373
	SW	17,675,500	4,979,775	33,221,622	35,683,725	5,080	7,933	62,830	69,057	74,369	10.6	1,274	187,542	27	113	221,530	1,705	-
	Total	33,350,000	9,395,802	68,851,297	73,487,719	10,529	14,968	139,928	151,678	162,031	23.2	7,936	353,852	51	113	417,981	3,217	373
NU	HW							-					-	-	185			-
	MW	451,200	166,610	1,025,622	401,832		203	2,128	2,256	12		202	-	-	185	11,642	74	0
	SW	488,800	180,494	918,714	364,385		219	1,882	2,021	8		46	-	-	185	12,612	80	-
	Total	940,000	347,104	1,944,336	766,217		422	4,009	4,278	20		249			185	24,254	154	0
Canada	**HW**	**48,348,000**	**9,845,119**	**56,218,617**	**22,428,756**	**10,938,355**	**124,784**	**45,317**	**127,551**	**50,887**	**24,817**	**62,874**	**204,165**	**88,051**		**1,795,004**	**16,845**	**14,478**
	MW	**88,638,000**	**18,327,782**	**100,246,043**	**78,106,062**	**13,349,109**	**172,708**	**134,596**	**232,336**	**180,198**	**30,955**	**88,166**	**374,303**	**161,427**		**2,975,951**	**28,184**	**18,031**
	SW	**265,914,000**	**52,845,280**	**253,493,786**	**86,757,546**	**45,111,076**	**515,259**	**248,857**	**527,046**	**180,061**	**93,772**	**62,542**	**1,122,909**	**484,282**		**11,253,566**	**114,420**	**-**
Canada	**Total**	**402,900,000**	**81,346,889**	**409,958,446**	**187,292,364**	**69,398,540**	**812,751**	**423,159**	**886,932**	**411,146**	**149,544**	**327,446**	**1,695,494**	**729,911**		**16,054,981**	**159,448**	**32,510**