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Sustainability of the western Canadian boreal forest under changing hydrological conditions. I. Snow accumulation and ablation

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Abstract To examine the dynamics of water and energy in the boreal forest and adjacent cleared lands during the winter and spring periods, the fluxes of snow accumulation, sublimation, radiation and snowmelt were measured in central Saskatchewan, Canada. The results show a strong relationship between the magnitude of fluxes and vegetation cover. Clear-cuts accumulate more snow than forested land and undergo an earlier and more rapid melt, hence the clearing of boreal forest land may lead to higher snowmelt freshets and the earlier exposure of the land surface to warming and evaporation.

INTRODUCTION

The boreal forest of western Canada resides on a margin between the drought-prone, semiarid prairie to the south and the cool subarctic forest-tundra to the north. The area is subject to an intensely variable climate that may be changing due to modifications of the Earth's atmosphere by greenhouse gases. Warming over the last century is significant and of the order of 1.7°C in winter and 2.1°C in spring (Environment Canada, 1995). Some suggest that the boreal forest will retreat northwards from its present location in response to warming from doubled CO_2 (Hogg & Hurdle, 1995). It is suggested here however, that the intact boreal ecosystem promotes its own sustainability by managing the near-surface dynamics of water and energy in the atmosphere, biosphere and snow cover to produce states of water/energy storage and fluxes of snowfall, radiation, turbulent heat transfer, evaporation and melt that are preferential to the continued existence of this biome. As the 6-7 month winter dominates the hydrology of the boreal forest, the winter accumulation of snow and the timing and rate of its melt in the spring are extremely important for the replenishment of water in soils, wetlands, lakes and streams. It is hence important to understand the effects of land clearing in forestry operations (clear-cutting) on the snow hydrology of the boreal forest and the implications of these effects on the annual water balance. It is the objective of this paper to document winter snow accumulation and sublimation and the energy and mass fluxes during spring melt as a function of canopy cover, and the impact of removing this cover on snow accumulation and melt.

FIELD SITES AND MEASUREMENTS

Field sites were chosen in the southern boreal forest of central Saskatchewan, Canada in the Prince Albert Model Forest (54°N, 106°W). The region has a dry sub-humid, continental climate with a cold dry winter. Four forest cover types were instrumented: jack pine, mixed wood (trembling aspen and white spruce), regenerating jack pine (15 years since harvest) and a recent clear-cut (4 years since harvest) with aspen regrowth. Winter leaf area index values for the sites were 2.2, 0.7, 0.8 and 0.05 m^2 m^{-2}, respectively.

Measurements were made from scaffolding towers extending well above the canopy. Radiation, air temperature, wind speed, and snowfall were measured above and below the canopy. Intercepted snow was measured from a weighed, suspended tree. Snow water equivalent, soil heat flux and snow depth were measured under the canopy. Details of this and other instrumentation at these sites have been described by Harding & Pomeroy (1996) and Pomeroy & Dion (1996).

HYDROLOGICAL FLUXES

Snowfall in the winter 1995-1996 totalled 92 mm snow water equivalent (SWE). This snow was not equally distributed to the surface snow cover however. Interception of snow can retain substantial amounts of cumulative winter snowfall in the canopies of conifers, exposing this snow to the atmosphere to which substantial proportions sublimate. Midwinter interception approximated about 40% of cumulative snowfall in the pine canopy, 30% in the regenerating pine canopy and less than 6% in the mixed wood. Intercepted snow sublimation estimates from late winter snow surveys approximated 24% in the pine and regenerating pine and 6% in the mixed wood.

Table 1 shows the pre-melt period snow cover accumulation and coefficient of variation for the forest types on 1 March (Julian Day {JD} 61) along with cumulative winter snowfall to that point. Substantial differences between the forest types and between snow accumulation and cumulative snowfall are evident. The consistent difference between snowfall and snow cover accumulation for open areas where relocation of snow is considered small (clear-cut, mixed wood, other sites not listed) suggests that some early winter snow ablation occurred. By 1 March there is no intercepted snow load, hence differences in snow accumulation between sites are primarily due to sublimation of intercepted snow.

Table 1 Pre-melt (1 March 1996) snow accumulation, properties and snowfall.

	Snow cover accumulation (mm)	Density (kg m^3)	Coefficient of variation of SWE	Snowfall (mm)	Sub-canopy snowfall (mm)
Jack Pine	49	190	0.220	78	54
Mixed wood	57	160	0.104	78	66
Regenerating	44	200	0.305	75	-
Clear-cut	59	170	0.188	75	-

The energetics of melt in the boreal forest can be described by an energy balance equation where:

$$Q_M = Q^* - Q_G + Q_s + Q_e - \frac{dU}{dt} - T$$
$$Q^* = Q_c^* N_r = Q_s^* + Q_A + T \tag{1}$$

and Q_M is the energy used in snowmelt, Q^* is the net radiation over the sub-canopy surface, Q_G is the ground heat flux, Q_s is the turbulent sensible heat flux, Q_e is the turbulent latent heat flux, U is the internal energy of the snowpack, t is time, Q_c* is the net radiation over the canopy, N_r is the ratio of Q^*/Q_c^*, Q_s* is the net radiation to the snow covered area on the ground, Q_A is the small scale advection of sensible heat from bare ground or plant stems to the snow cover and T is the energy used to heat the forest canopy that does not contribute to melt. All terms are fluxes in W m^{-2}. Pomeroy & Dion (1996) describe the calculation of N_r, while Shook (1995) and Marsh & Pomeroy (1996) discuss the division of net radiation into its components.

The melt period began with an isolated melt in the clear-cut from 10-14 March (JD 70-74) triggered by a warm air mass with strong winds and a general melt period which depleted the winter snow cover from 3-18 April (JD 94-109). The general melt period is examined in detail. A wide variety of energy regimes is found for melt under various canopy covers as shown in Fig. 1 where cumulative ($Q^* - Q_G$) is graphed against time during the melt period. The accumulation of ($Q^* - Q_G$) during melt varies with the canopy, as high leaf area restricts the penetration of short wave radiation to the underlying snow. The complex diurnal fluctuation in ($Q^* - Q_G$) reflects the daily variation in Q^*, T and variation in Q_G which is influenced by infiltration of meltwater into frozen soils as melt progresses. The clear-cut has notably higher ($Q^* - Q_G$) than the forested sites and reaches quite high cumulative energy levels in a very short time. The forested sites have roughly similar rates of increase in ($Q^* - Q_G$), though the pine stand has the least ($Q^* - Q_G$) of the forested sites.

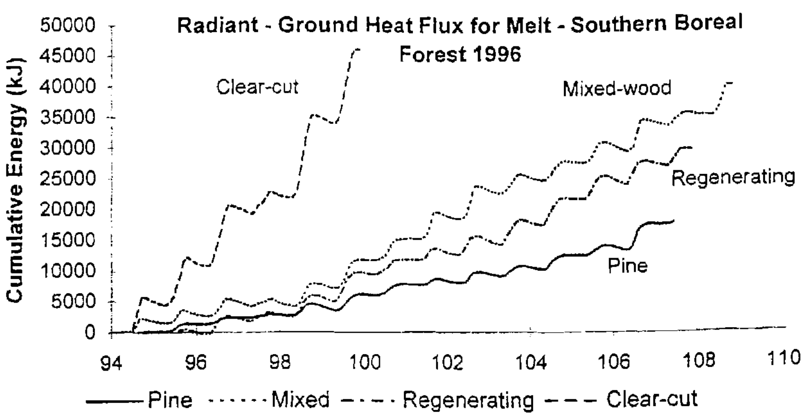

Fig. 1 Cumulative net radiation under the canopy less ground heat flux during the melt for the four cover types. Cumulative energy values are added from the beginning of meltwater production in the snow pack.

The translation of incoming energy to Q_M is shown in Fig. 2 where cumulative melt energy is graphed over time for the four cover types. The melt does not progress as steadily as does $(Q^* - Q_G)$, due to changes in U and contributions of Q_e and Q_s. The trend for the clear-cut site to melt much faster than the forested sites matches the trend in $(Q^* - Q_G)$ between sites. The slowest melt however, occurs in the regenerating pine stand, rather than the pine stand as $(Q^* - Q_G)$ would indicate. This suggests a significant source of turbulent transfer of heat to the pine snow cover that is not available to the regenerating pine snow cover.

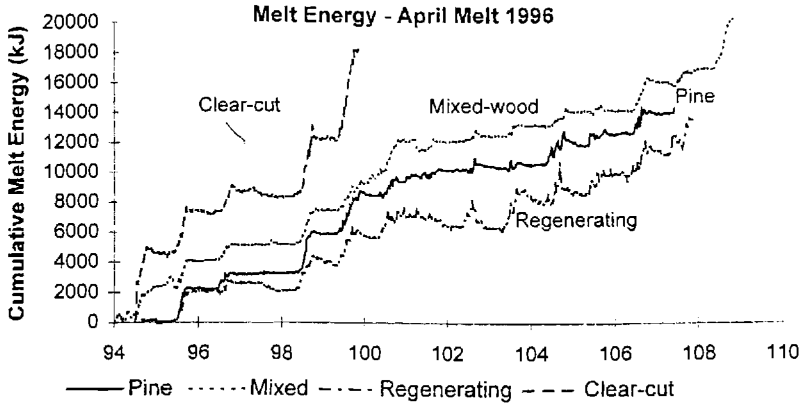

Fig. 2 Cumulative melt energy calculated from the decrease in SWE in the pack for the four cover types.

Figure 3 shows the proportion of "residual energy", $Q_s + Q_e - \mathrm{d}U/\mathrm{d}t - T$, required to supply melt requirements in excess of the measured $(Q^* - Q_G)$ flux. This residual energy is presumed to be primarily the sum $(Q_s + Q_e)$. It is seen that for all surfaces $(Q_s + Q_e)$ is important at the very start of melt and contributes all of Q_M for short periods early in the melt. As melt progresses, $(Q_s + Q_e)$ becomes less important to varying degrees, depending upon the canopy cover. The clear-cut is distinctive in that $(Q_s + Q_e)$ becomes insignificant within the first 24 h of melt. For the forested sites $(Q_s + Q_e)$ provides significant energy for several days (10 days for the pine canopy, 5.5 days for the mixed wood and 2.5 days for the regenerating pine stand). There are several reasons for the decline in contribution from $(Q_s + Q_e)$, the primary being the decline in snow surface albedo and snow covered area during melt and the consequent counting of net radiation to bare patches as part of the total net radiation. Radiant energy absorbed by bare patches can be convected to the overlying air mass and advected to the remaining snow. While this process is actually a turbulent transfer, it would not be detected with the crude energy balance instrumentation employed here. Similarly, radiant energy absorbed by tree and bush stems just above the snow surface would be counted as part of net radiation but actually contributing in some part to small scale advection of turbulent heat as found in open environments by Shook (1995) and Marsh & Pomeroy (1996).

Bulk properties of energetics during the melt period are shown in Table 2 where the total melt energy, length of time to melt the snowpack, total radiant ground heat energy

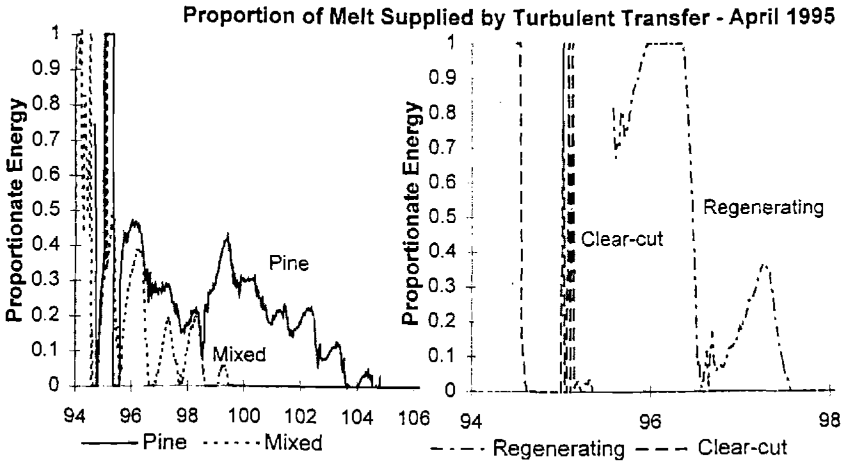

Fig. 3 Proportion of melt energy supplied by turbulent transfer of sensible and latent heat ($Q_s + Q_e$) for the four cover types.

Table 2 Total melt energy, melt time, net radiation – ground heat flux, and proportion of melt energy provided by turbulent transfer, April melt 1996.

	Jack Pine	Mixed wood	Regenerating	Clear-cut
Melt energy (kJ)	14 500	20 000	14 000	18 000
Melt length (days)	13	15	13	5
Radiation – ground heat flux (kJ)	18 000	40 000	30 000	46 000
% Turbulent contribution	18.6	7.9	8.5	2.5

and the percentage of melt energy contributed by turbulent transfer are shown. The largest melt energy occurred where the SWE was greatest, the mixed wood. It did not occur for this period in the clear-cut because of a previous local melt, however with consideration of this previous melt energy (7000 kJ) and the short period of time, the clear-cut melt was by far the most energetic. The melt energy in the pine stands was lower because of snow cover lost over the winter to sublimation of intercepted snow. The clear-cut snow cover melted in almost one third of the time of the forested sites, because it had by far the most favourable radiative environment of all sites, with more than double the net radiation that the pine snow cover received. In all cases turbulent transfer was quite small compared to expectations provided by the common use of temperature index models to predict snowmelt rates in forested environments.

The measurement of net radiation over the snow surface + bare patches + lower tree and bush stems probably overestimated actual radiative transfer to the snow. Net radiation in this case is composed of net radiation plus a locally-adverted turbulent transfer flux (probably sensible heat). However it is still instructive that the source of energy for melt in the forested environment is radiation beneath the canopy and not turbulent transfer sensible heat as implied by temperature index melt models. Interestingly, in the relatively open environment of the clear-cut, sensible and latent heat are unimportant to driving melt, in contrast to the situation on the prairie environment to the south where they can contribute notably to early melts (Shook, 1995). The difference is likely to be due to the exposure of aspen stems throughout the melt in the clear-cut. These stems would absorb short wave radiation and heat the surrounding air providing a local advection of sensible heat that would be undetected in this experimental design.

CONCLUSIONS

The effect of forest cover on the interception and sublimation of snow in the boreal forest is shown to be dramatic and dependent upon species, leaf area and removal of canopy as in clear-cutting. As the canopy of conifers is removed by clear-cutting, there is a resulting increase in snow accumulation. Clear-cutting of mixed wood canopies would not achieve the same increase because of the small amounts of snow intercepted by these canopies.

Snow accumulation after sublimation loss affects the energetics of melt, requiring less energy for melt from the low energy environment under dense conifers such as the pine canopy. Net radiation under the canopy drives most of the melt of forest snow covers and almost all of the melt of the clear-cut snow cover. The only significant contribution from turbulent heat terms through the canopy is found under the pine canopy.

After 15 years of regrowth the regenerating pine stand functioned normally with respect to interception and sublimation despite its shorter tree height. The melt from the clear-cut was markedly larger, earlier and more rapid than any of the natural forest covers or the regenerating pine stand. On a daily basis meltwater production was greatest from the clear-cut. The flashier and greater melt from the clear-cut suggests much greater potential for large spring runoff when boreal forests are cleared, though a recovery is found for 15 year old regenerated stands.

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