The impact of converting grassland to pine forest on water yield in Viti Levu, Fiji

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Abstract Evapotranspiration (ET) in 6-year-old and mature pine plantations and natural grassland in southwest Viti Levu, Fiji, were compared. Dry season ET (Bowen ratio energy balance method) of the young pine stand over 145 days in 1990 was 3.6 ± 1.0 mm day⁻¹. The corresponding value for the mature stand over 1990 (basin water balance) was 4.3 mm day⁻¹. Penman open water evaporation ($E_0$) for 1990 was 1812 mm, suggesting $BT/E_0 = 0.86$ for mature pine. Average ET for grassland over 131 days during the dry season of 1991 was 1.0 ± 0.3 mm day⁻¹ (Penman-Monteith), with a corresponding $E_0$ of 3.7 ± 1.0 mm day⁻¹. The resulting low value for $ET/E_0$ (0.25) was attributed to the gradual dying of the grass as the dry season progressed. Because of the large difference in dry season ET between grassland and pine forest, the reafforestation of Fijian grasslands will produce a significant decrease in water yield during a time of year when water is already scarce.

NOTATION

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>$c_p$</td>
<td>Specific heat of air at constant pressure</td>
<td>[J kg⁻¹ K⁻¹]</td>
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<tr>
<td>$d$</td>
<td>Zero plane displacement length</td>
<td>[m]</td>
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<tr>
<td>$e$</td>
<td>Actual vapour pressure</td>
<td>[mbar]</td>
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<tr>
<td>$e_s$</td>
<td>Saturation vapour pressure</td>
<td>[mbar]</td>
</tr>
<tr>
<td>$G$</td>
<td>Flux density of heat into the soil (positive if downwards)</td>
<td>[W m⁻²]</td>
</tr>
<tr>
<td>$k$</td>
<td>Von Kármán’s constant, set at 0.4</td>
<td></td>
</tr>
<tr>
<td>$R_n$</td>
<td>Net radiation</td>
<td>[W m⁻²]</td>
</tr>
<tr>
<td>$R_g$</td>
<td>Flux density of short-wave solar radiation</td>
<td>[W m⁻¹]</td>
</tr>
<tr>
<td>$r_a$</td>
<td>Aerodynamic resistance</td>
<td>[s m⁻¹]</td>
</tr>
<tr>
<td>$r_c$</td>
<td>Canopy resistance</td>
<td>[s m⁻¹]</td>
</tr>
<tr>
<td>$U_z$</td>
<td>Wind speed at height $z$ above the surface</td>
<td>[m s⁻¹]</td>
</tr>
<tr>
<td>$z_0$</td>
<td>Aerodynamic roughness length</td>
<td>[m]</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>Rate of change of saturation vapour pressure with temperature</td>
<td>[mbar K⁻¹]</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Latent heat of vaporization of water</td>
<td>[J kg⁻¹]</td>
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INTRODUCTION

The area covered by degraded and largely unproductive grasslands in the tropics is growing. In view of increasing demands for timber and perceived environmental improvement, calls for the reafforestation of such land are becoming more frequent. On the other hand, work in warm-temperate areas has suggested large drops in water yield after maturation of forest planted on former grasslands, particularly during the dry season (Van Lill et al., 1980). Despite the urgency of the issue, virtually no sound information is available to date with respect to the hydrological consequences of reafforesting degraded grassland to fast-growing evergreens in the humid tropics (Bruijnzeel, 1990). To partly fill this gap a study of the water and nutrient dynamics of an age series of Pinus caribaea plantation forests and, to a lesser extent, Pennisetum polystachyon grassland was initiated in late 1989 in Nabou, about 25 km south of Nadi in the western part of Viti Levu, Fiji. The study was a collaborative effort of the Free University of Amsterdam, the Netherlands, and Fiji Pine Limited.

During the wet season, ET rates for forest and grassland will differ somewhat as a result of differences in albedo (0.19 for grass vs. 0.10 for pine forest; Waterloo, 1993) and rainfall interception. In the study area, the contrast in forest and grassland ET can be expected to become more pronounced during the dry season since most of the grass normally dies off, with the dead leaves effectively shading the ground and suppressing evaporation from the soil. The larger rooting depth of the pines (1-2 m vs. less than 0.7 m for the grass), on the other hand, will enable the trees to continue to extract water from the subsoil even though the surface layer may have reached wilting point. Therefore, the present paper will pay particular attention to ET for pine forest and grassland during the dry season.

STUDY AREA

The three study sites were located within the Nabou Forest Estate in southwestern Viti Levu (18°S, 177°E) at elevations of 115 m (Tulasewa site, 6-year-old pines), 110-250 (Oleolega basin, 15-year-old pines) and 90 m a.m.s.l. (Nabou, grassland). Topography at Oleolega was steeply dissected but gently undulating at the two other sites. Soils were generally shallow (0.5-1.5 m) and derived from andesitic to dacitic lavas and tuffs. Average annual rainfall at Nabou (1980-1991) was 1578 ± 416 mm, with a

<table>
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<tr>
<th>Table 1</th>
<th>Average monthly rainfall amounts and standard deviations (mm) for Nabou weather station (1980-1991). Source: Fiji Meteorological Service, Nadi.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>251</td>
</tr>
<tr>
<td>St. dev.</td>
<td>138</td>
</tr>
</tbody>
</table>
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distinct dry season from May to October during which period average monthly rainfall ranges between 57 and 80 mm (Table 1).

Mean monthly temperatures (1960-1975) at nearby Nadi airport ranged from about 23°C in July (southern winter, dry season) to 26.5°C in January (Coulter, 1981). Average monthly relative humidities at Nabou station (1974-1985, 8:00 a.m.) varied from 67% (beginning of rainy season) to 79% (height of rainy season) with intermediate values during the dry season (Basher, 1986). Similarly, average daily sunshine durations at Nabou (1974-1988) ranged between 5.6 h day\(^{-1}\) in March and 7.1 h day\(^{-1}\) in November (Coulter, 1982; Reddy, 1989). Easterly to southeasterly trade winds blow throughout the year. Wind speeds are generally low (about 2 m s\(^{-1}\)) and slightly higher during the dry season. However, two or three major hurricanes pass through Fiji per decade, often causing severe damage to the forests, as occurred on 29 November 1990 when cyclone Sina struck the study basin (see below).

The pines at Tulasewa had been planted in 1984 and had reached an average height of 12.4 m by mid 1990. Stocking was 837 trees ha\(^{-1}\) and leaf area index 3.6 ± 1.5 m\(^2\) m\(^{-2}\) (Waterloo, 1993). The trees showed vigorous growth and undergrowth was dominated by Mission grass. The pines of the 60-ha study basin were planted in 1975 over 83% of the area, the remainder being occupied by grass, reeds and native forest in the riparian zone. Average height of the pine trees in 1990 was c. 18.5 m at a stocking of about 600 trees ha\(^{-1}\). The Nabou grassland site was dominated by 1.8 m tall Mission grass (*Pennisetum polystachyon*) with minor contributions of ferns and other grasses (*Mimosa pudica*, *Sporobolus indicus*). The area had not been burned in the last 5 years. This type of vegetation shows active growth during the wet season (December-April), a flowering period at the start of the dry season (May-June) and a gradual dying off during the dry season (July-October) (Waterloo, 1993).

**INSTRUMENTATION AND METHODS**

**Tulasewa site (6-year-old pines)**

A 21.85 m meteorological tower was equipped with instrumentation to measure temperature, humidity and wind speed at 4 levels, viz. at 21, 17, 13 and 6 m (no anemometer at the lowest level). Of the three types of instruments available for the measurement of temperature and humidity (see Vugts *et al.*, 1993), only the Rotronic sensors at 13 and 21 m have been used here for the derivation of Bowen ratios (Angus & Watts, 1984). A pyranometer, an albedometer and a net radiometer were installed at 13 m to determine radiation characteristics whilst rainfall was measured using a tipping bucket recorder, also at 13 m. All instruments were calibrated before and at the start of the experiment, with subsequent intercalibration of sensors on several occasions. The soil heat flux was measured with two heat flux plates placed 2 cm below the surface. Equipment was sampled every 30 s and average values plus their standard deviations were calculated for 30-min periods using a micrologger system. The tower experienced a fetch of about 1 km towards ESE (the prevailing wind direction) and of 1.5-2.5 km in other directions. Throughfall was determined by means of 20 randomly located standard gauges which were re-randomized after every sampling event. Rainfall interception was approximated by subtracting mean
throughfall values from corresponding totals of incident rainfall as measured with a standard gauge in a nearby clearing. Stemflow was not measured.

Oleolega drainage basin (15-year-old pines)

Rainfall and discharge measurements were made throughout 1990. Rainfall was measured with a tipping bucket recorder (0.4 mm resolution) placed at the basin outlet and by three standard gauges placed along the basin perimeter. Areal averages were obtained using the Thiessen method. Discharge was measured by volumetric, dilution and current meter techniques in conjunction with a water-level recorder placed 2.5 m upstream from a culvert which acted as a flume. Due to maintenance work on the culvert, water-level data was missing from 22 February until 8 March 1990. Streamflow amounts for this period were simulated by means of a model developed by Schellekens (1992).

Nabou grassland site

Daily rainfall was measured with a standard raingauge at Nabou station situated 100 m from the site. A pre-calibrated capacitance probe (Didcot Instruments) was used to measure soil moisture profiles between 28 March/24 April (access tubes 1/2) and 4 October 1991 at least once a week at 2 cm intervals down to a depth of 1.1 m. ET was calculated as total soil moisture loss above a divergent zero flux plane during periods without drainage (Wellings & Bell, 1980). Daily totals of grassland ET were also computed by summing two-hourly averages calculated with the Penman-Monteith equation (Monteith, 1965):

\[
\lambda E = \left[ \Delta (R_n - G) + \rho c_p (e_s - e) / r_a \right] / \left[ \Delta + \gamma (1 + r_s / r_a) \right]
\]

Meteorological observations commenced on 10 May when part of the grass was just starting to turn yellow and were terminated on 21 September when most of the grass had died. Wind speed and direction were measured at 5.9 m above the surface with an anemometer and a wind vane. Temperature and relative humidity were measured at 5.5 m using a thermo-hygrograph (regularly calibrated) housed in a Stevenson screen. Solar radiation was measured with a pyranometer above a mature pine forest about 4 km from the site whereas a pre-calibrated actinograph acted as a backup on the grassland site. In the absence of a continuous record of net radiation, a relationship was derived between net and shortwave radiation from synchronous measurements during 4 days in June and July at 15-min intervals between 0900 and 1800 h using a portable pre-calibrated net radiation indicator (Thornthwaite Associates). The resulting equation \( R_n = -77.7 \pm 27.2 + 0.76 \pm 0.03 * R_g, r^2 = 0.98 \) was similar to those found for mixed prairie grassland in Canada (Ripley & Redman, 1976) or Amazonian ranchland (Wright et al., 1992). Grassland albedo and a relationship between solar radiation \( (R_g) \) and soil heat flux \( (G) \) had been determined previously for another grassland site in February/March of 1991 using the same equipment as described for the Tulasewa site \( (G = -2.5 \pm 3.2 + 0.015 \pm 0.002 * R_g, r = 0.81) \). The aerodynamic resistance was calculated as:
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\[ r_a = \left( \ln \left( \frac{z - d}{z_0} \right) \right)^2 / (k^2 U_z) \]

where \( z_0 \) and \( d \) were assumed to be 0.12 and 0.75 times the grass height respectively (Thom, 1975). An automatic porometer (Delta T Instruments MK3) was used for the determination of stomatal resistances at 0.3, 1.0 and 1.5 m above the ground on 4 days between 18 June and 23 July. Grass biomass, specific leaf area (SLA; based on 50 fresh leaves) and leaf area index (LAI) were determined by destructive harvesting of three plots of 1 m\(^2\) each on 10 May, 30 July and 1 September.

RESULTS AND DISCUSSION

Tulasewa

Average day-time net radiation \( (R_n) \) above the 6-year-old forest during the 145 days of observation was 309 ± 96 W m\(^{-2}\), with typical maximum values of c. 650 W m\(^{-2}\) around noon on clear, sunny days and about half this value on cloudy days. Night-time minimum values were usually close to -30 W m\(^{-2}\). The daytime storage of heat (both sensible and latent) in the soil and/or in the air column between the top of the canopy and the soil surface constituted on average about 3% of \( R_n \) (range 13%) and was, therefore, taken into account (Frumau, 1992). Bowen ratios were derived from temperature and humidity profiles between 13 and 21 m and were combined with corresponding values of available energy to determine daytime totals of ET (Fig. 1). An average value of 3.6 ± 1.0 mm day\(^{-1}\) was obtained. Dry-canopy evaporation rates at night were generally very low or nil (condensation) (Frumau, 1992). Since rainfall interception by the canopy over the period 9 May-28 September 1990 was estimated at 82 mm or 16% of total rainfall, water uptake by the vigorously growing pines \( (E_r) \) amounted to 507 mm (86% of total ET; 91% of corresponding Penman open water evaporation, \( E_0 \); Penman, 1956). The influence of soil water status on the magnitude of ET is clearly illustrated by Fig. 1.

![Fig. 1 Daytime evapotranspiration in a 6-year old stand of Pinus caribaea during 145 days in the dry season of 1990 as derived with the Bowen ratio energy balance method.](image)
Oleolega

Total rainfall for 1990 amounted to 1847 mm, whereas streamflow was 293 mm (16% of rainfall). Some 115 mm (39%) was discharged as quickflow and 178 mm (61%) as baseflow. The overall change in groundwater storage was negligible (<0.5 mm) while that in soil moisture was neglected as well (rainfall in December 1989 and 1990 being 67 and 84 mm, respectively). Total ET, calculated as the difference between rainfall and streamflow, was 1554 mm or 4.3 mm day\(^{-1}\), which is slightly higher than that derived earlier for the 6-year-old forest. On the basis of throughfall data for a nearby 11-year-old stand (Waterloo, 1993), which may be considered representative for the situation at Oleolega as well, the partition of ET at Oleolega was estimated as follows. The mature pines intercepted 23% of the precipitation (c. 425 mm, or 27% of ET), leaving 1130 mm year\(^{-1}\) (by difference) for \(E_t\) and evaporation of water intercepted by the understorey and litter complex. Since \(E_0\) for Nabou station in 1990 was 1812 mm, an average value of 0.86 is suggested for the ratio \(ET/E_0\) for mature \textit{Pinus caribaea} forest. It should be borne in mind, however, that the latter figure includes the (as yet unknown) water use by the broadleaved riparian forest (covering 17% of basin area).

Nabou

Grassland ET was derived from changes in soil moisture contents of the root zone (65 cm above a divergent zero flux plane. Any water losses below 65 cm were assumed to be due to drainage (Wellings & Bell, 1980). Changes in soil moisture with time down to 110 cm as measured in two access tubes are shown in Fig. 2. As expected, the range in concentrations was smaller for the subsoil (0.04 cm\(^3\) cm\(^{-3}\), drainage only) than that within the root zone (0.06 cm\(^3\) cm\(^{-3}\); removal of moisture by both drainage and evapotranspiration). An average value for ET of 0.9 ± 0.2 mm day\(^{-1}\) over 48 days when a divergent zero flux plane had developed around both access tubes was found.

![Fig. 2 Changes in soil moisture content (theta) within and below the rooting zone of a natural grassland during 131 days in the dry season of 1991 as measured in two access tubes.](image-url)
To calculate daytime ET for the whole period, use was made of the Penman-Monteith equation, taking ET obtained from the depletion of soil moisture during specific periods ($ET_{sm}$) as a reference to derive representative values for the variation with time of $r_c$, the canopy (or surface) resistance of the grassland. A good fit ($ET_{pm} = 0.9 \pm 0.3 \text{ mm day}^{-1}$ vs. $ET_{sm} = 0.9 \pm 0.2 \text{ mm day}^{-1}$) was obtained when using the function:

$$r_c = 441 - 282 * \text{LAI} \quad r^2 = 0.6, \quad n = 7$$

where LAI is the leaf area index ($\text{m}^2 \text{ m}^{-2}$). With LAI decreasing linearly from $1.3 \text{ m}^2 \text{ m}^{-2}$ in May to $0.2 \text{ m}^2 \text{ m}^{-2}$ in September, corresponding values of day-time $r_c$ ranged from 74 to 385 s m$^{-1}$. To smoothen the transition from day-time to night-time conditions (stomatal closure), nocturnal values for $r_c$ were arbitrarily set at $1000 * e / e_c$ and ranged from 500 to 1000 s m$^{-1}$. Finally, $r_c$ was assumed to be zero during and immediately after rainfall events (Monteith 1965). Calculated day-time $r_c$ values for May and June, when the grass started to die off, were within the general range for grass ($60-200 \text{ s m}^{-1}$) given by Rowntree (1990) and similar to dry season values reported by Wright et al. (1992) for Amazonian ranchland. The high values derived for August and September are not unrealistic in view of the fact that most of the vegetation had died by then. Mean day-time stomatal resistances generally were quite high at 187-330 s m$^{-1}$ above a height of 70 cm vs. 1240-1675 s m$^{-1}$ between ground level and 70 cm (Waterloo, 1993).

Daily rainfall totals as well as changes in $E_0$, $ET_{pm}$ (24-h totals) and $ET_{sm}$ with time are given in Fig. 3. An average value of $1.0 \pm 0.3 \text{ mm day}^{-1}$ was obtained for $ET_{pm}$ for the period 11 May until 19 September 1991. Since $E_0$ over the same period amounted to $3.7 \pm 1.0 \text{ mm day}^{-1}$, the ratio $ET/E_0$ attained the low value of 0.26, reflecting the gradual dying of the grass as the dry season progressed. Total ET from the grassland over the above period was 128 mm (40% of rainfall).

The present data confirm the circumstantial evidence reported by Kammer & Raj (1979) of strong reductions in dry season flows in western Viti Levu following
afforestation of degraded grassland with pines. Total ET during the dry season from both young and mature pine plantations were much higher (by c. 3 mm day\(^{-1}\)) than that observed for natural grassland. Although our observations pertained to two different dry seasons with marked contrasts in rainfall (533 mm during 145 days in 1990 vs. 319 mm during 131 days in 1991), there can be little doubt that reafforestation of Fijian grasslands will produce a significant decrease in water yield during a period of year when water is already scarce.

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**REFERENCES**


