Sustainability of the western Canadian boreal forest under changing hydrological conditions. II. Summer energy and water use

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Abstract The partitioning of energy in various natural and disturbed stands in the Canadian boreal forest is documented. A comparison of the energy balance, evapotranspiration and surface heating indicates that conifer canopies absorb the greatest solar radiation and produce the most evapotranspiration. The recent clear-cuts produced the lowest evaporation and the greatest heating, with surface temperatures exceeding those at other sites by as much as 15°C at mid-day. Midday surface temperatures in clearings often exceeded the critical wilting point temperatures for spruce seedlings. Satellite-derived indices demonstrate varying degrees of water and energy management by forest stands as they regenerate after cutting. The implications of these findings for understanding the prospects for regeneration of stands after a disturbance and for the sustainability of the boreal forest in conditions of changing climate are demonstrated.

INTRODUCTION

In Canada, the western boreal forest represents the transition between semiarid (water-limited) prairies to the south and subarctic (temperature-limited) regions to the north. The forest ecosystem has sustained itself through its ability to act as a water, climate and nutrient regulation system, interacting with the atmosphere and soils to produce the specific conditions of water retention and flow, nutrient status and surface climate required for its development. The western boreal forest is very sensitive to disturbances, both natural and man induced; it is also located in that area of the Northern Hemisphere which, according to recent climate change predictions, will encounter the greatest warming due to the accumulation of greenhouse gases in the atmosphere (Environment Canada, 1995; Hogg & Hurdle, 1995). The boreal forest's ability to regulate the water and energy that it receives, and its capacity to respond after disturbances such as harvesting and fire are the subject of this special study.

SITES AND INSTRUMENTATION

The study area includes the mixed wood district in north-central Saskatchewan, specifically forest stands within and to the east of Prince Albert National Park. Research sites have been established in undisturbed forest stands (mature mixed wood and jack pine stands), in a recent clear-cut and in a regenerating jack pine stand. The mixed wood stand consists of a mixed canopy of approximately 75% aspen (18-25 m in height) and

25% white spruce (10-12 m) with an under-storey of grasses and small shrubs. The pine site consists of a mature jack pine stand (16-22 m) with a sparse under-storey of deciduous bushes. The clear-cut site is an area logged after the summer of 1990, trenched and replanted to white spruce; presently, the vegetation is dominated by grass, bushes and small aspen trees typically less than 1 m tall. The regenerating site is an area that was logged, trenched and planted to jack pine in 1981; the vegetation is dominated by closely spaced jack pine 3-4 m tall. At each site instrument towers were erected to enable deployment of the instrumentation required to obtain continuous measurements of the energy and water balance components, including evapotranspiration, interception and infiltration.

SUMMER ENERGY BALANCE AND EVAPOTRANSPIRATION

The energy balance, neglecting storage terms, of a natural surface is described simply by:

$$Q^* = Q_G + Q_E + Q_S \qquad (1)$$

where Q^* is the net all-wave radiation to the surface, Q_G is the heat flux into the soil, Q_E is the latent heat flux and Q_S is the sensible heat flux. In equation (1), Q^* is taken as positive towards the surface, while the other fluxes are considered positive if directed away from the surface.

The energy balance of a forest canopy is strongly influenced by the fate of the water it receives. Intercepted water from precipitation is directly available for evaporation. Water retained in the organic soil layer and in the upper zones of the mineral soil is available for use by the trees in the transpiration process. Both evaporation and transpiration are driven by the transformation of incoming solar energy into latent energy. Following the energy balance, when evapotranspiration increases, less energy is left for surface heating. By controlling its evapotranspiration rate, the forest can thus control, to some degree, its own microclimate. The forest microclimate can be an important factor in the success of seedlings and the regeneration of forests. Knowledge of the relationship between the partitioning of energy and the use of water can be of great importance to the forest manager concerned with the sustainable use of this resource.

The amount of solar radiation energy absorbed by a surface is governed by its reflectivity, or albedo. The albedo of the various forest cover types was determined as

Table 1 Observed albedo values for various land cover types in the boreal forest.

Land cover	Albedo
Mature jack pine	0.091 ± 0.005
Regenerating jack pine	0.129 ± 0.007
Mature aspen mixed wood	0.145 ± 0.015
Clear-cut	0.152 ± 0.023

the ratio of the reflected and incoming short wave radiation measured directly at each site. The average daily albedo values for the four land cover types are resented in Table 1; values are the means of 1994 and 1995 observations. The values are consistent with those presented by André *et al.* (1989) for coniferous forest and by Brutsaert (1982) for coniferous and deciduous forest covers. As expected, the conifer stands (mature and regenerating jack pine) show the highest rate of radiation absorption, indicating that more energy is available for evapotranspiration as well as for heating the air and the forest soil.

SURFACE HEATING AND PARTITIONING OF ENERGY

The daily energy balance was derived for each of the forest stands. The net radiation (Q^*) and the soil heat term (Q_G) were measured directly. The latent heat term (Q_E) was calculated from observed temperature and humidity observations using a method developed by Granger & Gray (1989) and modified by Granger (1996). The sensible heat term (Q_S), calculated as the residual in equation (1) then includes both the turbulent transfer of sensible heat above the surface and the heat storage within the canopy. On a daily basis the canopy heat storage term will tend to be small and is usually neglected (Brutsaert, 1982).

Figure 1 shows the monthly energy balances at the four study sites for June 1994. As can be seen, the differences in the net radiation at these sites correspond generally to the differences in albedo (Table 1). The soil heat term is small in all cases. For the mature stands, the ratios of sensible to latent heat terms are similar, with monthly Bowen ratios near 0.5. However, the regenerating and clear-cut sites produce much less evapotranspiration, with Bowen ratios of 0.70 and 0.94, respectively, indicating higher surface heating.

The partitioning of the incoming energy (net radiation) into the various energy components, in particular the turbulent latent and sensible heat terms, provides a very

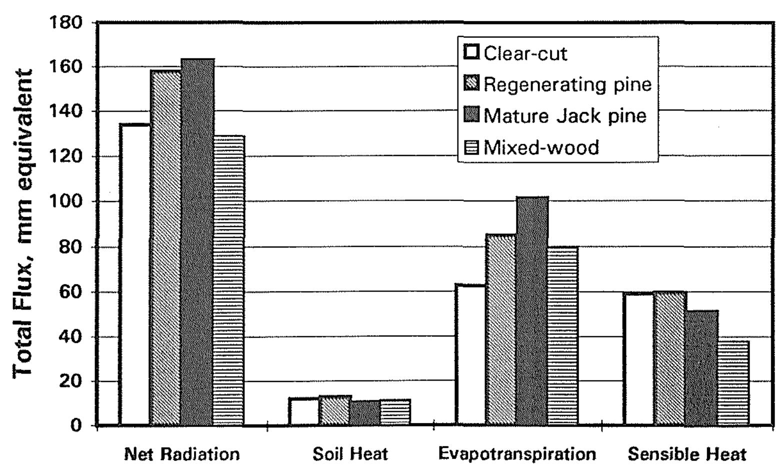

Fig. 1 Comparison of the monthly energy balance terms at the four study sites for June 1994.

descriptive indication of the forest's capacity to manage its own environment. Figure 2 shows the monthly Bowen ratios (Q_S/Q_E) at the four forest sites for the period May to September (average of 1994 and 1995). As can be seen, the largest difference between these sites occurred in the early months, May and June. The mature sites were able to draw on soil moisture reserves from snowmelt to ensure the early summer development of the required foliage; the regenerating pine produced less evapotranspiration and the clear-cut site was the least effective. Soil moisture withdrawal patterns indicate that the harvested sites have much shallower root zones than do the mature stands; these sites are also affected by the absence of an organic upper layer, and greater soil compaction. A direct consequence of the reduced evapotranspiration is greater surface heating.

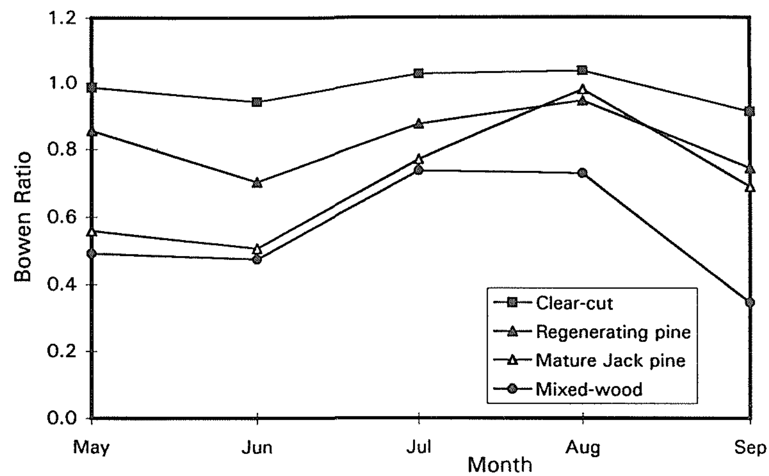

Fig. 2 Comparison of the monthly Bowen ratios at the four forest sites for the period May to September (averages for 1994 and 1995).

All sites reduced their water use during the warm months of July and August. The amplitude of this adjustment during dryer periods is also an indication of the forest's ability to respond to its environment. The mature forest stands, in particular the jack pine, show a significant reduction in the evapotranspiration during the warm, dry months. For the clear-cut site, the July and August water use remained similar to that of May and June, indicating that the immature vegetation exerts little control over the partitioning of the energy. The change in Bowen ratio at the regenerating pine site during the warm summer months is less significant than that at the mature stands, suggesting that, although it appears to be well established, the young plantation does not yet have the characteristic water use behaviour of a mature forest. All the sites showed an increase in relative evapotranspiration in September.

The effect of the partitioning of energy can also be demonstrated by the response of the surface temperatures. Figure 3 shows the daily maximum surface temperatures observed at these sites in June 1994. The surface temperatures are observed using infra red sensors mounted above the canopy. The figure shows that at the three established sites, the surface temperature trends are similar, with the mixed wood canopy being only slightly cooler than the conifer canopies. However, the clear-cut site shows maximum

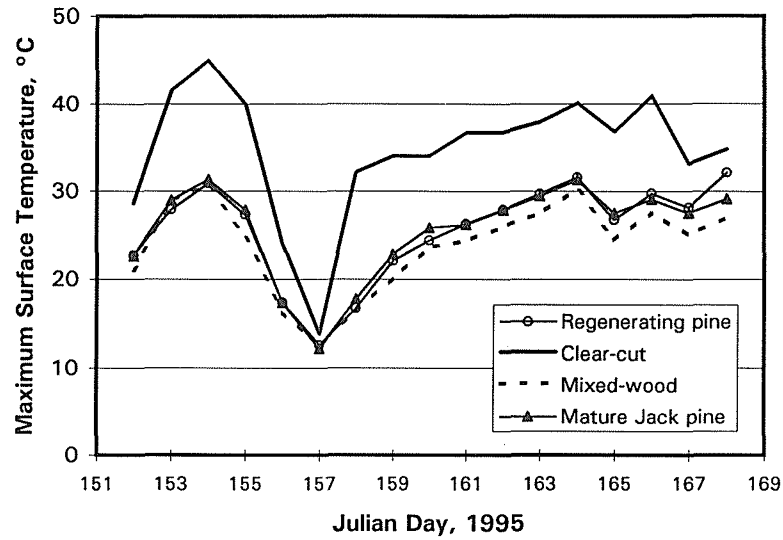

Fig. 3 Daily maximum surface temperatures observed at the four study sites in June 1994.

surface temperatures which are an average 10 °C higher than the other sites. These surface temperatures often exceed the critical seedling wilting point of 35 °C. This, of course, can have serious implications for the successful regeneration of spruce and pine seedlings.

SATELLITE-DERIVED INDICES OF FOREST REGENERATION

Remote sensing can prove to be a very useful tool for forest managers. Indices, such as the Normalized Vegetation Index (*NDVI*), are already available which provide a measure of the vegetative matter present. When working with a Landsat image, this index is calculated as:

$$NDVI = \{[(TM4 - TM3)/(TM4 + TM3) + 0.5]^{1/2}\}100 - 60 \quad (2)$$

where *TM*3 and *TM*4 are the reflectance values observed in the thematic mapper channels 3 and 4, respectively. Although an index such as *NDVI* can provide a very good estimate of the mass of vegetation present, it does not provide a complete picture of the effectiveness of forest regeneration since, as shown above, the forest's ability to manage the energy it receives is also a factor in its regeneration. A second index, the Transformed Thermal Index (*TTI*), was therefore devised to provide an indication of the forest stand's ability to partition the energy:

$$TTI = \{[(TM5 - TM4)/(TM5 + TM4) + 0.5]^{1/2}\}100 - 40 \quad (3)$$

Larger values of *TTI* indicate surfaces subjected to greater heating. The combination of the two indices, *NDVI* and *TTI*, can provide a more complete picture of forest stand regeneration. Figure 4 shows a transect of these two indices for four forest stands, mature aspen dominated mixed wood, mature jack pine, a fresh clear-cut and a jack pine plantation. The two indices show an inverse response to the surface vegetation; generally, the greater the vegetation index, the lower the thermal index, showing the effect of vegetation on the partitioning of incoming energy. The mature aspen mixed wood shows more vegetation and lower surface heating than does a mature conifer stand; this concurs with the net radiation and surface temperature observations shown in the previous section. The clear-cut, as expected, shows the least vegetation and a very large thermal index as can be expected for a site where, with little vegetation for evapotranspiration, the incoming energy is used largely for heating the surface and the air. The regenerating jack pine stand, however, provides an interesting case; although the vegetation index suggests that this stand has almost recovered to the level of the adjacent mature stand, the thermal index remains significantly higher suggesting, as shown in the previous section, that this stand has not yet fully regained its ability to manage the water and energy that it receives.

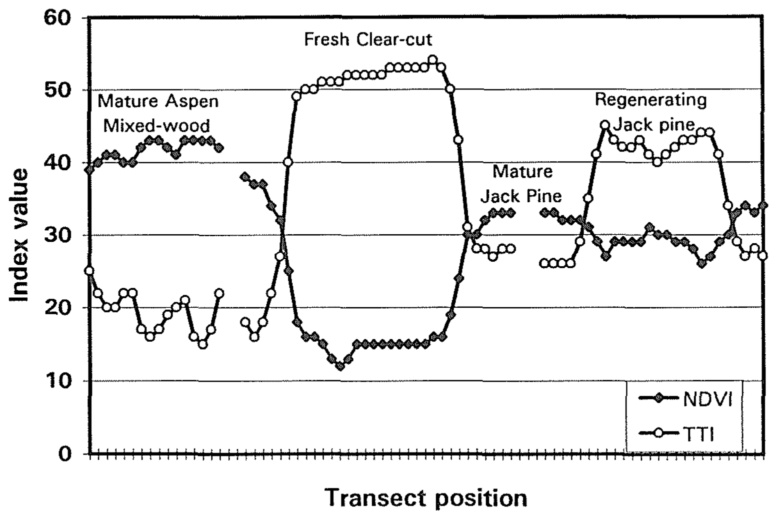

Fig. 4 Transects of the Landsat-derived vegetation and thermal indices for four forest stands: mature aspen dominated mixed wood, mature jack pine, a fresh clear-cut and a jack pine plantation (June 1992).

CONCLUSIONS

The sustainability of the boreal forest depends on its ability to make effective use of the energy and water it receives. It has been demonstrated that disturbances, such as clear-cutting, do affect the forest's ability to manage energy and water. Knowledge of the relationships between the partitioning of energy, surface heating, and water use by the forest stands must be recognized as important by forest managers concerned with the sustainable use of this resource.

A satellite-derived thermal index is shown to be useful, when used in conjunction with a vegetation index, for monitoring the effectiveness of forest stand regeneration.

Acknowledgements Funding by the Prince Albert Model Forest Association is gratefully acknowledged. The expert and diligent assistance of Mr Newell Hedstrom is also recognized.

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