Effects of forest clear-cutting on abundances of oxygen and organic compounds in a mountain stream of the Marmot Creek basin

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Refractory compounds in the waters of streams draining the Marmot Creek basin in the east slopes of the Rocky Mountains appeared to increase as a result of forest clear-cutting. The vegetation of the basin is dominated by spruce–subalpine fir forests. Clear-cutting was done at six selected sites, each about 10 ha in size. The saleable wood was harvested and the slash was left on the ground. The effect of clear-cutting was most pronounced in the case of tannins and lignins, with concentrations being increased by as much as a factor of four. The effect appeared to persist for several years, from the onset (and completion) of the clear-cutting in 1974 to near the end of the decade. Humic substances were increased to a much lesser degree (from 790 to 900 μg/L) and the effect died out in less than 2 years. Forest clear-cutting appeared to have no effect on the abundances of oxygen and labile organic compounds.

Direct data were not available for the refractory and labile compounds in the mountain stream prior to clear-cutting. Accordingly, an analogue approach was used. In this approach the data for the clear-cut stream were compared with those for a neighboring stream. In this way the need for prior data was met, but more importantly, any variations stemming from climatic variability were taken care of during the 5-year study.


Les composés réfractaires dans les eaux des ruisseaux drainant le bassin Marmot Creek sur le flanc est des Rocheuses semblent augmenter suite à une coupe à blanc de la forêt. La végétation qui couvre le bassin est dominée par les forêts d’épinettes et de sapins subalpins. La coupe à blanc a été effectuée sur six sites sélectionnées; chaque site ayant une superficie d’environ 10 ha. Le bois commercial fut exploité et les déchets de coupe furent laissés sur place. L’effet de cette coupe à blanc fut surtout prononcé sur les tannins et les lignines, avec des concentrations pouvant augmenter jusqu’à un facteur de quatre. Cet effet semble persister pour plusieurs années, du début (et aussi de l’achèvement) de la coupe en 1974 jusqu’au près de la fin de la décennie. Les substances huitiques furent augmentées à un degré moindre (de 790 à 900 μg/L) et l’effet devint imperceptible en moins de 2 ans. La coupe à blanc de la forêt semble ne pas avoir d’effet sur l’abondance d’oxygène et sur les composés organiques labiles.

Les données directes concernant les composés réfractaires et les composés labiles n’étaient pas disponibles pour les cours d’eau montagneux avant les coupes à blanc. Conformément à cette situation, une approche analogue fut adoptée. Dans cette approche, les données pour les cours d’eau localisés à proximité des coupes à blanc furent comparés avec celles d’un cours d’eau voisin. De cette façon, le besoin de données avant coupes fut satisfait, mais encore plus important. On prit soins de noter tous les changements attribuables à la variabilité du climat pendant les 5 années de l’étude.

Introduction

Research in various watersheds on the effects of forest clear-cutting on water resources has been concerned with snow accumulation and melt rates (Golding 1977), streamflow (Rice and Wallis 1962), stream temperature (Levone and Rothacher 1967; Patric 1970; Swift and Messer 1971), stream turbidity (Reinhart and Eschner 1962), sediment load (Rothwell 1977; Fredrikson 1970), and only recently with the chemical constituents of stream waters (Singh et al. 1974; Likens et al. 1970; Aubertin and Patric 1974).

While stream waters contain both inorganic and organic constituents, effects of forest clear-cutting on the chemical constituents of stream waters have been considered only in terms of dissolved inorganic constituents. This is because inorganic constituents were easier to detect and quantify than organic constituents. Recent advances in the analysis of organic compounds, particularly in techniques of separation and methods of identification, have now made it possible to detect and quantify a variety of organic compounds that occur in trace amounts in water.

In 1974, we initiated a study of organic compounds in the mountain streams of the Marmot basin (Telang et
on organic compounds in surface waters of the Marmot Creek drainage basin formed a part of numerous research projects carried out in the basin. The basin, about 9.4 km$^2$ (Swanson 1977), consists of three subbasins: Twin Fork, Middle Fork, and Cabin Creek. The Twin Fork subbasin faces north, the Middle Fork faces east, and the Cabin Creek faces south. The three major streams flowing from these subbasins combine to form a single larger stream (Main Marmot) which drains into the Kananaskis River.

Streams draining the Marmot basin are of first and second order (Mutch 1977). They are small, perennial, and turbulent, with an average daily discharge of 50 L/s each for Twin and Middle Fork subbasins, 20 L/s for Cabin Creek, and 130 L/s for the Main Marmot. Peak discharge for streams occurs in June (Water Survey of Canada, Calgary District). Streams are snowed throughout the year by vegetation. The pH of stream waters is generally around 8.0. Stream water temperatures vary from 0 to 2°C in March to nearly 10°C in July (Mutch 1977). The buildup of ice cover over streams starts in November and breakup occurs in May.

The climate is characterized by short, cool summers and long, cold winters. The mean precipitation is 1080 mm, about three-quarters of which is snow (Singh and Kalra 1972). Rain occurs during the June–September period. The average July temperature ranges from 18 to 2°C; average January temperature ranges from −6 to −18°C. Chinook winds bring thawing periods frequently in all winter months; week-long periods with maxima of about 10°C are common during the winter months (Kirby and Ogilvie 1969).

The vegetation is dominated by spruce–subalpine fir forests. The vegetation types included 6 nonforest types (willow, heather, white dryas, sedge–everlasting, hairy wildrye, and kobresia) and 10 forest types (lodgepole pine–aspen, krummholz spruce–fir/grouseberry, spruce/horsetail, spruce–fir/rusty menziesia, spruce–fir/grouseberry, spruce/sedge–sphagnum—Labrador tea, lodgepole pine/feather moss—ground dogwood, spruce–fir/feather moss—ground dogwood, spruce–fir/pine grass and fir—alpine larch) (Teleng et al. 1975). The main types of soil are brunisolic grey-wooded, podzolic, regosolic, local gleysolic, and organic soils (Stevenson 1967; Karkanis 1972). The basin is underlain by Mesozoic formations consisting mainly of shale and sandstone with lesser amounts of limestone, conglomerate, and coal (Mutch 1977). The stream bed is composed of sands, gravels, and boulders, and is inhabited by stream microflora including benthic invertebrates, algae, and bacteria. A variety of wildlife is also seen in the basin. Some differences are found in the vegetation, soil, and bedrock of the subbasins (D.R. Jaques, personal communication). In the Cabin Creek subbasin limestone appears to be the dominant bedrock,
Fig. 2. Clear-cut areas in the Cabin Creek subbasin.

whereas bedrock in the other basins is dominantly clastics. In the Cabin Creek subbasin coniferous forest makes up 74% of the total vegetation, whereas in the other subbasins it accounts for only 33%. In 1936, small areas of the Cabin Creek and Middle Fork subbasins were burned by a forest fire. Cabin Creek lost 3.6% of its forest cover and Middle Fork lost 2.1%. Since then, the vegetation in these two subbasins has been restored and no significant differences are observed in the vegetation of the burned section of the two subbasins.

The Cabin Creek subbasin was clear-cut in August–September 1974 at six selected sites, each about 10 ha (Fig. 2). Clear-cutting was done with heavy machinery in irregular patterns with the retention of buffer strips of 200–300 m next to the stream (D. Fisera, personal communication). Clear-cut blocks were 150–275 m wide and 200–400 m long (Golding 1977). Clear-cut areas were located on the upper and midslope positions away from stream channels. The maximum and minimum distance between stream channels and the lower edges of the cut blocks was 630 and 78 m, respectively (Rothwell 1977). Approximately 20% of the total forested area of the Cabin Creek subbasin was clear-cut (D. Fisera, personal communication). During the clear-cutting operation, a total of 20 km of skid road and access road was constructed, with 90% of it in skid roads (Rothwell 1977). Most of the saleable wood was harvested and the slash was left on the ground.

Effects of forest clear-cutting were sought by analyzing the stream water for oxygen and indicator organic compounds, both refractory and labile. Refractory organic compounds used as indicators were tannins and lignins, and humic and fulvic acids. Labile indicator compounds included amino acids, fatty acids, phenols, and carbohydrates.

Methods

One sampling site was chosen on each of the four Marmot basin streams (Figs. 1 and 2). Analyses for organic compounds in surface waters of the Marmot Creek drainage basin were initiated in June 1974, and the results include samples taken up to December 1977. Initiation of analyses for oxygen and the various organic compounds are shown in Table 1. Water samples were collected monthly (on the 18th of each month) to study abundances and seasonal variations of oxygen and organic compounds. This scheduling of sampling was adopted to obtain data at the regular time intervals. Because analyses of organic compounds are time consuming, no at-
TABLE 1. Average abundances of oxygen and organic compounds (in micrograms per litre) in stream waters of the clearcut Cabin Creek subbasin and undisturbed subbasins of the Marmot Creek drainage basin

<table>
<thead>
<tr>
<th></th>
<th>Cabin Creek subbasin</th>
<th>Undisturbed subbasin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolved oxygen*</td>
<td>11 000</td>
<td>11 000</td>
</tr>
<tr>
<td>Biochemical oxygen demand*</td>
<td>2 000</td>
<td>2 000</td>
</tr>
<tr>
<td>Chemical oxygen demand*</td>
<td>3 800</td>
<td>3 900</td>
</tr>
<tr>
<td>Labile organic compounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phenols†</td>
<td>1.9</td>
<td>2.0</td>
</tr>
<tr>
<td>Total fatty acids†</td>
<td>1.5</td>
<td>2.9</td>
</tr>
<tr>
<td>Carbohydrates‡</td>
<td>46.1</td>
<td>48.1</td>
</tr>
<tr>
<td>Total amino acids*</td>
<td>8.9</td>
<td>9.7</td>
</tr>
<tr>
<td>Hydrocarbons‡</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>Refractory organic compounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tannins and lignins*</td>
<td>500</td>
<td>102</td>
</tr>
<tr>
<td>Humic and fulvic acids‡</td>
<td>850</td>
<td>790</td>
</tr>
</tbody>
</table>

NOTE: Average values are based on monthly values obtained in 1974-1977(1), 1975-1977(2), and the spring months of 1975 and 1976(3).

A vacuum at 30°C. The aqueous solution was adjusted to pH 9.0 and filtered, and the filtrate was divided into two parts. One part was adjusted to pH 6.0 and the total organic carbon content (humic and fulvic acids, D1) was determined. The other part was acidified to pH 2.0 with hydrochloric acid, and refrigerated for 5 days in a nitrogen atmosphere. The acidic solution was then centrifuged to separate precipitated humic acid. The total organic carbon content (fulvic acid, D2) was determined on the clear acid solution. The difference between D1 and D2 was the humic acid content. On occasion, water was added to the precipitated material and the carbon content of the resulting colloidal suspension was also directly determined for humic acid for confirmation of the results by subtraction. The colloidal nature of the solution, however, prevented precise direct determinations.

Results and discussion

Since analyses of organic compounds began almost simultaneously with clear-cutting operations in the Cabin Creek subbasin, (clear-cutting began 2 months after sampling was initiated), it was not possible to obtain annual baseline data on organic compounds in surface waters of the clear-cut Cabin Creek subbasin. Therefore, organic compounds in the stream waters of the Cabin Creek subbasin were compared with those of undisturbed areas of the same basin. This analogue approach was found to be valid, since these subbasins are located within the same watershed area and therefore their streams should be similar in their natural organic content. The specific analogue subbasin chosen was Middle Fork, referred to as the "undisturbed subbasin."

Abundances and seasonal variations in the levels of oxygen and organic compounds in the Marmot basin waters were published by Telang et al. (1981).

Oxygen and labile organic compounds

Clear-cutting in the Cabin Creek subbasin had no measurable effect on the stream's oxygen level and on abundances of labile organic compounds. This is illustrated by Figs. 3 and 4 which compare stream waters of the clear-cut Cabin Creek subbasin with those of the undisturbed subbasin for abundances of dissolved oxygen and one of the classes of labile organic compounds (amino acids), respectively. As shown in Table 1, the average abundance of oxygen and labile organic compounds in stream waters of the clear-cut Cabin Creek subbasin were similar to those of the undisturbed subbasin. Although seasonal variations in abundances of oxygen and labile organic compounds were observed in stream waters of the Cabin Creek and undisturbed subbasin, no significant differences were observed in their seasonal abundances, as is illustrated by Figs. 3 and 4 for dissolved oxygen and total amino acids, respectively.

Of the identified organic compounds (Table 1), humic and fulvic acids accounted for 42% of the measured
biochemical oxygen demand in the Cabin Creek sub-basin and 39% in the undisturbed subbasin. The next most abundant compounds, tannins and lignins, accounted for 25% in the disturbed subbasin and 5% in the undisturbed subbasin. Other compounds in a mass sense accounted for only 3% of the biochemical oxygen demand in both the disturbed and undisturbed subbasin.

In the case of chemical oxygen demand, humic and fulvic acids accounted for 22% of chemical oxygen demand in the Cabin Creek subbasin and 21% in the undisturbed subbasin. Tannins and lignins accounted for 13% of the chemical oxygen demand in the disturbed subbasin and 3% in the undisturbed basin. Other organic compounds accounted for only 1.5% of chemical oxygen demand. Clearly, organic loading put little strain on the oxygen supply in the turbulent mountain stream.

**Refractory organic compounds**

**Tannins and lignins**

Tannins and lignins are very common complex polycyclic aromatic compounds that are synthesized by plants. They form 25–30% of the organic matter of conifers and 15–25% of the organic matter in hardwoods and grasses (Brauns and Brauns 1960; Sarkanen and Ludwig 1971; and Canadian Forestry Service 1967). These compounds are highly resistant to biodegradation. Two groups of microorganisms, the white rot fungi and certain aerobic organisms, attack lignin oxidatively, but at slow rates, via phenolase enzymes.
(Tabak et al. 1959; Sorenson 1962; Lawson and Still 1957). Distribution of tannins and lignins in sediments and natural waters is not well documented, but they appear to range from 20 µg/L to 50 µg/L in seawater samples (Pocklington and McGregor 1973), and from 100 µg/L to 1700 µg/L in surface waters (Baker et al. 1976). In the stream waters of the undisturbed subbasin they averaged about 100 µg/L (Telang et al. 1981).

The abundance of tannins and lignins in the waters of the clear-cut Cabin Creek subbasin was much higher, averaging 500 µg/L (Fig. 5) than those in the undisturbed subbasin waters (100 µg/L). During the first 2 months of the study period (June and July), levels of these compounds in the waters of the Cabin Creek were about 180 µg/L. After clear-cutting in August 1974, levels of tannins and lignins in the Cabin Creek waters increased fourfold (from 180 µg/L to 735 µg/L). During the same period, tannins and lignins in the waters of the undisturbed areas of Twin and Middle Fork remained much lower, ranging from 10 µg/L to 250 µg/L (Fig. 5). The increased tannins and lignins in the waters of Cabin Creek are thus probably due to clear-cutting of the vegetation in the subbasin. The increased abundance of tannins and lignins in Cabin Creek waters persisted for the next 4 years. Two years after the end of the study, the tannins and lignins were found to have fallen to about 160 µg/L, 215 µg/L, 200 µg/L, and 235 µg/L on the basis of analysis carried out on October 17, November 11, December 17, 1980, and January 19, 1981, respectively.

It is clear that tannins and lignins in the waters of the clear-cut region during the course of the study were four times more abundant than those in the analogue stream. It is not clear, however, whether they were four times as abundant before the clear-cutting. It now appears that they are dropping toward the original levels. It is important to try to analyze the significance of the data in terms of effects that might be attributed not only to clear-cutting but to (a) differences in vegetation and soils due to differences in bed-rock type, and (b) differences in vegetation and soils due to a forest fire 40 years before.

In the first instance, if the tannins and lignins before clear-cutting were at the same level as in the undisturbed analogue basins, it may be argued that the implicit fourfold increase followed the "cause" far too closely in time. It is important to note in Fig. 5 that the levels in June and July 1974, which may have represented levels before clear-cutting, appeared to cycle annually through the data of the next 4 years. Accordingly, it may be unwise to take the June and July levels of 1974 as the steady levels before clear-cutting.

On the other hand, assuming that the indicated rise in 1974 was real, surface runoff movement could account for almost immediate transportation of these compounds from the clear-cut area to the stream waters. Surface runoff may have been augmented by damage to soil structure during the clear-cutting operation. This would have resulted in more extensive leaching of these compounds from plants and soil.

The waters of the undisturbed areas of Twin Fork and Middle Fork and the clear-cut area of Cabin Creek drain into the waters of Main Marmot (Figs 1 and 2). The effect of clear-cutting at Cabin Creek was therefore expected to be reflected in the Main Marmot waters. The levels of tannins and lignins in the Main Marmot waters (60 µg/L to 500 µg/L) were consistent with such a hypothesis.

Abundances of tannins and lignins remained high in the Cabin Creek waters (average 500 µg/L) and in the Main Marmot waters (average 225 µg/L) through 1978. This suggested that the forest-stream ecosystem of the Cabin Creek subbasin had yet to stabilize the levels of tannins and lignins after clear-cutting, if indeed they had been elevated by the clear-cutting.

It needs to be pointed out that there is a difference in
the vegetation pattern of the Cabin Creek subbasin and that of the undisturbed subbasin. In the Cabin Creek subbasin, 26% of the total vegetation is nonforest and alpine vegetation and the other 74% is coniferous forest. In the analogue Middle Fork subbasin 67% of the total vegetation is nonforest and alpine vegetation and the other 33% is coniferous vegetation. It may therefore be argued that higher levels of tannins and lignins in the Cabin Creek stream waters could be attributed to the dominance of coniferous forest vegetation, since tannins and lignins are 25–30% of the total organic matter in conifers (Brauns and Brauns 1960; Sarkar and Ludwig 1971; and Canadian Forestry Service 1967). It is, however, possible that higher levels of tannins and lignins in the Cabin Creek waters reflect differences in vegetation as well as the clear-cutting effect. If this is true, then the low values (160 μg/L to 235 μg/L) observed for water samples of October 17, 1980 to January 19, 1981 indicate that the clear-cutting effect is dying, or over, and the higher values (160 μg/L and 235 μg/L) observed in October 1980 to January 1981, compared with the undisturbed stream (80 μg/L), reflect the ambient level due to the contribution of coniferous vegetation.

It may also be argued that there is a relationship between the forest fire of 1936 in the Cabin Creek subbasin and the higher abundances of tannins and lignins in the stream waters of the subbasin. Assuming for the moment that the forest fire of 1936 was the cause, then groundwater movement should account for the transportation of these compounds to stream waters. It is possible that after the forest fire, organic compounds were leached out of dead vegetation, infiltrated into groundwater and may have reached surface waters after 40 years due to slow groundwater movement. Based on hydraulic conductivity studies and the distance from which water infiltrates, Wallis (1978) concluded that the time taken by groundwater to reach stream water averages about 11 years in the Marmot basin. Separate studies using tritium isotopes conducted by Sklash (1978) in the Marmot basin also confirmed this time period. Thus, the effect of the 1936 forest fire on levels of organic compounds, particularly refractory compounds such as tannins and lignins, should have been noticeable by 1947. Levels of tannins and lignins would have remained high for a few years and then returned to normal levels after some time period. Just for argument, even if the time taken by groundwater to reach stream water is doubled to 22 years, then the effect should have been noticeable by 1958 and the levels returned to normal well before the present study began in 1974. Thus, the forest fire of 1936 appears unlikely to account for higher levels of tannins and lignins in the clear-cut Cabin Creek basin. No attempt was made to assess the leachability of tannins and lignins from soil columns of burned and unburned areas of the Cabin Creek subbasin. Although the leaching experiment could have been valuable, it was beyond the scope of this study.

**Humic and fulvic acids**

After the development of a suitable analytical procedure, humic and fulvic analyses were undertaken in June 1975. Humic and fulvic acids, collectively referred to as humic substances, are among the most widely distributed natural products of plant decomposition on the surface of the earth. Humic substances, like tannins and lignins, are highly resistant to microbial degradation and represent the most stable fraction of organic matter. By definition, humic and fulvic acids are the organic constituents which are soluble in 0.5 M sodium hydroxide, with the fulvic acids being distinguished by their solubility in acid solutions at pH 2. Humic acids are precipitated from acid solutions at pH 2. Humic and fulvic acids mentioned in this paper refer to organic compounds that are not extractable with benzene at the above pH values. Although investigations on the chemical structures of humic and fulvic acids continue, various investigators have determined their gross composition and in some cases the range of molecular weights in each fraction (Brown et al. 1972; Rashid and King 1969, 1970, 1971; Bordovskiy 1965; Nissenbaum and Kaplan 1972). Fulvic acids are commonly of low molecular weight (less than 10,000), and humic acids are of high molecular weight (300,000 or more).

Humic substances in the waters of the undisturbed subbasin averaged 790 μg/L. The proportion of humic substances found in waters in the form of carbon amounted to about 20% of the total organic content of the water. Levels of humic substances in natural waters are not well documented in the literature. However, water quality studies at the Red Deer basin in Alberta (Baker et al. 1976) indicated that these compounds in these waters ranged from 900 μg/L to 950 μg/L.

Effects of clear-cutting at Cabin Creek on the concentration of humic substances were apparent, but to a much lesser degree than on tannins and lignins (Fig. 6). Humic substances were more abundant in the waters of the clear-cut area of the Cabin Creek subbasin (average 850 μg/L) than they were in the waters of the undisturbed areas (average 790 μg/L). Levels remained high until the end of 1975. The higher values observed for the Cabin Creek waters may be attributed to the deforestation treatment, which certainly caused some damage to the soil structure and increased surface runoff which would have resulted in extensive leaching of the compounds from the soil. After January 1976, the levels of humic substances in the Cabin Creek waters appeared to approach those of waters of the undisturbed
areas of the basin. This suggests that the damaged soil structure of the Cabin Creek ecosystem was stabilizing 1.5 years after clear-cutting.

Conclusion

Clear-cutting in the Cabin Creek subbasin had no effect on the stream’s oxygen level and on the concentration of labile organic compounds. The analogue approach indicated that clear-cutting probably increased the concentration of tannins and lignins, and humic and fulvic acids in the waters of the subbasin. Clear-cutting of conifers and shrubs and extensive leaching of plant material and soil are possibly responsible for increases in the tannins and lignins. Increased levels of humic substances were apparently due to damage to soil structures during the clear-cutting operation. The apparent effect of clear-cutting was still noticeable in the tannin and lignin content after 4 years but it disappeared in the case of humic and fulvic acids about 1.5 years after the clear-cutting was completed.

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