A comparative study of radiation balance above forest and grassland

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SUMMARY

Daily net radiation above a Pinus radiata plantation was found to exceed that measured above nearby grassland by about 12% during the winter and 24% during the summer months. This difference was related to differences in the albedo and net longwave radiation associated with the surface temperature of each vegetation. Forest albedo was found to be 0.11 ± 0.01 throughout the winter and did not exhibit a significant diurnal variation. The grassland albedo was found to give the usual diurnal trend and a mean winter albedo of 0.27 ± 0.03 which decreased to 0.24 ± 0.01 in summer, consistent with increasing solar elevation.

Hourly values of net radiation \( R_n \) above the forest during daylight hours were found to exceed those for grassland by about 15% during the winter and about 25% during the summer. When the forest was wet and the change in canopy heat storage \( Q \) and ground heat flux \( G \) were small, such differences also applied to the energy \( (R_n - G - Q) \) available for evaporation. However, when the canopy was dry, values of \( Q \) during the day were sufficiently large to reduce the forest available energy to about that of the grassland. This forest canopy energy was generally lost during the night.

1. INTRODUCTION

Accurate estimates of net radiation \( R_n \) above natural surfaces, including e.g. soil, grassland, crops or forests, are important for the determination of the energy that is available for latent heat (water vapour) and sensible heat transfer processes between these surfaces and the atmosphere. Such estimation is therefore important for the determination of evaporation in hydrological studies and the heat budget in climatological studies. When direct measurements made with net radiometers are not available, net radiation may be estimated from the measurement or prediction of components of the radiation balance, given by

\[
R_n = S\downarrow - S\uparrow + L\downarrow - L\uparrow
\]

where \( S\downarrow, S\uparrow \) = incoming and outgoing shortwave radiation, and \( L\downarrow, L\uparrow \) = incoming and outgoing longwave radiation. Given similar climatic conditions, the important differences in net radiation above different surfaces depend on two surface characteristics. One is the albedo given by

\[
\alpha = S\uparrow / S\downarrow
\]

whose value may depend on factors such as vegetation type and structure or soil moisture. Estimates of the albedo for coniferous forest have varied from 0.08 to 0.14 (Stewart 1971) and 0.13 to 0.21 (Federer 1968) and for grassland from 0.23 to 0.27 (Monteith and Szeicz 1961) and 0.21 to 0.29 (Nkemdirim 1972). Difficulties arise in presenting values of the albedo, as it can depend not only on surface characteristics, but also on solar elevation \( \theta \). This can produce a characteristic diurnal pattern with minimum albedo near maximum solar elevation (cf., e.g., Mukammal 1971), and a seasonal variation related to varying maximum solar elevation.

The other surface characteristic affecting the net radiation is the surface temperature \( T_s \) (K) through the relationship

\[
L\uparrow = \sigma T_s^4
\]

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where $\sigma = 5.67 \times 10^{-8} \text{Wm}^{-2}\text{K}^{-4}$. It is assumed that the surface emissivity is close to unity. Again, given similar climatic conditions, differences in surface temperature between different vegetation canopies may depend on such factors as canopy structure, soil moisture or transpiration rate. To isolate differences in net radiation above various surfaces resulting from their properties, it is important to eliminate the effect upon the measurements of large-scale factors such as sky-cover, climate, rainfall regime or even the soil regime. This may be done most simply by taking measurements over each vegetation type concurrently, at sites that are a short distance apart.

This approach was adopted for a comparative micrometeorological investigation of grassland and pine forest (Moore 1974, 1976) to assess the water use by these two extreme types of vegetation cover. An important part of such an investigation was considered to be a study of the radiation balance of each vegetation. This would provide information on the net radiation above each vegetation, necessary for energy budget studies, and its relationship to other components of the radiation balance, useful for predicting $R_e$ when measurements were not available. This paper describes some of the results from this study.

2. EXPERIMENTAL SITES AND INSTRUMENTATION

Measurements of net radiation, incoming and outgoing shortwave radiation were taken over two sites, one a 10-year-old Pinus radiata (D.Don) forest plantation about 11 km north of Mt. Gambier (140°45'E 37°50'S) in the southeast of South Australia, and the other a grassland site about 9 km farther east. At the forest site a CSIRO polystyrene-shielded net radiometer and downward facing Kipp solarimeter were supported about 2 m above the tallest trees at the end of a beam attached to a micrometeorologically instrumented tower. The net radiometer was aspirated with dry nitrogen and did not have a heating ring. An upward facing Kipp solarimeter was supported on the tower platform guard-rail. A more detailed description of the tower and forest site has been given by Hicks et al. (1975). The radiation measurements were taken during the summer months November–January 1972–1973, when some moisture stress was probably experienced by the vegetation, and during the winter months July–October 1973, when above average rainfall ensured no moisture stress was experienced. During this period the forest was approximately 14 m high and the canopy was fully closed.

At the grassland site a net radiomer and downward-facing solarimeter were supported 2 m above a grazed pasture which consisted mainly of subterranean clover (Trifolium subterraneum, L.), perennial rye grass (Lolium perenne, L.) and strawberry clover (Trifolium repens, L.). Signals from each sensor at both sites were converted to pulses and registered on counter-printers. The totals were recorded every hour. Temperature and humidity measurements were obtained from platinum resistance sensors or from meteorological records taken at a Commonwealth Bureau Meteorological station about 1 km south of the forest site in open grassland. Calibration of the net radiometers was carried out by CSIRO in 1970 and 1974 to a stated 2.5% accuracy, while the Kipp solarimeters were calibrated by the manufacturers in 1971 and recalibrated against a sub-standard actinometer in 1972. No significant changes in the calibration coefficients were found.

3. RESULTS

(a) Forest radiation balance

Figure 1 shows the daily variation of each of the components in the forest radiation balance for three days with near-cloudless skies in summer (31 Dec. 1972), winter (5 July 1973) and spring (28 Sep. 1973). The daily incoming shortwave radiation was 33.1, 10.3 and
22.5 MJ m$^{-2}$ day$^{-1}$ (or, in units equivalent to evaporation of water, 13.5, 4.2 and 9.2 mm day$^{-1}$). For these days the daily (24-h) net radiation was 23.0, 2.9 and 13.7 MJ m$^{-2}$ day$^{-1}$ (9.4, 1.2 and 13.7 mm day$^{-1}$) respectively. Erratic behaviour of the net longwave radiation during the afternoon of the 31 Dec. 1972 probably arose from errors in measurements of net and shortwave radiation due to the presence of a small amount of cloud.

(b) Grassland radiation balance

Figure 2 shows the daily patterns of the grassland radiation components for three days with near cloudless skies, one in summer (31 Dec. 1972) and two in winter (5 July 1973,
15 Aug. 1973). The daily incoming shortwave radiation for each of these days was 33.1, 10.3 and 15.2 MJ m\(^{-2}\) day\(^{-1}\) while the daily net radiation was 17.7, 2.7 and 5.6 MJ m\(^{-2}\) day\(^{-1}\) (7.2, 1.1 and 2.3 MJ m\(^{-2}\) day\(^{-1}\)) respectively.

The maximum hourly net radiation over the forest during daylight hours in summer exceeded that above the grassland by about 23%. In winter it was in excess by 15% or less.

**(c) Forest albedo**

To assess the diurnal and seasonal variations of the forest albedo, hourly values of the albedo for each month considered were plotted against solar elevation \(\theta\). The mean values of \(a\) were determined for 3° intervals of \(\theta\) and are shown in Fig. 3. During July–October 1973 the albedo at a given solar elevation was approximately constant, while the diurnal variation gave a consistently symmetric pattern. The albedo increased from 0.104 ± 0.004 for solar elevations greater than 50° to 0.116 ± 0.010 at \(\theta = 30°\). At lower solar elevations the mean albedo did not increase but remained about 0.11 ± 0.04. As these values were derived from days with generally cloudy skies, the low albedo at low solar elevation was probably due to a relative increase in diffuse incoming shortwave radiation. On the four days with clear skies on which data were collected, the albedo generally increased with decreasing solar elevations.

During the summer months December 1972 and January 1973 the albedo showed an asymmetrical diurnal variation with afternoon values exceeding the morning values. Instrumental error was ruled out because (i) reflected radiation is diffuse and errors due to solarimeter tilt are consequently small, and (ii) heating of the body of the inverted solarimeter would have produced an underestimate of the albedo because of a sensor negative temperature coefficient. It thus appeared that the albedo of the forest canopy foliage increased during summer afternoons, presumably in response to increased water stress that would be expected during these periods. However, further measurements under these conditions are required.

In summary, for the conditions under which the data for the 1973 period were obtained, a mean albedo of 0.11 ± 0.01 over all \(\theta\) may be applied to the forest canopy. This is consistent with the mean daily albedo, calculated as the ratio of outgoing daily to incoming daily shortwave radiation, as shown in Fig. 5, where the small decrease in the mean albedo from winter to summer corresponds to the increase in the maximum solar elevation.

![Figure 3. Albedo of *Pinus radiata* forest as a function of solar elevation. Points are mean monthly values.](image-url)
(d) Grassland albedo

The diurnal variation of the grassland albedo is shown in Fig. 4. Hourly values of albedo were averaged over $10^2$ intervals of $\theta$ and plotted against $\theta$. Open circles show the winter and spring, and closed circles the summer values. A large scatter in the data points was found probably due to the distance between the solarimeter measuring the reflected radiation at the grassland site and the upward facing solarimeter at the forest site. Measurements were taken in generally scattered cloud conditions. This scatter reduced the possibility of finding any significant variations in the grassland albedo over the season, although summer afternoon values appeared to exceed those in other conditions. This trend is similar to that observed for the forest data.

The grassland albedo showed a generally greater diurnal variation than that for the forest, suggesting that the radiation 'penetrating/trapping' explanation (Graham and King

Figure 5. Seasonal variation of the regression coefficients $a_1$ and $a_2$, the mean forest albedo, and the long-wave exchange coefficient, $\Lambda$. 

Figure 4. Albedo of grassland as a function of solar elevation. Points are means of winter (○) and summer (●) months.
1961; Monteith and Szeicz 1962) for the dependence of albedo on solar elevation may not be adequate. The grassland albedo decreased from about $0.30 \pm 0.07$ at low solar elevations to $0.22 \pm 0.03$ at high solar elevation.

![Graph](image)

Figure 6. Seasonal variation of the regression coefficients $a_1$ and $a_2$, the mean grassland albedo, and longwave exchange coefficient $A$.

The mean albedo for the grassland site, determined from measurements of daily incoming and outgoing shortwave radiation and shown in Fig. 6, decreased from about $0.27 \pm 0.03$ in winter to $0.24 \pm 0.01$ in spring and summer, consistent with increasing solar elevation.

(e) Longwave radiation

The greater reflection of shortwave radiation from the grassland accounts for some of the observed differences of net radiation between grassland and forest. However, in winter the differences in albedo appeared to be compensated by a greater average longwave radiation loss by the forest. In summer the grassland experienced greater longwave radiation loss (cf. Figures 1, 2 and 10). This suggests that the forest canopy surface temperatures were on average higher in winter and lower in summer than the grassland surface temperatures, a phenomenon that may be explained by the relative amounts of transpiration from each surface. During the summer, when the soils become very dry, transpiration from grassland appears to be more restricted than from the forest. During the rainy season (winter), evidence (to be presented) that forest transpiration is more restricted than that for grassland when both canopies are dry, combined with greater forest net radiation, leads to higher forest surface temperatures.

4. Regression equations

(a) Regression of net and solar radiation

Figure 7 shows a plot of diurnal net radiation against incoming shortwave radiation for a number of days. The daily cycle for the days with near-cloudless skies shows that for a given incoming shortwave radiation, the net radiation is less in the afternoon than in the
morning, possibly due to higher surface temperatures in the afternoon. The separation of the morning and afternoon data gives a measure of the asymmetry of the diurnal net radiation patterns.

![Graph showing regression of the forest net radiation $R_n$ and incoming shortwave radiation $S\downarrow$ for three cloudless days and one cloudy day as shown.](image)

**Figure 7.** Regression of the forest net radiation $R_n$ and incoming shortwave radiation $S\downarrow$ for three cloudless days and one cloudy day as shown.

The absence of such a separation in the plots of diurnal net radiation above the grassland site against incoming shortwave radiation shown in Fig. 8 indicates the possibility, however, that an east-west tilt of the forest net radiometer may have occurred, in spite of a determined effort to maintain this instrument level.

Therefore, in determining the general relationship between net and shortwave radiation over each day, such separation of data was ignored and regressions including both morning and afternoon data were carried out. The net radiation and incoming shortwave radiation may be related by the equation (Monteith and Szeicz 1961; Idso et al 1969; Gay 1971)
Figure 8. Regression of grassland net radiation $R_n$, and incoming shortwave radiation $S\downarrow$, for three cloudless days and one cloudy day (13-8-73).

$$R_n = a_1 S\downarrow + L_0,$$

or

$$R_n = a_2 (1 - \alpha) S\downarrow + L_0,$$  \(\text{(4)}\)

where the regression coefficients $a_1$, $a_2$ and the longwave radiation $L_0$, i.e. the net longwave radiation when $S\downarrow = 0$, are usually assumed to be constants for a given surface.

The monthly means and standard deviations of $a_1$ and $a_2$ are shown in Fig. 5 for the forest data, and Fig. 6 for the grassland data. For the forest, $a_1$ increased from 0.67 ± 0.07 in July to 0.85 ± 0.03 in January, while $a_2$ increased from 0.77 ± 0.08 to 0.94 ± 0.05 over the same period. In contrast, $a_1$ and $a_2$ for the grassland did not show similar trends, but gave respective means of 0.60 ± 0.10 and 0.78 ± 0.10 for most of the period. During September and October an increase to 0.70 ± 0.10 and 0.90 ± 0.10 was noted, although the data during this period were scattered and a high reliability should not be placed on these results. However, if the results are valid, this increase cannot be explained by a change in albedo but represents a decrease in the fraction of absorbed shortwave radiation that is lost as outgoing longwave radiation. The rate of plant growth of the grassland increased rapidly during this period, and it is possible that a greater fraction of the absorbed shortwave radiation was used for transpiration.

(b) Longwave exchange coefficient

An attempt to relate the above variation of the regression coefficients to the seasonally varying radiation balance was made by considering the longwave exchange coefficient $\Lambda$ introduced by Gay (1971). This parameter describes the change in net longwave radiation over a surface per unit change in absorbed shortwave radiation, and is given by

$$\Lambda = (L_n - L_0) / [(1 - \alpha) S\downarrow],$$  \(\text{(5)}\)

which leads to $R_n = (1 + \Lambda) (1 - \alpha) S\downarrow + L_0$.

A plot of $\Lambda = a_2 - 1$ for the forest data (Fig. 5) shows a variation from −0.23 in July to −0.06 in January, while the grassland data (Fig. 6) shows that $\Lambda$ increased from −0.24 in July to a peak of −0.10 in October and then decreased to about −0.2 in December. Negative values of $\Lambda$ are consistent with the suggestion put forward by Gay (1971) that $\Lambda < 0$.
whenever the absorbed shortwave radiation increases more rapidly than the amount of net radiation that is partitioned into evapotranspiration at the surface. The remainder of the net radiation thus made available must be transformed into sensible heat loss or change in heat storage at the surface. In either case, the surface temperature must rise and thus increase the net longwave radiation loss.

On the basis of this model, values of \( \Lambda \) would be expected to become more negative during the period July to December as the surface became drier and transpiration was more restricted. The forest data and the grassland data (until at least October) indicated that this clearly did not happen. The model assumes that the rate of change of incoming longwave radiation is negligible compared to rate of change of absorbed shortwave radiation. This is probably a reasonable assumption for short, diurnal periods, but not for longer, seasonal periods when changes in atmospheric emissivity associated with seasonal changes in vapour pressure become significant.

(c) Prediction of net radiation

The preceding sections indicate that the coefficients of regression of net and shortwave radiation above a surface depend not only on the surface characteristics, but also on meteorological conditions in a manner that is not well understood. It is therefore hazardous to apply the results presented here to other areas with different meteorological conditions even if surface characteristics are very similar. If the net longwave radiation can be estimated \( (L_n) \) then the data indicate that net radiation \( R_n \) may be predicted from the incoming shortwave radiation \( S \) using the following equations:

\[
P. \text{ radiata forest:} \quad R_n = 0.89S + L_n \quad (6)
\]

Grassland:

\[
R_n = 0.73S + L_n \quad \text{(winter)}
\]

\[
R_n = 0.76S + L_n \quad \text{(summer)} \quad (7)
\]

For the region under study, these equations may be further reduced. The constant of regression \( L_0 \) (Eq. (4)) was determined as the mean net longwave radiation (net radiation) during the night, found by averaging each hourly night-time value over periods of many weeks. Equations (6) and (7) then become

\[
P. \text{ radiata forest:} \quad R_n = 0.67S - (45 \pm 10) \text{ W m}^{-2} \quad \text{(winter)}
\]
\[
R_n = 0.65S - (55 \pm 10) \text{ W m}^{-2} \quad \text{(summer)} \quad (8)
\]

Grassland:

\[
R_n = 0.60S - (35 \pm 10) \text{ W m}^{-2} \quad \text{(winter)}
\]
\[
R_n = 0.70S - (45 \pm 10) \text{ W m}^{-2} \quad \text{(spring)}
\]
\[
R_n = 0.64S - (35 \pm 10) \text{ W m}^{-2} \quad \text{(summer)} \quad (9)
\]

5. CONCLUSIONS

(a) Diurnal comparison of forest and grassland net radiation

To investigate the energy provided at a vegetative surface for partition into sensible and latent heat, the net radiation to that surface must be slightly modified to give the 'available energy' which is, for the forest \( A_f = R_n - G_f - Q \), and for the grassland \( A_g = R_n - G_g - Q \), where \( R_n \) is the net radiation, \( G \) is the ground heat flux and \( Q \) is the change in heat storage of the forest canopy (Moore 1976). A direct comparison of forest and grassland diurnal (daylight) net radiation and available energy is shown in Fig. 9.
The diurnal forest net radiation appeared to exceed the grassland net radiation by approximately 15% over the period of the experiment, except for large values of net radiation where differences appeared to be less. The number of data points for, and different cloud distributions over, the two sites probably combined to produce errors in some of the means, particularly for large values of $R_p$. The difference in the net radiation over the vegetation is related to differences in the albedo and surface temperatures as discussed in the previous sections.

In contrast, the available energy for the forest and grassland during the 30 days' data (three or more days after the previous rainfall) used, when each vegetation was externally dry, did not appear to be significantly different. The extra 15% net radiation at the forest was reduced mainly by the heat storage term $Q$ so that during the day the available energy at both sites was nearly equal. This energy $Q$ absorbed by the forest canopy is released during the night when it may be used for evaporation of surface water. The difference between the available energy of each site during days when the foliage was wet from intercepted rainfall appeared to be generally less than the differences in the net radiation, although often the heat storage terms were small and $A_f$ exceeded $A_g$ by about 15%.

(b) Daily and seasonal comparison of forest and grassland radiation

The difference between the daily components of the forest and grassland radiation balances during the summer (1972–1973) and winter (1973) may be found by comparing the traces shown in Fig. 10. Each interval represents a 7-day mean, where at least five days' data have been used to determine the mean for the periods when data were missing. During the winter the daily net radiation to the forest appeared to exceed that to the grassland by an average of about 12%, consistent with the hourly values mentioned above, although it was
Figure 10. Seasonal variation of the average forest and grassland radiation balance components shown.

less than that to the grassland for a few periods associated with rainfall and heavy overcast. During the summer the forest daily net radiation exceeded that to the grassland by about 24% on average.

REFERENCES