WORKING PAPER 445

WATER BALANCE STUDIES IN MOORLAND BRACKEN WITH REFERENCE TO THE CHANGES FOLLOWING BRACKEN CLEARANCE

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plane displacement (m/s)
k is von Karman's constant

There are good reasons to think that this equation may not apply in the case of upland bracken[4,7,8] and further field data are required in order to confirm the appropriateness of its use here.

When the canopy is dry, transpiration plus litter evaporation is given by equation (1) with the bulk canopy resistance, r_s, calculated from

$$1/r_s = (1-A)/r_{sc} + A/r_{ss} \tag{3}$$

where r_{sc} is the crop surface resistance (s/m)
r_{ss} is the bare soil or litter surface resistance (s/m)

$A = f^{LAI}$ where $f = 0.7$ and LAI is leaf area index

The crop surface resistance for bracken is derived, after correction for LAI, using the relationships suggested by Roberts *et al*[5] for woodland bracken in which the reciprocal of resistance, bracken stomatal conductance, is given by

$$g_s = F_1 F_2 F_3 \tag{4}$$

where $$F_1 = P_1 Q/(P_2+Q) \tag{5}$$

$$F_2 = 1 - P_3 D \tag{6}$$

$$F_3 = 1 - \exp[-P_4(\theta_s - P_5)] \tag{7}$$

where g_s is the bracken stomatal conductance (mm/s)
Q is the solar radiation (W/m^2)
D is the atmospheric specific humidity deficit (g/kg)
θ_s is the soil moisture volume fraction in the upper 0.5 m of the soil
P_1 to P_5 are empirical constants

Equations (4) to (7) were not developed for moorland bracken and future work must assess the validity of these equations in the moorland context.

As regards bracken interception, a model has been used in which the proportion of rainfall intercepted by bracken is estimated from

$$p = 1 - 0.8^{LAI} \tag{8}$$

and the total interception is given by

$$I = Rp \tag{9}$$

where R is rainfall (mm)

The canopy is regarded as having an equilibrium surface storage capacity, S, which is charged by rainfall and discharged by evaporation and drainage. Preliminary work on moorland bracken suggests that this storage capacity may be approximated by

$$S = 0.5\ LAI \tag{10}$$

where S is surface storage capacity (mm)

Following Rutter et al[6], when the amount of water on the canopy equals or exceeds this storage capacity, the evaporation rate from the vegetation canopy is given by equation (1) with r_s set to zero. When the amount of water on the canopy is less than the storage capacity, the evaporation rate is given by

$$E = IC/S \tag{11}$$

where I is potential evaporation rate given by equation (1) with r_s set to zero (mm)
C is amount of water on the canopy (mm)

The rate of drainage from the canopy is given by

$$D = D_s \exp\ [b(C-S)] \tag{12}$$

where D_s is the drainage rate from the canopy when storage is at capacity (typically 0.002 mm/min)
b is a constant

The final hydrological component of the model is a soil moisture store. The one used here is that based on Lockwood et al[9] and Lockwood[10] in which the water available for evaporation and transpiration is held in two reservoirs, X and Y, which at any time may contain reserves of x and y mm water respectively. All water in X is freely available, while that in Y becomes increasingly difficult to extract as the water content decreases. Water is drawn from the soil until X is completely exhausted and only replenishes Y when X is filled. X and Y can be regarded as conceptual stores and do not necessarily represent discrete soil layers. The soil moisture control on stomatal conductance in equation (7) is calculated using the sum of x and y. Bare soil or litter surface resistances are taken to be 100 s/m when store X contains moisture and, in other cases, calculated as in MORECS (4) using

$$r_{ss} = 100\ [3.5\ (1 - y/y_{max}) + \exp(0.2(y_{max}/y - 1\ ))] \tag{13}$$

where y_{max} is soil moisture storage capacity of Y (mm)

This completes a description of the model used in the calculations presented here. Although, as pointed out, some of the relationships are not specifically designed for upland bracken, their use is thought to be adequate in this preliminary discussion paper.

MODEL CALIBRATION

In order to calibrate the numerical model presented above, the hydrology of an extensive area of moorland bracken near Pateley Bridge, North Yorkshire, has been monitored since September 1983. The site lies at an altitude of 250 m OD and is covered by Glacial Drift overlying Millstone Grits. The resulting podzolic soils are mostly ill-differentiated and of very variable depth. The texture is predominantly sand. Surface layers of litter and decomposing bracken debris are for the most part at least 20 cm thick.

The instrumentation of the site consists of a Didcot type automatic weather station modified to include a soil heat flux plate and an albedo meter. Two 12m by 0.105 m troughs feeding into tipping bucket raingauges measure the throughfall below the bracken canopy, while two similar troughs collect seepage below the bracken litter. An area 10 m by 20 m surrounding the troughs is fenced to prevent

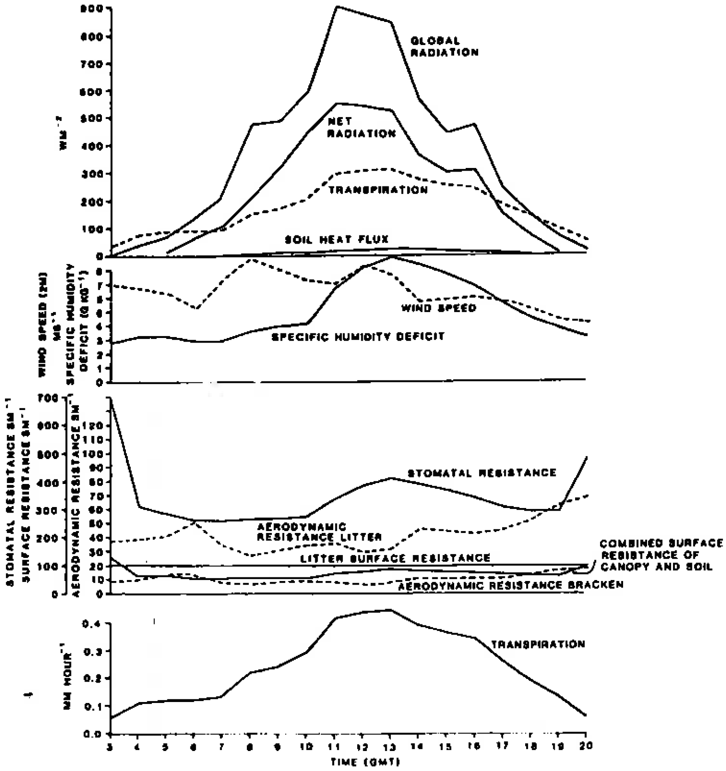

Figure 1 Hydrometeorological parameters during a typical sunny day in summer. All values are measured except transpiration and the resistances which are model predictions. The soil is moist, bracken leaf area index 5, bracken height 0.94m. Values are for the following hour. Transpiration includes litter evaporation. Soil heat flux is measured below the litter layer.

grazing and trampling. Automatic weather station and rainfall interception readings are taken at 5 minute intervals, while the seepage measurements are taken over two hourly periods. Soil moisture is monitored weekly at a number of sites using an Institute of Hydrology Neutron Probe.

Figure 1 shows the application of the model to a typical bright day in high summer. Soil moisture is assumed to be adequate and not limiting litter evaporation or plant transpiration. Input data are provided in the two upper graphs while outputs from the model as applied to a fully developed bracken canopy are given in the two lower graphs. Looking at the resistance values it is clear that the bulk canopy resistance of bracken is similar to other short green crops whereas its aerodynamic resistance is comparatively low due to its greater height. The highest transpiration losses (including litter moisture loss) occur around mid-day but are considerably less than the net radiation, and appear to be less than those expected from a short green crop such as grass. Values of aerodynamic resistance for bare litter are shown as a comparison. The soil heat flux, measured just below the litter layer, is small and downwards.

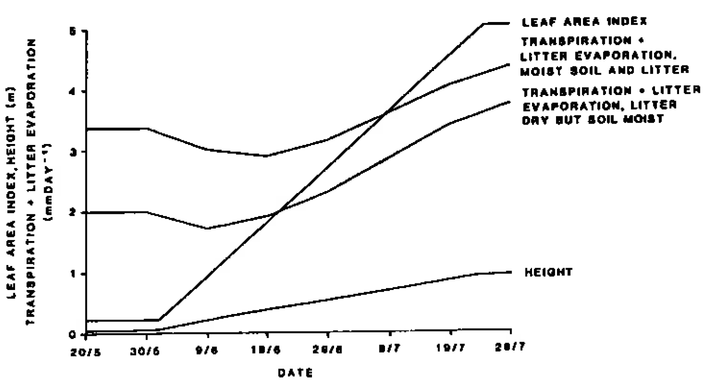

Figure 2 Variation in bracken model predictions as the bracken canopy develops.

Figure 2, constructed from model runs using the same meteorological input as given in figure 1, shows something of the effects of bracken growth on evaporation losses. Combined transpiration and litter evaporation show an initial decrease as the young bracken grows. When the leaf area index exceeds about 2, total evaporation loss rates increase as the canopy develops. A comparison of the curves for dry and moist litter suggests that evaporation rates from litter are relatively high and that the combined daily evapotranspiration loss for a fully developed bracken canopy with moist soil may exceed 4 mm. Figure 2 is interesting in that it does suggest that under certain meteorological inputs the total evaporative loss from sparse bracken could be less than that from bare litter

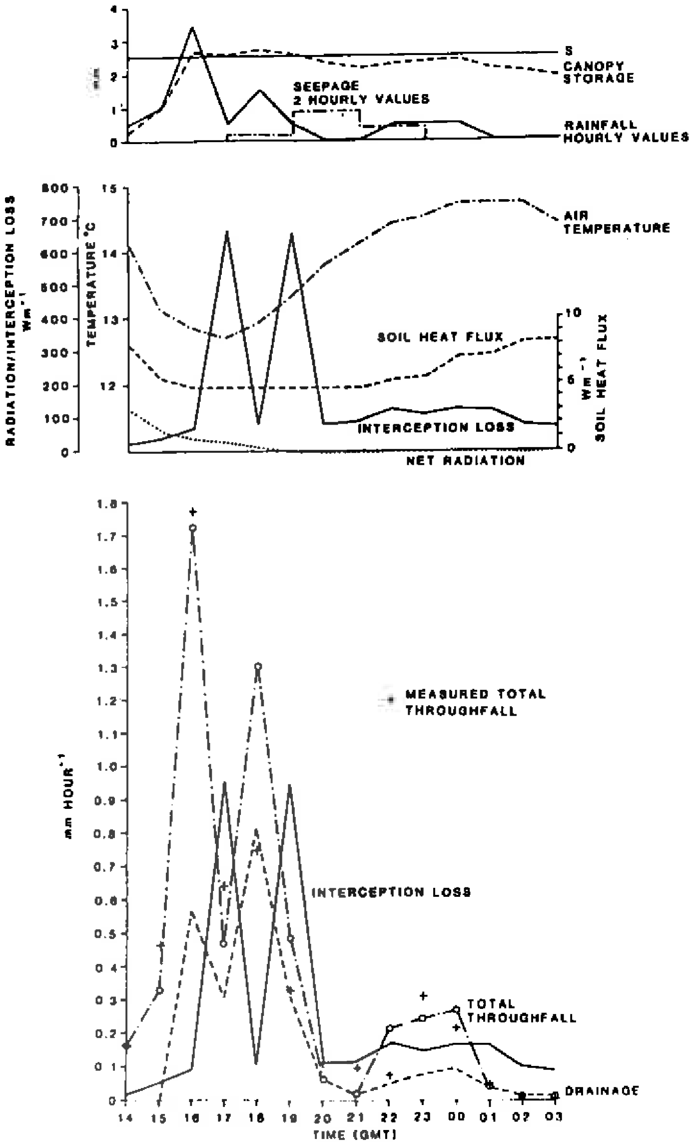
S
CANOPY STORAGE
SEEPAGE 2 HOURLY VALUES
RAINFALL HOURLY VALUES
AIR TEMPERATURE
SOIL HEAT FLUX
INTERCEPTION LOSS
NET RADIATION
RADIATION/INTERCEPTION LOSS Wm⁻¹
TEMPERATURE °C
SOIL HEAT FLUX Wm⁻²
MEASURED TOTAL THROUGHFALL
INTERCEPTION LOSS
TOTAL THROUGHFALL
DRAINAGE
mm HOUR⁻¹
TIME (GMT)

Figure 3

covered ground. This is due to the interaction of the bulk surface and aerodynamic resistances referred to in the introduction.

Under wet conditions, interception loss becomes extremely important. The application of the model to a wet canopy is shown in figure 3 - for the storm of 27 July 1984. The figure shows measured and predicted values of rainfall interception, the values being for the following hour. Conditions were dry prior to 1400 GMT. Thereafter, measured rainfall and seepage below the litter layer are given in the top graph as is the canopy storage capacity, S, and the predicted canopy storage level. Other measured meteorological conditions are given in the second graph as is the calculated interception loss in energy terms. The fact that interception losses are considerably higher than the net radiation values highlights the existence of strong sensible heat advection and this may be reflected in the air temperature curve at 2m. The importance of this is further reinforced by the fact that the soil heat flux, just below the litter layer, is down into the ground throughout the storm. In the third graph of figure 3, measured throughfall values (represented by crosses) are compared with the calculated values of total throughfall ie. free throughfall plus canopy drainage (dot-dashed line), canopy drainage (pecked line) and interception loss (solid line). These suggest reasonable agreement between the model and collected data. As an indication of the overall importance of interception loss in the water balance of a broken canopy, it may be noted that, of the 9.0 mm rain which fell during the storm, only 4.98 mm reached the litter layer and only 1.38 mm was recorded as seepage below the litter layer.

POTENTIAL APPLICATION OF THE MODEL TO BRACKEN CLEARANCE

This section discusses the application of the model outlined above to the bracken site over the months May to October 1984 and compares soil moisture variation under bracken with that under a nearby pilot plot sprayed with asulam in July 1983.

In addition to the site instrumentation discussed above, leaf area index was measured weekly on samples taken from two 0.5 m^2 randomly-chosen plots using an integrating TV camera. The measurements show a large amount of scatter reflecting the high spatial variability of the canopy. The top two graphs of figure 4 show the general pattern of leaf area index and green leaf area index per frond respectively.

Average values of weekly soil moisture deficit measured using a neutron probe are shown in the third graph both for bracken and for the cleared plot (under bracken litter). The values apply to the top 50 cm of the soil profile which is considered to contain the bulk of the bracken roots. Between the start of the growing season and the peak of bracken development at the end of July, about 70% of the soil moisture loss down to a depth of 150 cm was in the top 50 cm of the profile. Compared to the assumed available soil moisture capacity of upland soils of about 50 mm[4,9], the soil moisture deficits reported here under bracken are high for upland areas but low compared to many agricultural crops.

Measured rainfall (up to late August), throughfall below the bracken canopy and seepage below the litter are shown in the fourth

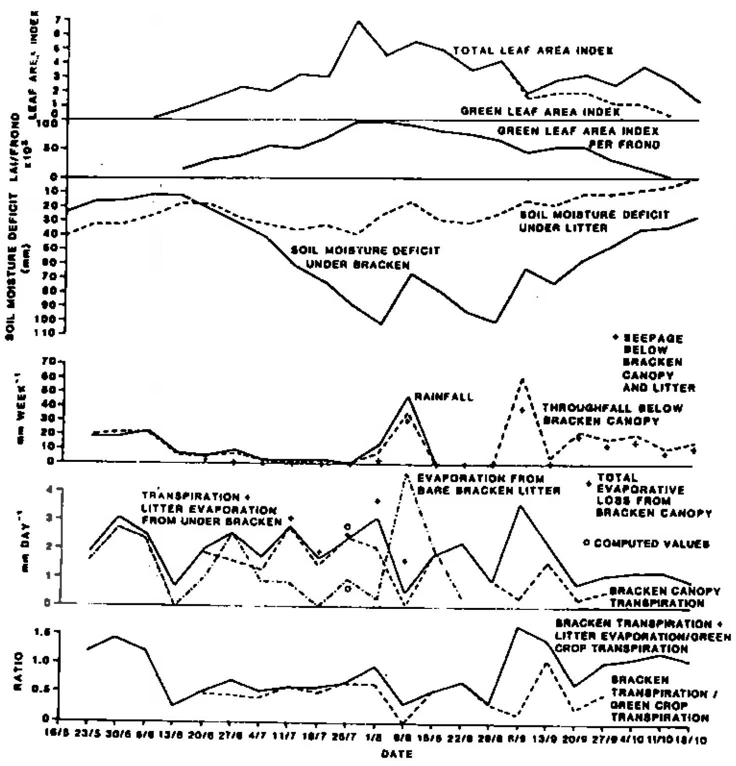

Figure 4 Hydrometeorological observations for a moorland bracken site during summer 1984. Values are for the previous week. Computed values refer to model predictions for week ending 25 July.

graph of figure 4. Assuming that soil drainage in summer is small, rough estimates, based on a simple water balance, have been made of the bracken canopy transpiration, the bracken canopy transpiration plus litter evaporation from under the bracken, and the evaporation from the cleared plot. These are shown in the fifth graph of figure 4. They compare reasonably well with the preliminary model calculations available of bracken transpiration plus canopy litter evaporation, and bare litter evaporation, for the week of 18-25th July and confirm the difference in the transpiration and evaporative losses from bracken and bare litter under dry summer conditions.

Before the bracken canopy is partly developed the evaporative losses from both the bracken covered and cleared plots are similar.

However, during the dry conditions of the early summer, evaporation from the cleared plot is low compared with that from the bracken because of the very high bulk surface resistance of the dry litter. This explains the relatively low soil moisture deficits observed under the cleared plot in summer. The reaction of the cleared plot to the intense rainfall during the week prior to the 9th August, however, is interesting. In the case of the bracken covered plot, most of the rain is used to recharge the soil moisture, and the total evaporation and transpiration losses remain small. In contrast to this, the evaporation from the wet litter is high and soil moisture recharge is limited. Under summer conditions, often with strong sensible heat advection, interception losses from bracken can be large. Total evaporation losses (transpiration + litter evaporation + interception loss) for bracken are shown by crosses in the fifth graph of figure 4. It is seen that during wet weeks the contribution of interception loss to total evaporative loss is significant. A detailed example of a rain storm was examined earlier.

As preliminary evidence of the likely effect on the hydrology of replacing bracken by an alternative green crop, the ratios of bracken transpiration and transpiration plus litter evaporation to the calculated transpiration rates from a standard fully developed short green crop with a moist soil are given in the final graph of figure 4. Values of the ratio bracken transpiration plus litter evaporation to standard crop transpiration are generally greater than unity at the beginning and end of the growing season. The surface resistances of wet bracken litter are low (or zero), as in the case of wet canopies, and model calculations suggest that these high evaporative losses can be explained by the evaporation from wet litter after rainfall. During the growing season, however, the transpiration from bracken is less than that expected from a "standard green crop" which suggests that the interaction of the two resistances of the bracken canopy and the high soil moisture deficits are limiting bracken transpiration. Up to 1 August there is no evidence that variations in soil moisture deficits are causing significant variations in the ratio of bracken transpiration to standard crop transpiration. However, in late August, when the bracken is no longer actively growing, large soil moisture deficits do appear to be strongly influencing transpiration loss. There is no clear evidence that the dieback in September is due to frost damage. Dieback in September is one possible mechanism for decreasing transpiration loss by reducing very high values of leaf area index and, therefore, increasing surface resistance.

CONCLUSIONS

This paper has presented some preliminary results relating to the likely effects of bracken clearance on the hydrology of upland areas during the summer months. In particular, it is clear that interception losses are high from both bracken and exposed wet litter. It is also clear that the evaporation losses from a dense bracken cover are far greater than for a cleared litter-covered plot, except during rainfall events. The picture with respect to other replacement crops is more complicated, with transpiration losses slightly lower in the case of bracken compared to a "standard crop" during the growing season of June to August. However, further research is required in order to apply the numerical model outlined here more specifically to a moorland environment and realistic alternative vegetation types.

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