Effects of a Windstorm and Forest Fire on Chemical Losses from Forested Watersheds and on the Quality of Receiving Streams

D. W. SCHINDLER, R. W. NEWBURY, K. G. BEATY, J. PROKOPOWICH, T. RUSZCZYNSKI, AND J. A. DALTON

Department of Fisheries and Oceans, Freshwater Institute, Winnipeg, Man. R3T 2N6

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A severe natural windstorm followed by a high intensity forest fire caused significant increases in runoff and in losses of nitrogen, phosphorus, and potassium from two small Precambrian watersheds. Both the windstorm and the fire had significant effects on water and chemical yields. Water yields in the two basins were 1.6 and 1.8 times the pre-impact means, respectively, in the year after the burn. Maximum chemical losses were observed for nitrate, with values of 3.4 and 9 times the pre-impact means for the two basins in the year after the burn. Increases in annual yields of most chemical parameters were 1.1 to 2.9 times the background. Both increased concentrations and increased flow volumes appear to be responsible for the increased nutrient losses.

Key words: forest fire, windstorm, stream water quality, phosphorus, nitrogen, potassium losses, water yield

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Une forte tempête de vent suivie d'un intense feu de forêt eut pour effet une augmentation importante du ruissellement et des pertes d'azote, de phosphore et de potassium dans deux petits bassins hydrographiques précambriens. Le vent et l'incendie eurent tous deux d'importants effets sur les rendements en eau et en substances chimiques. Durant l'année qui suivit l'incendie, les rendements en eau dans les deux bassins furent 1,6 et 1,8 respectivement plus élevés que les moyennes d'avant ces catastrophes. C'est avec les nitrates qu'on a observé les plus grandes pertes de substances chimiques, les valeurs étant 3,4 et 9 fois plus grandes dans les deux bassins pendant l'année qui suivit l'incendie. Les augmentations de rendements annuels de la plupart des paramètres chimiques furent de 1,1 à 2,9 fois celles des concentrations de base. Ces concentrations et débits accrus semblent tous deux responsables de l'augmentation des pertes de substances nutritives.

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A number of recent publications have shown that the success of several important species of trees in boreal forests is dependent upon periodic forest fires (Wright and Heinselman 1973). Some investigators predict that current fire suppression policies will lead to the decline and possible extinction in the future of a number of important species and suggest that where human life and property are not endangered, forest fires should be allowed to burn or controlled burning should be undertaken. On the other hand, the general public has vigorously supported fire suppression, largely on esthetic or short-term economic grounds.

One poorly known factor in this controversy on forest management is the amount of nutrient lost from a watershed after it has been burned by a forest fire, and the effect of the nutrient on receiving waters. Several earlier studies of this subject (Wright 1976; McColl and Grigal 1975, 1977) have relied on the analysis of burned vs. control basins. However, in our experience, control streams which are side by side often have quite different water chemistry, even though superficially both watersheds look very similar. Year-to-year differences in chemistry within one watershed are also highly variable and difficult to generalize without sufficient record (Schindler et al. 1976).

Studies reported here were conducted on two experimental watersheds in the Experimental Lakes Area of northwestern Ontario (Lat. 49°40′ Long. 93°44′) which were monitored for 4 yr before they were severely damaged by a windstorm and burned almost exactly 1 yr later in an uncontrolled forest fire. An adjacent

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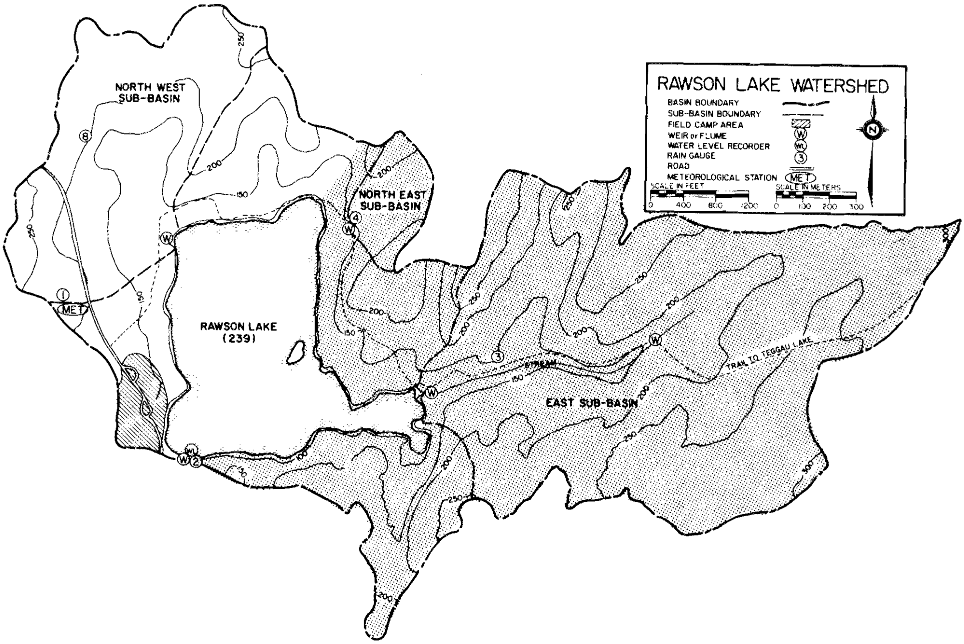


FIG. 1. Rawson Lake (Lake 239) and its drainage, showing the locations of the three subbasins studied. Areas burned by the forest fire are shaded. Locations of hydrological and meteorological equipment are also shown. Contour intervals are in feet, relative to the lake surface, which is 100.0 ft (30.5 m) (assumed).

third experimental watershed, monitored for the same period, was only slightly wind damaged and was unburned (Fig. 1). The unique opportunity afforded by these "before and after" studies allows us to make detailed interpretations without having to consider the differences in soils, geology, or vegetation, which may be sources of considerable error when "side by side" basins are compared.

The area burned is in the Great Lakes–St. Lawrence Forest Region (Rowe 1972). The forest community in all three watersheds was essentially similar, characterized by commercially valuable mature stands of jack pine (*Pinus banksiana* Lamb.) and black spruce (*Picea mariana* Mill. of 80–100 yr old) with isolated groves of deciduous species, white birch (*Betula papyrifera* Marsh.) and trembling aspen (*Populus tremuloides* Michx.).

Windstorm and Fire Conditions

At 05:00 on July 7, 1973, a severe windstorm struck the experimental watersheds. For a period of 20 min, gusts in excess of 150 kph uprooted trees or snapped them off above the ground. Up to 50% of the trees in valley bottoms and 100% of the trees on hilltops were blown down in a 350 km^2 area. In our three experimental watersheds, estimated blowdown ranged from less than 20% in the Northwest Subbasin to 70–100% in the East Subbasin (Ontario Ministry of Natural Resources, unpublished maps).

Almost exactly 1 yr later, at 12:08 on June 26, 1974, following 2 wk of low humidity, strong winds, and warm temperatures, a man-caused industrial fire was set accidentally in an area 3 miles (4.8 km) southeast of our experimental watersheds. Driven by a southeast wind in "extreme" fire weather, the fire spread quickly in the dry year-old windfall, reaching the experimental watersheds by late afternoon. Flames 15–20 m in height and a smoke column rising to over 8000 m were observed. The East and Northeast Subbasins were burned completely, while the Northwest Subbasin was left untouched as the westerly course of the fire was checked at a hastily cleared fireline separating the Northeast and Northwest Subbasins.

The fire (known as Dryden No. 16) was extremely hot. The flame-front intensity (I) was estimated to be 13,000 kW/m as calculated after Byram (1959), with conversion to metric units (Van Wagner 1978):

$$(1)\ I = H \times w \times r$$

where H is the fuel low heat of combustion (KJ/kg), w is the fuel consumed (kg/m^2); and r is the forward rate of spread (m/s).

Virtually all vegetation less than 2.5 cm in diameter was consumed. In the most intensely burned areas, organic matter in surface soils was mineralized to a depth of several centimetres, and the surface of exposed or thinly-covered bedrock was shattered. The fire-resistant cones of jack pine were consumed in many

TABLE 1. Annual precipitation (ppt) and water yields in metres from three stream basins. 1970–72 figures are means and 95% confidence limits. Values outside the 95% confidence limits are underlined.

	Northwest (Control)				Northeast (Burned)				East (Burned)			
	1970–72 control	1973–74 windstorm	1974–75 fire 1	1975–76 fire 2	1970–72 control	1973–74 windstorm	1974–75 fire 1	1975–76 fire 2	1970–72 control	1973–74 windstorm	1974–75 fire 1	1975–76 fire 2
(1) ppt	0.824±0.268	0.858	0.679	0.636	0.824±0.268	0.858	0.679	0.636	0.824±0.268	0.858	0.679	0.636
(2) runoff	0.314±0.233	0.323	0.218	0.173	0.364±0.269	<u>0.692</u>	0.422	0.353	0.281±0.072	<u>0.448</u>	<u>0.374</u>	0.286
(3) runoff/ppt	0.381±0.235	0.376	.321	0.272	0.442± .036	<u>0.803</u>	<u>0.618</u>	<u>0.555</u>	0.341±0.048	<u>0.522</u>	<u>0.551</u>	<u>0.450</u>
(4) 3 as % of control mean	100±62	99	84	71	100±8	<u>182</u>	<u>140</u>	<u>126</u>	100±14	<u>153</u>	<u>162</u>	<u>132</u>

areas because of their close proximity to the ground. The fire occurred after most herbaceous plants had flowered. Little precipitation fell in July and early August following the fire. As a result, there was very little revegetation of the basins. Two subsequent rainstorms of slightly more than 5 cm each, occurred in mid and late August. The area burned, near the Experimental Lakes Area camp (Fig. 1), has only thinly distributed overburden, and is typical of the more fragile parts of the boreal forest. Conditions were therefore optimal for high nutrient losses.

The final size of Fire 16 was 1457 ha. A much larger fire, Dryden No. 18, was started by lightning on June 29, burning 323 km^2 directly east of and adjoining the area. This fire, in similar terrain and vegetation, has been analyzed by Stocks (1975).

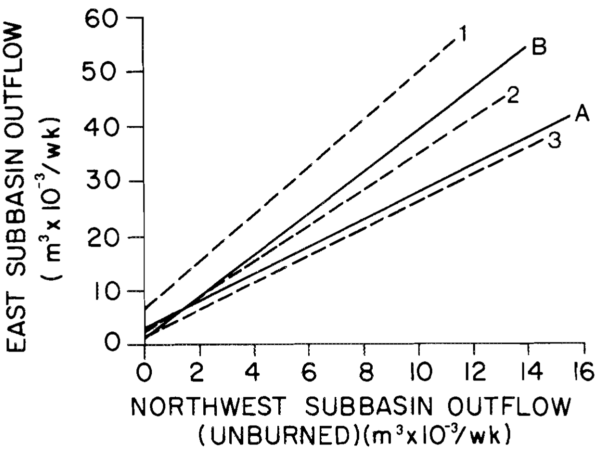
Data Collection and Analysis

Flows from the Northwest and East Subbasins were measured continuously with weirs and stage recorders. The Northeast Subbasin was metered manually to obtain a continuous flow record. Chemical analyses were done at least weekly, and up to several times per day during the first large storms after the fire. Hydrological and chemical methods were discussed by Schindler et al. (1976). Only results for nitrogen, phosphorus, and potassium, elements of special interest to biologists, are reported here. We reasoned that total watershed yields could be due either to increased water flow, or increased chemical concentration, or both. Dividing total annual yield by annual water flow gives a mean chemical concentration, which allows the effects of flow to be distinguished from increased concentration. Total annual yields and mean annual concentrations were calculated for each of the "pre-impact" calendar years, 1970, 1971 and 1972, as well as the three "post-impact years." July 1973 through June 1974 is referred to as "windstorm year," July 1974 through June 1975 as "fire year 1" and July 1975 through June 1976 as "fire year 2." Mean annual yield and 95% confidence limits were calculated for the pre-fire years. Annual precipitation was treated in the same manner.

Precipitation and Runoff

Precipitation in the post-impact years was within the 95% confidence envelope generated from pre-impact data (Table 1). Runoff and runoff/precipitation ratios were also within these limits for the unaffected Northwest Subbasin, with the ratios decreasing in the drier years of 1974, 1975, and 1976. In the blowdown and burned basins the ratios increased initially to 1.6× and 1.8× the pre-impact values in spite of the drier years and then followed a rapidly decreasing trend similar to that of the unburned basin.

The surprisingly short period of recovery of the pre-fire hydrological characteristics of the burned basins is illustrated in Fig. 2, showing the relative yield of the East and Northwest Subbasins under coincident rainfall conditions. Prior to the impacts, the larger East Subbasin produced approximately 2.5× the stream outflow of the Northwest Subbasin in larger and more



CURVE	PERIOD	NO. OF WEEKS	INTER-CEPT	SLOPE	COEFF. OF CORR.
A	PRE-IMPACT	34	2980	2·51	·94
B	WINDSTORM YEAR	20	1048	3·79	·94
1	FIRE YEAR 1	20	6333	4·35	·91
2	FIRE YEAR 2	29	2207	3·26	·88
3	FIRE YEAR 3*	17	1407	2·46	·68

*partial year to October 1976

FIG. 2. Relationship of measured weekly streamflow volumes between the unburned Northwest Subbasin and the East Subbasin from 1971 to 1976 during the open water season under coincident rainfall conditions. Segments of the period are represented by Curve A: pre-windstorm, Curve B: year following the windstorm, Curve 1: first year following the fire in the East Subbasin, Curve 2: second year following the fire, Curve 3: third partial year following the fire ending in October 1976. The pre-impact relationship between basin outflows (volumetric) was reestablished in three growing seasons.

prolonged storm runoff hydrographs and higher "base" flows between storm runoff events. The relative yields are consistent with the relative basin areas of 170.3 ha (East) and 62.8 ha (Northwest) and the large groundwater storage potential of the East Subbasin. In the year following the windstorm, the relative yield from the East Subbasin increased by 50% during periods of storm runoff. In the first year following the fire, the relative yield increased by 70% primarily in the form of a higher base flow between storm events. However, within 2 yr, in fire year 3, the relative yield had decreased to its pre-impact value. From these data it is apparent that the period of excess runoff following a fire is relatively short (3 yr), corresponding to the rapidly developed evapo-transpiration demand of the flourishing post-fire vegetative cover. A study of changes in the relative base flows and storm hydrograph peaks and durations is presently being undertaken by R. W. Newbury and K. G. Beaty (Freshwater Institute, Winnipeg).

Nitrogen Yields

Yields from the unaffected Northwest Subbasin in the "post-impact years" were within the 95% confidence limits generated from "pre-impact" years (Table 2). The one exception, suspended particulate N, is near the lower confidence threshold for 1975–76, the driest year in recent history.

In contrast, yields of all nitrogen fractions from both of the affected watersheds were significantly higher in the windstorm year. After the burn, all fractions were higher than background in the East Subbasin and all but suspended particulate nitrogen were higher in the Northeast Subbasin. Greatest increases were for nitrate in the year after the burn, with annual yields 3.4 and 9× higher than pre-impact means. Yields of total nitrogen were roughly 2× higher than normal in both basins in all of the disaster years.

Mean annual concentrations did not increase as much as total yields, although values for all dissolved fractions and total nitrogen were significantly higher in the post-impact years in both of the affected basins (Table 3). Total dissolved nitrogen concentrations were also significantly higher in post-fire years in the unaffected basin. This may be due to the lower water yields in the latter years.

Suspended particulate nitrogen concentrations in some post-impact years were not significantly higher, indicating that most of the effect observed in yield was due to the increased water flow.

Phosphorus Yields

The pattern of total yields for phosphorus is very similar to that observed for nitrogen. Losses of both suspended and dissolved fractions as well as total phosphorus increased 1.4 to 3.2× in the post-impact years (Table 4).

Some differences are noted in mean annual concentration. The windstorm did not cause significant increases in concentration of any phosphorus fraction in the East Subbasin, while in the Northeast Subbasin a 2.5× increase in suspended P was recorded (Table 5). The fire caused increases of 2–2.4× in the Northeast Subbasin, and 1.1–1.5× in the East Subbasin. Concentrations in the East Subbasin did not increase significantly until the second year after the fire.

Potassium Yields

With a few exceptions, both annual yields and mean annual concentrations of potassium were higher after the impacts (Tables 4 and 5). As for phosphorus and nitrogen, increases were in the 1.4–2.9× range.

Discussion

In studies of the Little Sioux Fire in the nearby Boundary Waters Canoe Area, McColl and Grigal (1977) and Wright (1976) concluded that the con-

TABLE 2. Annual yields (kg/ha) of nitrogen from three stream basins. 1970–72 figures are means and 95% confidence limits. Values outside the 95% confidence limits are underlined.

	Northwest (Control)				Northeast (Burned)				East (Burned)			
Element	1970–72 control	1973–74 windstorm	1974–75 fire 1	1975–76 fire 2	1971–72 control	1973–74 windstorm	1974–75 fire 1	1975–76 fire 2	1970–72 control	1973–74 windstorm	1974–75 fire 1	1975–76 fire 2
(1) NH_4-N	0.033 ± 0.022	0.051	0.039	0.019	0.057 ± 0.009	0.183	0.128	0.158	0.038 ± 0.009	0.103	0.087	0.082
(2) NO_3-N	0.052 ± 0.034	0.080	0.054	0.025	0.027 ± 0.001	0.060	0.093	0.044	0.068 ± 0.016	0.221	0.609	0.403
(3) Tot. Diss. N	0.888 ± 0.281	0.926	0.835	0.684	1.283 ± 0.032	2.559	2.191	2.746	0.874 ± 0.032	1.573	2.177	1.860
(4) Susp. partic. N	0.141 ± 0.062	0.125	0.104	0.078	0.339 ± 0.083	0.882	0.384	0.372	0.160 ± 0.021	0.253	0.270	0.323
(5) $\sum$ N	1.029 ± 0.343	1.051	0.939	0.762	1.622 ± 0.115	3.441	2.575	3.118	1.034 ± 0.053	1.826	2.447	2.183
(6) 5 as % of control mean	100 ± 33	102	91	74	100 ± 7	212	159	192	100 ± 5	177	237	211

TABLE 3. Mean annual concentrations (mg/m^3) of nitrogen from three stream basins. Columns are labeled as in Table 2.

	Northwest (Control)				Northeast (Burned)				East (Burned)			
Element	1970–72 control	1973–74 windstorm	1974–75 fire 1	1975–76 fire 2	1971–72 control	1973–74 windstorm	1974–75 fire 1	1975–76 fire 2	1970–72 control	1973–74 windstorm	1974–75 fire 1	1975–76 fire 2
(1) NH_4-N	105 ± 70	158	179	110	157 ± 25	264	303	448	111 ± 26	197	158	182
(2) NO_3-N	166 ± 108	248	248	145	74 ± 3	87	220	125	199 ± 47	423	1105	896
(3) Tot. Diss. N	2828 ± 895	2867	3830	3954	3525 ± 88	3698	5192	7779	2563 ± 94	3013	3951	4133
(4) Susp. Partic. N	449 ± 197	387	477	451	931 ± 228	1275	910	1054	469 ± 62	485	490	718
(5) $\sum$ N	3277 ± 1092	3254	4307	4405	4456 ± 316	4973	6102	8833	3032 ± 155	3498	4441	4851
(6) 5 as % of control mean	100 ± 33	99	131	134	100 ± 7	112	137	198	100 ± 5	115	146	160

TABLE 4. Annual yields (kg/ha) of phosphorus and potassium from three stream basins. 1970–72 figures are means and 95% confidence limits. Values outside the 95% confidence limits are underlined.

Element	Northwest (Control)				Northeast (Burned)				East (Burned)			
	1970–72 control	1973–74 windstorm	1974–75 fire 1	1975–76 fire 2	1971–72 control	1973–74 windstorm	1974–75 fire 1	1975–76 fire 2	1970–72 control	1973–74 windstorm	1974–75 fire 1	1975–76 fire 2
(1) Tot. Diss. P	0.032 ± 0.020	0.022	0.020	0.013	0.061 ± 0.022	<u>0.100</u>	<u>0.169</u>	<u>0.180</u>	0.036 ± 0.014	<u>0.054</u>	<u>0.053</u>	<u>0.054</u>
(2) Susp. Partic. P	0.019 ± 0.012	0.010	0.008	<u>0.006</u>	0.032 ± 0.001	<u>0.103</u>	<u>0.043</u>	<u>0.036</u>	0.020 ± 0.005	<u>0.028</u>	<u>0.032</u>	<u>0.030</u>
(3) $\sum$ P	0.051 ± 0.032	0.032	0.028	0.019	0.093 ± 0.023	<u>0.203</u>	0.212	0.216	0.056 ± 0.019	<u>0.082</u>	<u>0.085</u>	<u>0.084</u>
(4) 3 as % of control mean	100 ± 63	63	51	37	100 ± 25	<u>218</u>	<u>228</u>	<u>232</u>	100 ± 34	<u>146</u>	<u>152</u>	<u>150</u>
(5) Diss. K	0.778 ± 0.334	1.014	0.802	0.603	1.621 ± 0.068	<u>3.010</u>	<u>4.263</u>	<u>3.021</u>	1.514 ± 0.323	<u>3.151</u>	<u>4.425</u>	<u>3.239</u>
(6) 5 as % of control mean	100 ± 43	130	103	78	100 ± 4	<u>186</u>	<u>263</u>	<u>186</u>	100 ± 21	<u>208</u>	<u>292</u>	<u>214</u>

TABLE 5. Mean annual concentrations (mg/m³) of phosphorus and potassium from three stream basins. Columns are labeled as in Table 4.

Element	Northwest (Control)				Northeast (Burned)				East (Burned)			
	1970–72 control	1973–74 windstorm	1974–75 fire 1	1975–76 fire 2	1971–72 control	1973–74 windstorm	1974–75 fire 1	1975–76 fire 2	1970–72 control	1973–74 windstorm	1974–75 fire 1	1975–76 fire 2
(1) Tot. Diss. P	102 ± 64	68	92	75	168 ± 60	145	<u>400</u>	<u>510</u>	128 ± 50	121	142	<u>189</u>
(2) Susp. Partic. P	61 ± 38	31	37	35	88 ± 3	<u>149</u>	<u>102</u>	<u>102</u>	71 ± 18	62	86	<u>105</u>
(3) $\sum$ P	162 ± 102	99	128	110	255 ± 63	293	<u>502</u>	<u>612</u>	199 ± 68	183	227	<u>294</u>
(4) 3 as % of control mean	100 ± 63	61	79	68	100 ± 25	115	<u>197</u>	<u>240</u>	100 ± 34	92	114	<u>148</u>
(5) Diss. K	2478 ± 1064	3139	<u>3679</u>	3486	4453 ± 187	4350	<u>10102</u>	<u>8558</u>	5388 ± 1149	<u>7033</u>	<u>11832</u>	<u>11325</u>
(6) 5 as % of control mean	100 ± 43	127	<u>148</u>	141	100 ± 4	98	<u>227</u>	<u>192</u>	100 ± 21	<u>131</u>	<u>220</u>	<u>210</u>

centrations of nutrients did not increase in streams following the fire, even though soil and groundwater concentrations of nutrients increased. There are a number of possible reasons for this difference from our studies.

The above authors had no pre-fire data for their basins. Our previous work (Schindler et al. 1976) and the pre-fire data presented in Tables 1 to 5 indicate that there are differences of at least 2× in both year-to-year and basin-to-basin variation in nutrient yields. It is therefore difficult to distinguish the effects of fire from variation under nonfire conditions. The later occurrence and much more intensive burning of the Experimental Lakes Area fire would also have contributed to the difference. The Little Sioux Fire occurred early in the spring, before the flowering of major herbs in the area. It did not appear to have burned as intensely or as thoroughly as the Experimental Lakes Area fire described above. In striking contrast to the slow recovery of terrestrial vegetation in the first year following the Experimental Lakes Area fire, the Little Sioux watersheds had extensive herbaceous ground cover within a few weeks.

For most nutrients, wind damage to the forest caused effects as severe as a forest fire, even though understory vegetation was intact in the former case and totally destroyed in the latter.

After the fire, annual losses of phosphorus and nitrogen from watersheds via the streams were less than 40% of the annual inputs from rain, snow, and dustfall (Schindler et al. 1976). Even with short-term increases in water yields, there appears to be little likelihood that fire-caused losses of nutrients will significantly affect the regrowth of forests. On the contrary, the extensive remineralization of organic matter in soils during the fire left high concentrations of soluble reactive phosphorus and NH_4-N in the upper 5 cm, little of which was removed during subsequent rainfalls (D. W. Schindler and G. Morrison unpublished results).

There also appears to be little reason for fearing that the increased nutrient losses after a fire or windstorm will have adverse effects on receiving waters. The phytoplankton and nutrient concentrations in Rawson Lake have not increased detectably since the fire (D. W. Schindler unpublished data), although due to the long water renewal time of the lake (about 7 yr), maximum effect may follow maximum yield from the input stream by several years.

Our results indicate that in the absence of an unusually short fire interval, there are no chemical or limnological reasons for supporting fire suppression programs in similar areas of the boreal forest of North America.

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