International Journal of Research in Chemistry and Environment
Vol. 1 Issue 1 July 2011(165-172)
ISSN 2248-9649

Research Paper

Pre- and Post-Clearcutting Effects on Mass Loading and Leaching of Phosphorus and Carbon from Litterfall to Boreal Headwater Lakes

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Available online at: www.ijrce.org

(Received 25th May 2011, Accepted 22th June 2011)

Abstract: *Shoreline trees (predominantly black spruce, jack pine and white cedar) surrounding four boreal lakes located in northwestern Ontario, Canada were found to contribute an average of 0.3 $\pm$ 0.1 (SD) kg ha^{-1} lake surface yr^{-1} total dissolved phosphorus (TDP) and 1.8 $\pm$ 0.7 (SD) kg ha^{-1} lake surface yr^{-1} dissolved organic carbon (DOC). These values are estimated to represent from 19 to 56% of the total allochthonous TDP inputs and less than five percent of the total allochthonous DOC inputs to the study lakes. Inputs of airborne and laterally transported litterfall were reduced 77% around two lakes following riparian and catchment clearcutting. About half of this decline in litterfall was attributable, however, to non-treatment, inter-annual climatic effects. No differences were found in the mass losses, and therefore inferred nutrient leaching rates, of either leaf or wood litter in lakes following clearcutting. Despite major decreases in mass element loadings from litterfall, no substantial differences have been observed in the aqueous concentrations of TDP and DOC in lakes whose shoreline forests and catchments have been clearcut. One possible explanation for this result could be that decreased nutrient inputs from reduced litterfall were balanced out by elevated nutrient inputs to lakes from increased erosion following timber harvesting.*

Key words: boreal lakes, litterfall inputs, leaching, clearcutting, total phosphorus, dissolved organic carbon etc.

"I almost doubted if the lake would then be the self-same lake, - preserve its form an identity, when the shores should be cleared." – H.D. Thoreau, *The Maine Woods*
"Walden plainly can never be spoiled by the wood-chopper – for do what you will to the shore there will still remain this crystal well." – H. D. Thoreau, *Journal* Sept. 29, 1851

Introduction

Limnology has progressed considerably in the years since Forbes [1] published his seminal work entitled: "The lake as a microcosm". We now recognize lakes to be dynamically coupled to landscape processes occurring within their watersheds [2-4]. For example, the metabolism of oligotrophic, boreal lakes is closely dependent upon the allochthonous supply of total phosphorus [5] and dissolved organic carbon [6]. One source of these elements, riparian litterfall [7-8], can be a significant component in lake carbon and phosphorus budgets [9-12]. As a result, decreased litter inputs and consequent nutrient leaching due to riparian clearcutting could have the potential to alter lake metabolism. And it is possible that these effects could work their way up the food chain. The top pelagic predators in boreal lakes on the Canadian Shield are the commercially important lake trout (*Salvelinus namaycush*), animals whose well-being may be directly related to landscape modification [13-19] as well as indirectly affected by alterations in inputs of phosphorus and dissolved organic carbon [20, 21] due to forest clearance [22, 23].

A few studies have quantified litter inputs to lakes [24-26]. Yet attempts to assess the consequences of riparian tree removal have been limited to either theoretical modeling [27] or measurements made from previously clearcut shorelines [28]. Although the before and after effects of riparian tree harvesting on litterfall inputs, early mass losses due to leaching, and ensuing nutrient budgets, have been documented for streams, no such data presently exist for lakes. The objective of this study was to provide such information for a series of headwater boreal lakes exposed to experimental watershed clearcutting in northwestern Ontario, Canada.

Study area

The Coldwater Lakes Experimental Watersheds Project is located in northwestern Ontario, approximately 200 km northwest of Thunder Bay, Ontario and 150 km southeast of the Experimental Lakes Area (Fig. 1). This part of the Canadian Shield is situated within the transition zone between the Great Lakes/St. Lawrence and boreal forest regions. Riparian tree species include black spruce, jack pine and eastern white cedar in the coniferous fringe near the lakes, progressing into a more mixed backshore containing the deciduous species trembling aspen and paper birch [16]. Shoreline tree heights generally range from eight to 31 m [13]. Low terrestrial litterfall amounts [16, 29, 14] suggest low stand productivity. The study lakes are small, oligotrophic, headwater basins with little or no groundwater inputs [30], as is typical for the region (and very similar to the well-studied basins located in the nearby Experimental Lakes Area). Shoreline lengths are 3 186 m for Lake 42 (L42), 3 644 m for L39, 2 592 m for L26, and 7 293 m for L20. Surface areas are 28 ha for L42, 38 ha for L39, 27 ha for L26, and 57 ha for L20.

Two of the four study lakes (Lakes 42 and 39) had their catchments and over 60% of their shorelines logged during experimental clearcutting in the winters of 1995-1996 and 1997-98 [30, 31]. Residual pockets remained of uncut riparian trees (40% of shoreline length) of widths less than 20 m. A third lake (Lake 26) retained a complete shoreline buffer of 30-90 m around the entire lake following clearcutting of its catchment. The fourth lake (Lake 20) with no experimental clearcutting served as a reference.

Methods

Airborne litterfall inputs

Allochthonous litterfall traps were placed in the nearshore littoral zones of the four study lakes during September-October 1992 and again during September-October 1997 following clearcutting around L42 and L39. Litterfall traps were constructed from deep plastic tubs (0.05 m^2) inserted into inflated automobile innertubes and anchored with rocks or trees to the shoreline. These same apparati were used previously in a study of differences in the composition [29, 32] and amount [28] of airborne litterfall originating from uncut and previously cut shorelines for a different group of lakes.

Details concerning the 1992 collections in the present study lakes are described in France and Peters [27]. For the 1997 collections, a subset of 11 of the previous 18 sampling sites were selected to represent the range in litterfall amounts and differences in shoreline logging: two reference sites in L20 (Lake 20), four uncut bufferstrip sites in L26, L39 and L42, and five clearcut sites in L39 and L42. All assessments of climatic and logging effects on airborne litter inputs to the study lakes are based on site-specific comparisons between the two collection periods. Intra-site errors for litterfall collection were +/- 14% from multiple traps (n = 2 - 4) set within one meter of the shore.

For both years, after the two-month set period, litterfall was collected, frozen, type-sorted, oven dried at 60 ^oC, and then weighed. During 1992, frequent sampling of litterfall indicated that once deposited inside the floating collection traps, no litter was lost. Autumnal data were converted to estimated annual inputs based on knowledge that 75% of leaf [27] and 50% of wood [16] litterfall occurs during September-October in this region. Mass loadings of total dissolved phosphorus (TDP) and dissolved organic carbon (DOC) to the study lakes were calculated from: (a) empirical leaching equations for coniferous and deciduous leaf litter from France *et al*. [28] and for deciduous and coniferous wood litter from France *et al*. [33], and (b) lake morphometry data [30, 31]. SEs for laboratory leaf mass – TP/DOC leaching regression equations were 0.001.

Lateral transport inputs

Estimations of lateral inputs were made in relation to terrestrial litterfall using the empirical procedure developed previously for the study lakes [34]. Wire mesh window screens (0.9m^2) were placed 2 to 5 m from water's edge around the four study lakes during September 1992-August 1993 and again during September 1997-August 1998 following logging of the L39 and L42 shorelines. These same apparati were used previously in a cross-riparian zone study of the composition [32] and amount [29, 14] of litterfall in uncut and previously cut shorelines for a different group of lakes.

Details concerning the 1992-93 collections in the present study lakes are described in France *et al*. [16]. For the 1997-98 collections, a subset of six of the previous 11 sampling sites were selected to represent the range in litterfall amounts and differences in shoreline logging: two reference sites in L20, one uncut bufferstrip site in L26, and three clearcut sites in L39 and 42. All assessments of lateral transport and input of terrestrial litterfall to the study lakes are based on site-specific comparisons between the two collection periods. Intra-site errors were $\pm$ 17% from multiple (n = 2 – 4) sampling devices.

For both years, litter was collected in the autumn, spring and end of the set period, frozen, type-sorted, oven dried at 60 ^oC, and then weighed. As detailed in France [34], the lateral inputs were estimated from terrestrial litterfall amounts, average transport distances of 0.3m for coniferous needles and 0.5m for deciduous leaves (woody debris was assumed to have minimal lateral movement), proximity of trees to the water's edge for each lake, and riparian slopes and ground roughness characteristics for each lake. Mass loadings of TDP and DOC to the study lakes were calculated as for airborne inputs.

Leaching inferred from mass loss

Following immersion in water, allochthonous leaf and wood litter undergoes a process of mostly abiotic leaching that is reflected by substantial mass loss [33]. Mass loss was obtained for several litter types (black spruce and jack pine needles, speckled alder leaves, black spruce and trembling aspen twigs) selected for their range in leaching rates. Samples were placed in the littoral zones of the four study lakes during autumns of 1992 (wood) and 1993 (leaves) and again during autumn 1997 (both leaves and wood) following riparian clearcutting around L42 and L39. These same apparati were used previously in studies of long-term litter breakdown and macroinvertebrate colonization in the study lakes [29, 32].

For both years, fresh, undried litter was placed in mesh bags suspended one meter below the surface, and collected after an exposure of two weeks duration for leaf litter and seven weeks duration for wood litter, based on leaching results from laboratory experiments [33]. Mass loss was determined as differences in oven-dried (48 hr, 60 ^oC or until constant weight) values of leached litter from measurements in mass loss for control litter. Replicate sample number per litter type per lake was 16 for leaves and 20 for woody debris in 1992/1993, and five for leaves and five for woody debris in 1997. Errors for lake immersion mass loss were about ± 12% per litter species.

Results and Discussion

Litter inputs

As expected for these riparian forests [16], coniferous needles dominated the litterfall inputs (Table 1). In 1997-98, litterfall inputs to clearcut L39 and L42 were significantly (t-test; $p < 0.05$) reduced (by 77%) compared to that in 1992-93 prior to shoreline tree logging. A part of this reduction was due to natural inter-annual differences, possibility due to climatic variability (R. Steedman, unpubl. data), as litterfall inputs to reference L20 and bufferstrip L26 were significantly (t-test; $p < 0.05$) reduced (by 40%) between the two time periods with no shoreline timber removal.

As estimated previously for these study lakes [34], litter inputs originating from lateral transport (Table 2) contributed only about five percent of the total relative to direct airborne inputs. As with the airborne litterfall, lateral inputs were reduced substantially due to both climate (1997-98 compared to 1992-93) and clearcutting (L39 and L42).

Mass loadings

Annual areal mass loadings of TDP for the undisturbed lakes (both sampling periods for reference L20 and protective buffer L26, and the first sampling period for clearcut L42 and L39) averaged 0.2 kg ha^{-1} lake surface from airborne inputs and 0.01 kg ha^{-1} lake surface from lateral inputs (Table 3), for a total of 0.3 ± 0.1 (SD) kg ha^{-1} lake surface for 1992-93 and 0.1 +/- 0.05 (SD) kg ha^{-1} lake surface for 1997-98. Likens and Borman [2] measured, and Dillon *et al*. [35] empirically estimated, that terrestrial litter can account for 2 to 8% of the total phosphorus input to lakes in relation to the ratio of lake:watershed areas (summarized in France and Peters [27]. McCullough [26] determined forest litterfall (including pine pollen not sampled here, but not woody debris sampled here) to contribute 0.3 kg ha^{-1} lake surface yr^{-1} to Lake 239 in the nearby Experimental Lakes Area. Given phosphorus inputs from precipitation and runoff that averaged 0.3 kg ha^{-1} yr^{-1} in dry years to 0.9 kg ha^{-1} yr^{-1} for wet years for L239, McCollough's results suggest that forest litterfall can represent a very significant and previously unrecognized source of phosphorus to small boreal lakes. The present results agree. Litterfall and lateral litter transport to small headwater boreal lakes were estimated to contribute about 19 to 56% of the total allochthonous TDP inputs (Table 4). After clearcut logging of the catchments, the contribution of litter TDP declined to about five percent of total inputs. Some of this decline was probably due to drought, as undisturbed lakes with intact riparian forests also showed declines in litter TDP input over the same period (Table 4).

Annual areal mass loadings of DOC for the undisturbed lakes (n = six lake-years as above) averaged 1.4 kg ha^{-1} lake surface from airborne inputs and 0.1 kg ha^{-1} lake surface from lateral inputs (Table 5), for a total of 1.8 ± 0.7 (SD) kg ha^{-1} lake surface for 1992-93 and 0.2 +/- 0.1 (SD) kg ha^{-1} lake surface for 1997-98. Hanlon [11] believed that the contribution of litterfall to a lake's carbon budget could be as high as one quarter of that produced by phytoplankton production. An empirical compilation combining Hanlon's data with those from other studies [27] suggested that in oligotrophic lakes terrestrial litter may more realistically represent 10 to15% that of the total input from both allochthonous and autochthonous sources. The present results indicate that DOC from litterfall and lateral litter inputs actually accounts for less than five percent of total allochthonous DOC inputs to the study lakes (Table 4). After clearcut logging, this amount declined to less than one percent.

Leaching and element release

Regardless of the ultimate supply of terrestrial litter to aquatic systems, the rate at which that litter undergoes mass loss and element release [33] will determine the degree to which it can contribute to fueling system metabolism [36-42]. As expected from the minor changes in lake chemistry following watershed clearcutting around L39 and L42 [30, 31], no systematic and significant (ANOVA; $p < 0.05$) differences were found in the leaching mass losses of either leaf or wood litter in those lakes relative to the +/- five percent variability existing in reference L20 and bufferstrip L26 between the two sampling years (Table 6).

Implications of decreased litter inputs for lake chemistry

Despite major decreases in mass element loadings from litterfall, no substantial differences have been observed in the aqueous concentrations of either TDP or DOC in L42 and L39 in following clearcutting [30, 31]. Synoptic surveys have also shown that catchment clearcutting appears to have little [22, 23] effect on average TDP and DOC concentrations in other boreal lakes in the same region. Terrestrial litterfall plays an important role in reducing both interrill [14, 16] and aeolian [43] erosion (and consequent nutrient transport). It is therefore possible that elevated inputs of TDP and DOC to lakes due to increases in erosion following timber harvesting may balance out decreased inputs from diminished terrestrial litter. Also, because rates of litter breakdown in these cold, oligotrophic lakes are so low [29, 32, 44], the release of DOC and TDP from antecedent litter due to microbial and macroinvertebrate activity [45], may continue long after inputs have been reduced, as found elsewhere by Meyer *et al*. [42].

Finally, this work highlights the importance of considering natural temporal variability in any before-and-after impact study. Inter-annual effects on litter inputs and mass loadings were found to be comparable to those corresponding to treatment clearcutting. Meyer *et al*. [42] also found that inter-annual differences in litter inputs would have masked proper assessment of treatment effects on DOC production from leaching had not a contemporaneous reference system been monitored. There is thus a cardinal need to place the effects of clearcutting in both a larger spatial and temporal context. This would not be the first time that climate influences have trumped landscape modification influences in this same region of northwestern Ontario. For example, other work has demonstrated that climate warming and ensuing droughts can have a greater effect on reducing catchment erosion and sediment accumulation with little or no resulting alterations in lake chemistry or biology than any possible increases in nutrient inputs and consequent changes in chemistry and biology that might be ascribed to erosion from either logging or wildfires [46, 47]. It seems that catchment and riparian clearcutting only slightly alters the chemistry of these small boreal lakes [30, 31] with only mild effects being observed thereupon with respect to lake biology [48-50].

Acknowledgements

Robert Steedman is thanked for providing lake chemistry data and for reviewing an early draft of the manuscript. This work was funded by the Ontario Ministry of Natural Resources through Robert Steedman, a Canadian NSERC Strategic Research Grant to R. Peters, the Harvard Milton Fund, and faculty grants to R. France at the Harvard Design School and the Department of Engineering at the Nova Scotia Agricultural College.

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Table 1: Annual airborne litterfall (wood, coniferous and deciduous leaves, total) amounts (g m^{-1} shoreline yr^{-1}) in the four study lakes in 1992-93 (prior to clearcutting) and in 1997-98 (following clearcutting around Lakes 42 and 39).

	1992-93				1997-98			
Lake	**Wood**	**Conif**	**Decid**	**Total**	**Wood**	**Conif**	**Decid**	**Total**
42	5	27	1	33	0.002	4	3	7
39	6	38	2	46	0.001	8	3	11
26	2	31	3	36	1	19	2	22
20	1	21	3	25	0.3	13	2	15

Table 2: Annual lateral litter inputs (coniferous and deciduous leaves) amounts (g m^{-1} shoreline yr^{-1}) to the four study lakes in 1992-93 (prior to clearcutting) and in 1997-98 (following clearcutting around Lakes 42 and 26)

	1992-93			1997-98		
Lake	Conif	Decid	Total	Conif	Decid	Total
42	1.4	0.7	2.1	0.1	0.1	0.1
39	0.9	0.8	1.8	0.2	0.1	0.3
26	0.4	1.9	2.4	0.3	0.8	1.1
20	0.1	1.4	1.4	0.1	0.7	0.8

Table 3: Annual mass loadings of total dissolved phosphorus (total = kg yr^{-1} for entire lake: areal = kg ha^{-1} lake surface) from airborne litterfall and lateral transport to the four study lakes in 1992-93 (prior to clearcutting) and in 1997-98 (following clearcutting around Lakes 42 and 39).

	Airborne				**Lateral**			
	1992-93		**1997-98**		**1992-93**		**1997-98**	
Lake	**Total**	**Areal**	**Total**	**Areal**	**Total**	**Areal**	**Total**	**Areal**
42	11.4	0.4	1.0	0.04	0.2	0.01	0.02	0.001
39	16.4	0.4	1.5	0.04	0.2	0.01	0.04	0.001
26	6.7	0.2	3.6	0.1	0.3	0.01	0.1	0.003
20	9.5	0.2	7.2	0.1	0.6	0.01	0.2	0.004

Table 4. Mass loading budgets for total dissolved phosphorus (TDP) and dissolved organic carbon (DOC) to the four study lakes in 1992-93 (prior to clearcutting; "PRE-HARVEST") and in 1997-98 (following clearcutting around Lakes 42 and 39; "POST HARVEST"). All inputs are in kg yr^{-1}. Litter = both airborne and lateral inputs. TP inputs from atmospheric deposition calculated @ 25 mg m^{-2} yr^{-1} (Bayley et al. 1992) and from catchments @ 6 mg m^{-2} yr^{-1} (Linsey et al. 1987); DOC inputs from atmospheric deposition @ 2760 mg m^{-2} yr^{-1} (Linsey et al. 1987), and from catchments @ 2000 mg m^{-2} yr^{-1} (Brunskill and Wilkinson 1987). % retention in lake does not include airborne exports. Further lake chemistry data are tabulated in Steedman et al. (2000) and Steedman (2000).

	Lake			
Measurement	**20**	**26**	**39**	**42**
Litter TDP input PRE-HARVEST	10	7	17	12
Litter TDP input POST-HARVEST	7	4	2	1
% change in litter TDP	27	47	89	91
Atmospheric deposition TP input	14	7	10	7
Catchment TP input	28	5	9	3
Litter DOC input PRE-HARVEST	47	37	111	77
Litter DOC input POST-HARVEST	20	15	8	5
% change in litter DOC	58	60	92	93
Atmospheric deposition DOC input	1573	800	1076	718
Catchment DOC input	9340	1540	3100	880
Total TP inputs PRE-HARVEST	52	19	36	21
% TP retention in lake	84	91	91	90
% TP input as litter as TDP	19	37	47	56
Total TP inputs POST-HARVEST	50	16	21	10
% TP retention in lake	83	89	85	80
% TP input as litter as TDP	14	20	5	5
Total DOC inputs PRE-HARVEST	10961	2377	4287	1675
% allochthonous DOC retention in lake	34	72	67	65
% DOC input as litter	<1	2	3	5
Total DOC inputs POST-HARVEST	10933	2355	4185	1603
% allochthonous DOC retention in lake	34	72	67	63
% DOC input as litter	<1	1	<1	<1

Table 5: Annual mass loadings of dissolved organic carbon (total = kg yr^{-1} for entire lake; areal = kg ha^{-1} lake surface) from airborne litterfall and lateral transport to the four study lakes in 1992-93 (prior to clearcutting) and in 1997-98 (following clearcutting around Lakes 42 and 39).

	Airborne				Lateral			
	!992-93		1997-98		1992-93		1997-98	
Lake	**Total**	**Areal**	**Total**	**Areal**	**Total**	**Areal**	**Total**	**Areal**
42	76.5	2.9	5.4	0.2	0.4	0.02	0.04	0.001
39	109.0	2.8	8.4	0.2	1.6	0.4	0.04	0.002
26	34.7	1.2	14.0	0.5	2.0	0.07	0.8	0.02
20	43.6	0.8	18.2	0.3	3.8	0.07	1.7	0.03

Table: 6. Percentage mass loss of leaves (jack pine, black spruce, speckled alder) and wood twigs (black spruce, trembling aspen) primarily attributable to leaching and microbial conditioning following placement for either 2 wk (leaves) or 7 wk (wood) in the four study lakes in 1992-93 (prior to clearcutting) and in 1997-98 (following clearcutting around Lakes 42 and 39).

	Leaves						Wood			
	1992-93			1997-98			1992-93		1997-98	
Lake	Pine	Spruce	Alder	Pine	Spruce	Alder	Spruce	Aspen	Spruce	Aspen
42	8	-	-	11	-	-	7	-	7	-
39	4	13	9	5	18	14	11	6	8	10
26	7	-	-	4	-	-	8	-	4	-
20	4	17	21	4	14	19	8	15	11	18

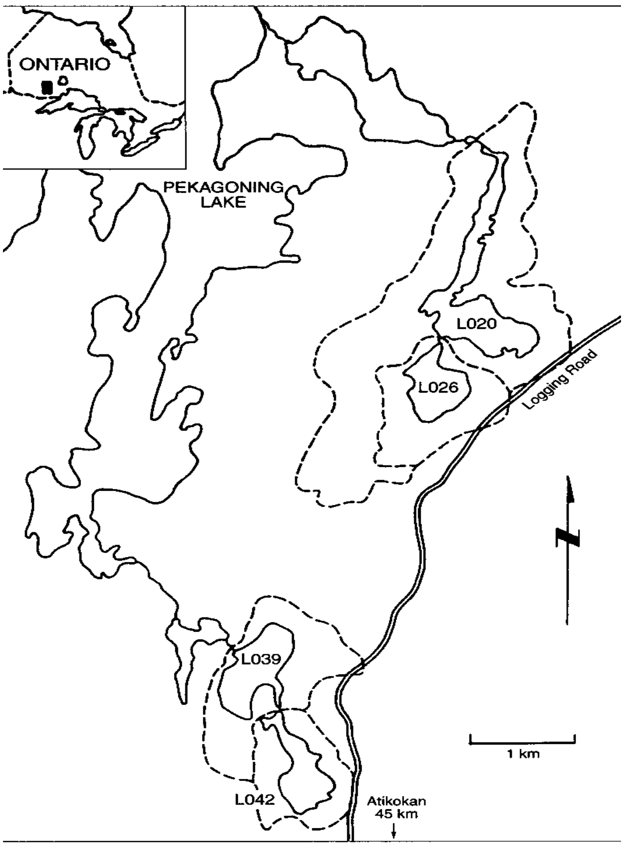

Figure 1: Location of study area in northwestern Ontario, Canada. Dashed lines represent watershed boundaries around the study lakes 42, 39, 26 and 20.