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THE IMPACT OF CLEARING FOR AGRICULTURE ON THE SURFACE ENERGY BUDGET

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ABSTRACT

A simple model is developed to analyse the surface energy balance from satellite observations for south-western Australia. This illustrates that the replacement of native vegetation with agriculture based on a winter growing annual species has led to a marked reduction in the sensible heat flux to the atmosphere during winter and spring. It is suggested that this reduction may be related to the observed decrease in winter rainfall observed throughout the agricultural region.

KEY WORDS: surface energy balance; native vegetation; agricultural crops; NOAA AVHRR; vegetation index; south-western Australia

INTRODUCTION

Native vegetation of south-western Australia is characteristically a woodland called mallee, with *Eucalyptus eremophila* the most consistent species. Patches of eucalypt woodland occur on lower ground, and scrub heath and *Casuarina* thickets are found on the residual plateau soils. The topography of the region is gently undulating country of low relief with duplex mallee soils, that is, sand overlying clay.

Since the beginning of this century, approximately 13 million hectares of this native perennial vegetation to the west of the vermin-proof fence (Figure 1) have been cleared for agriculture, which is based on winter growing annual species. Wheat is the major agricultural crop of the region and it grows during the austral winter and spring between May and November. The vegetation to the east of the fence has not been disturbed and is in its native state.

Analysis of long-term rainfall data indicates that following the extensive clearing of the native vegetation between 1950 and 1980, which transpires year round, and its replacement with annual vegetation, which transpires only during the winter and spring, rainfall during the winter growing season for this Mediterranean climate has declined by about 20 per cent (Pittock, 1983; Williams, 1991). Pittock (1983) and Allan and Haylock (1993) have ascribed this decrease to large-scale circulation changes but a process such as desertification initiated by deforestation is also in accord with observational and numerical studies (e.g. Anthes, 1984; Segal *et al.*, 1988). This large-scale clearing of native perennial vegetation and its replacement by winter growing annual species is known to cause a significant reduction in long-term evapotranspiration, as evidenced by rising water tables and increased salinity (Greenwood *et al.*, 1985). Rabin *et al.* (1990) and Lyons *et al.* (1993) also suggest that clouds form earliest over regions characterized by high sensible heat flux and are suppressed over regions characterized by high latent heat flux during relatively dry atmospheric conditions.

This paper uses a simple model combined with long-term satellite data of the region to characterize the change in the surface energy balance brought about by the extensive clearing of the native vegetation. Changes in the surface energy balance and the partitioning between sensible and latent heat affect boundary layer development and the

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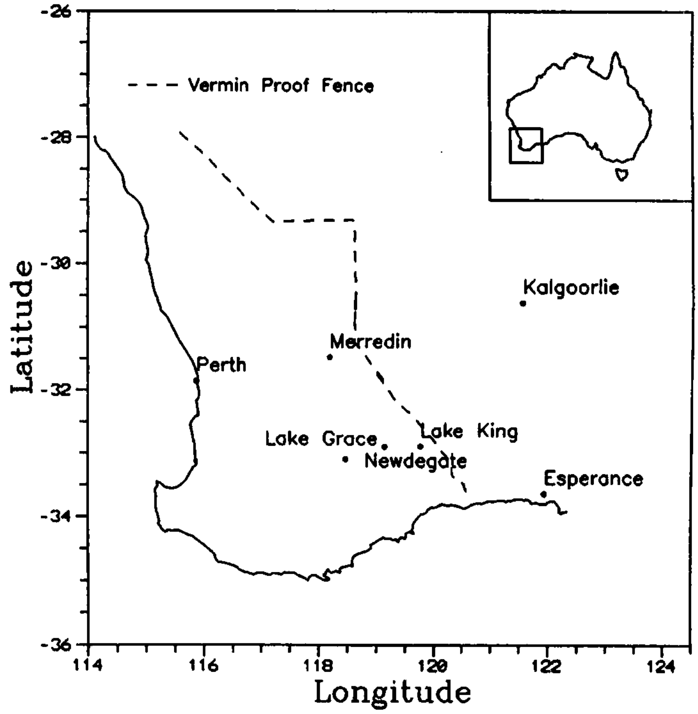

Figure 1. Study area—The Lake King district of Western Australia

vertical transport of heat and water vapour in the atmosphere. Given the relative remoteness of the location and the lack of long-term detailed meteorological data, this paper seeks to identify the impact of clearing through a comparison of the surface energy balance on either side of the vermin-proof fence. By necessity such an analysis is limited to the time of satellite overpass but provides an indication of the changes induced by clearing.

MODEL

Twelve NOAA AVHRR cloud-free afternoon overpasses (Table I) covering the area of native vegetation and agriculture for 100 km around the vermin-proof fence were selected from the Leeuwin Remote Sensing Centre archive to cover a 12-month period from April 1990 to March 1991 (Smith *et al.*, 1992). Five matched sites, representative of land surface conditions before and after clearing were sampled by displaying each overpass, identifying two 1 km^2 pixels of native vegetation in each area (Table II) and recording their digital counts. A matched area of agriculture at the same latitude was selected to the west of each native vegetation area, giving 20 values each month made up of 5 sites × 2 vegetation types × 2 replicates. The mean digital counts for NOAA AVHRR channels 1, 2, 4, and 5 were converted to reflectance or surface temperature.

Following Lyons and Edwards (1982), the direct irradiance was estimated as

$$I = I_0 \cos z \psi_{wa} \psi_{da} \psi_{ws} \psi_{rs} \psi_{ds} \tag{1}$$

where I_0 is the solar constant, z the solar zenith distance, and the remainder are transmissions due to water vapour absorption (ψ_{wa}), aerosol absorption (ψ_{da}), water vapour scattering (ψ_{ws}), Rayleigh scattering (ψ_{rs}), and aerosol scattering (ψ_{ds}). In estimating the diffuse irradiance it was assumed that absorption of the direct beam occurs before scattering and that half of the scattered irradiance reaches the earth as the diffuse component without further scattering. Thus

$$D = I_0 \cos z \psi_{wa} \psi_{da} (1 - \psi_{ws} \psi_{rs} \psi_{ds})/2 \tag{2}$$

and the clear-sky global irradiance is represented as

$$S_i = I_0 \cos z \psi_{wa} \psi_{da} (1 + \psi_{ws} \psi_{rs} \psi_{ds})/2 \tag{3}$$

Table I. Summary of NOAA 11 satellite overpasses used

Date	Time (WST)	Date	Time (WST)
8 April 1990	1421	26 October 1990	1436
24 May 1990	1424	5 November 1990	1426
21 June 1990	1421	10 December 1990	1441
9 July 1990	1426	6 January 1991	1442
31 August 1990	1444	10 February 1991	1442
28 September 1990	1444	9 March 1991	1453

Table II. Selected areas of native vegetation. Corresponding agricultural areas were selected 0·2–0·4 degrees to the west of each of these sites

Locality	Latitude (S)	Longitude (E)
Lake Magenta Reserve	33·54	119·00
Commander Rocks	33·20	119·45
Dragon Rocks	32·70	118·98
Rabbit Fence	33·20	120·20
Rabbit Fence	32·70	119·70

where typical values of these transmissions based on climatological data for this region of Western Australia have been used (Lyons and Edwards, 1982). Thus the net solar radiation is

$$S_n = (1 - \alpha)S_i \tag{4}$$

where α is the surface albedo.

The planetary broad-band albedo was calculated following Brest and Goward (1987), by using the reflectances of NOAA AVHRR channels 1 and 2, such that for $R_2/R_1 > 2$

$$\beta_p = 0{\cdot}526R_1 + 0{\cdot}418R_2 \tag{5}$$

and for $R_2/R_1 \leqslant 2$

$$\beta_p = 0{\cdot}526R_1 + 0{\cdot}474R_2 \tag{6}$$

where R_1 and R_2 are the reflectances of channels 1 and 2, respectively, after applying the pre-flight calibration and zenith correction. Chen and Ohring (1984) showed that the planetary albedo is related to the surface albedo by

$$\alpha = \frac{\beta_p - a}{b} \tag{7}$$

where a is the albedo of the atmosphere and b is a coefficient to account for the surface reflection of solar radiation back to space. The values of a and b, which are a function of solar zenith angle, given by Chen and Ohring (1984) were adopted.

Incoming longwave radiation was estimated as (Paltridge and Platt, 1976)

$$L_i = 5{\cdot}31 \times 10^{-13} T_r^6 \tag{8}$$

where T_r is the absolute air temperature at some reference height. In this study, we utilized the 1500 WST (local standard time) mean air temperatures observed at the nearby meteorological station of Lake Grace (Anonymous, 1975) because these corresponded most closely to the overflight of the satellite.

Outgoing longwave radiation is parameterized in accordance with Holtslag *et al.* (1981)

$$L_0 = \sigma T_g^4 + c_g S_n \tag{9}$$

where σ is the Stefan–Boltzman constant, c_g is a constant taken as 0·07 and T_g is the ground surface temperature. The second term in this equation approximately accounts for the difference between the surface and the air temperature at screen height (de Bruin and Holtslag, 1982).

Surface temperature was estimated from (Price, 1984)

$$T_g = T_4 + \frac{3\cdot3 \times (T_4 - T_5)(3\cdot5 + \varepsilon)}{4\cdot5} \tag{10}$$

where T_4 and T_5 are the radiant temperatures measured by channels 4 and 5 of the NOAA AVHRR sensors, and ε is the surface emissivity, which we arbitrarily assumed to be 0·95.

Net radiation can be estimated thus from satellite reflectances and standard climatological values as

$$R_n = S_n + L_i - L_0 \tag{11}$$

Ground heat flux declines with increasing vegetation cover and Kustas and Daughtry (1990) suggested it could be represented as

$$G = (0\cdot325 - 0\cdot208\text{NDVI})R_n \tag{12}$$

where NDVI, the normalized difference vegetation index, is defined as

$$\text{NDVI} = \frac{(R_2 - R_1)}{(R_2 + R_1)} \tag{13}$$

Huang *et al.* (1993) found that this equation provided a reasonable estimate of the heat flux for both native and agricultural vegetation when compared with independent measurements and so we have adopted it.

Thus by closing the surface energy balance, we can estimate the sum of the sensible, H, and latent heat, LE, fluxes as

$$H + LE = R_n - G \tag{14}$$

That is

$$H + LE = (0\cdot675 + 0\cdot208\text{NDVI})R_n \tag{15}$$

RESULTS AND DISCUSSION

Figure 2 illustrates the annual variation of NDVI for both agricultural and native vegetation. In particular, the native vegetation shows little variation throughout the year, as also noted by Huang *et al.* (1993). The slight mid-winter peak in the native vegetation NDVI is the result of local cloud on 21 June (day 172) requiring a slightly different area of native vegetation to be sampled thus resulting in the anomalous peak NDVI observed. The agricultural region NDVI goes from bare soil values in the early part of the year through to a peak as the crop reaches anthesis and then a decrease as the crop dries out before harvest in November. These changes are also reflected in the surface albedo (Figure 3) with a marked decrease in albedo during the growing season. Such trends are consistent with the spot values observed by Huang *et al.* (1993) but are greater than the observed changes in albedo induced by clearing in the Amazon (Bastable *et al.*, 1993).

The higher albedo over the agricultural area implies a lower net radiation at the time of satellite overpass throughout the year (Figure 4). Because the ground heat flux has been assumed proportional to R_n, the available energy, $R_n - G$, follows a similar trend. This suggests that the impact of clearing has been to reduce the flux of energy from the surface to the atmosphere by changing the albedo of the surface. Such clearing has also decreased the aerodynamic roughness of the land surface, but this impact is not incorporated in this data set.

Available energy is partitioned between sensible and latent heat fluxes at the surface. Clearly, with similar partitioning, the sensible heat flux over the native vegetation would be expected to be higher and thus clearing has reduced the sensible heat flux. However, the native vegetation tends to conserve moisture throughout the year, and consistently minimizes LE. Spot measurements over native vegetation at different times throughout the year illustrate that LE is generally less than 40 per cent of the available energy and can be as low as 12 per cent (Huang *et al.*, 1993).

On the other hand, modern cultivars are opportunistic in relation to available water having higher transpiration when soil moisture is favourable (Siddique *et al.*, 1990). Crops will generally extract most of the water available to them from the root zone, drying the profile to wilting point in the upper half of the profile and to near wilting point in

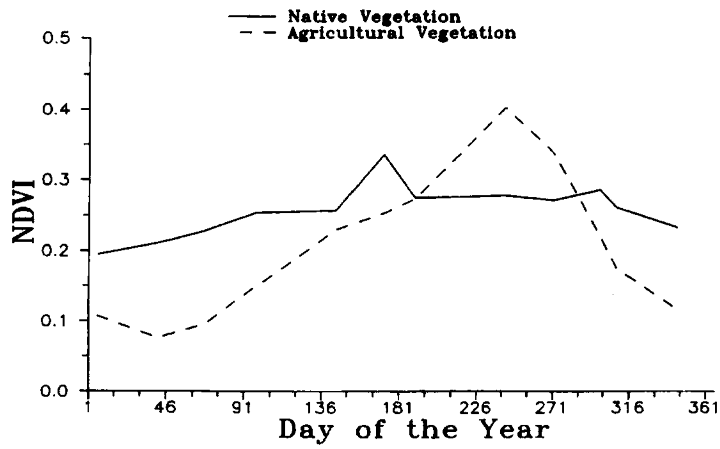

Figure 2. Annual variation of the normalized difference vegetation index (Jan 1 = day 1)

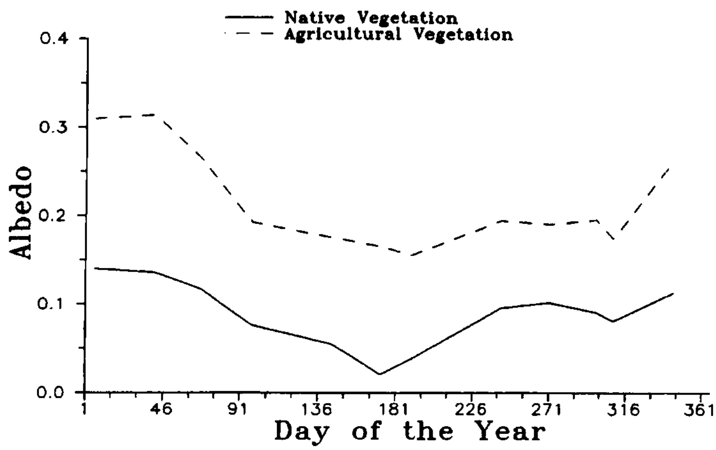

Figure 3. Annual variation of the surface albedo

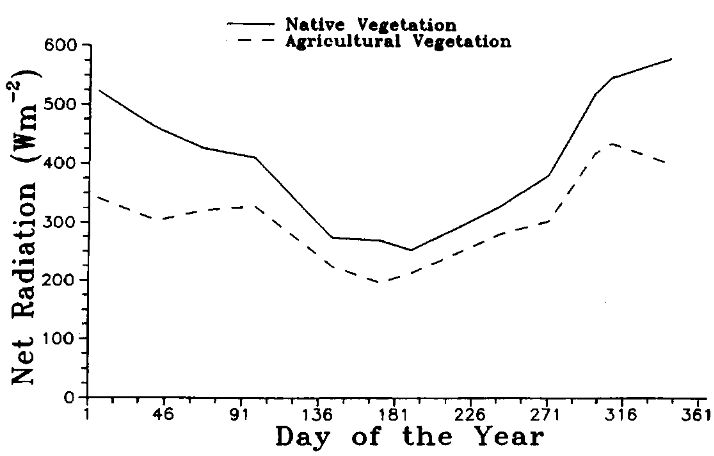

Figure 4. Annual variation of the net radiation at the time of the afternoon satellite overpass (approximately 1500 WST)

Table III. Observed albedo, NDVI, *H* and *LE* for agricultural and native vegetation (after Huang *et al.*, 1993)

Surface	Date	Albedo	NDVI	*H* (W m^{-2})	LE (W m^{-2})
Native vegetation	March 6	0·12	0·15	338	49
	August 31	0·08	0·15	200	149
	December 4	0·12	0·15	470	75
Agricultural	March 6	0·19	0·07	271	35
	August 31	0·17	0·36	71	178

Table IV. Assumed proportion (per cent) of available energy used in *LE* (following Kim *et al.*, 1989)

Date	*LE* (per cent)		Approximate development stage of winter wheat
	Native vegetation	Agricultural	
Jan	20	10	Bare Ground
Feb	20	10	Bare Ground
Mar	20	10	Bare Ground
Apr	25	20	Seeding
May	30	40	Emergence
Jun	35	60	
Jul	40	80	Anthesis
Aug	40	80	Milk development
Sep	35	70	Dough development
Oct	30	60	Ripening
Nov	25	40	Harvest
Dec	20	10	Bare Ground

the lower half (Tennant *et al.*, 1991). In general, soil evaporation is about 40 per cent of the total water use for a crop (Tennant *et al.*, 1991). Kim *et al.* (1989) showed that energy partitioning for a wheat crop was controlled by atmospheric evaporative demand and the availability of soil water. During anthesis 80–90 per cent of R_n was consumed by *LE*, 70–90 per cent during milk development, 50–60 per cent from dough development through ripening. The decrease in evapotranspiration from anthesis to ripening resulted from maturity of crop and the rapid decline in the area of the transpiring surface as well as the possible depletion of available soil water later in the growing season. Huang *et al.* (1993) observed consistently similar fluxes of *LE* from spot measurements over winter wheat in the Lake King district (see Table III).

In the absence of detailed data for the Lake King district, we have assumed that the annual variation of the proportion of available energy partitioned into *LE* is as shown in Table IV. This accounts for the moisture conservation of the native vegetation while at the same time recognizing the increased soil moisture available during the winter months. It also implicitly assumes that the agricultural area is totally covered by wheat. In any one year, the amount of agricultural land devoted to cropping is a complex result of farming management practices as well as forward estimates of cereal prices. Land that is not used for winter wheat is invariably left as pasture and hence will have a lower evapotranspiration (Greenwood *et al.*, 1985). An overall assessment of the climatic impact of clearing would involve an assessment of the energy partitioning over the pasture as well as an assessment of the average area devoted to both agriculture and pasture over the longer term. Such assessments are beyond the scope of this analysis. Nevertheless, the partitioning shown in Table IV indicates the significant change in the surface energy balance caused by replacing perennial native vegetation with a winter growing annual species.

Figure 5 illustrates the resultant variation of the sensible and latent heat fluxes throughout the year. The darker native vegetation, conserving moisture throughout the year, has a consistently higher sensible heat flux but the major difference occurs during the spring when the cropped areas are transpiring rapidly. Although clearing has reduced the sensible heat flux, the opportunistic use of water by winter wheat means that the majority of the available energy is expended in evapotranspiration. Lyons *et al.* (1993) observed similar differences in spot measurements and noted

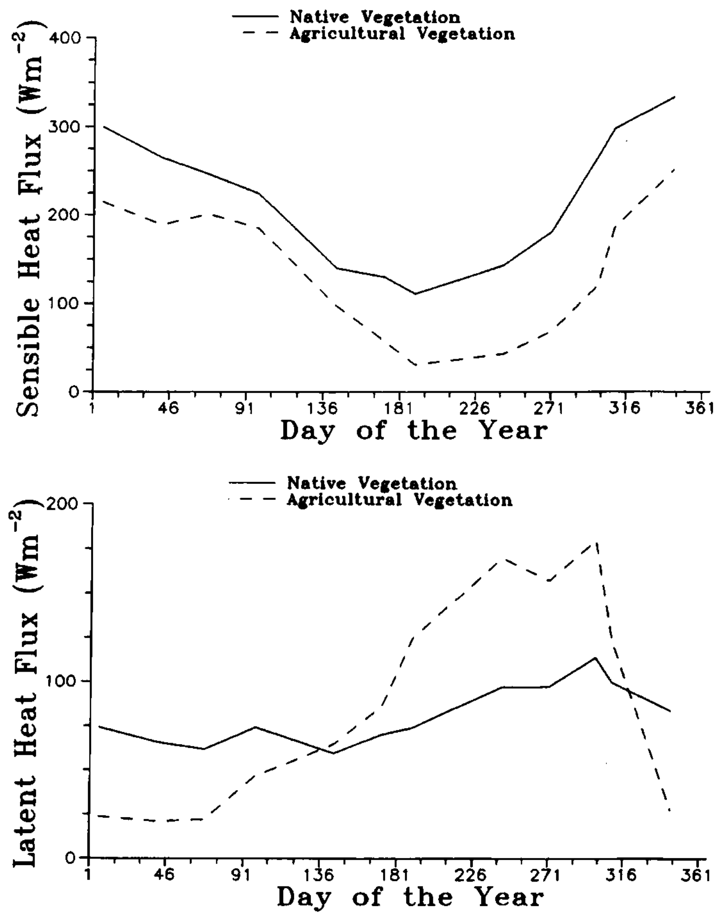

Figure 5. Annual variation of the sensible and latent heat flux at the time of the afternoon satellite overpass

that clouds tended to form over the native vegetation well in advance of cloud formation over the agricultural region. Although there is a greater latent heat flux over the agricultural areas, greater convective mixing over the native vegetation is the driving mechanism for cloud formation. Because the major difference in surface fluxes also corresponds to the period of observed rainfall decrease, it poses the question as to whether a decrease in convective activity over the agricultural region has led to the observed decrease in rainfall.

The climate of this region is dominated by the movement of frontal systems from the Southern Ocean and the role of convective enhancement of precipitation is not well understood. However, in observing the decrease in rainfall throughout the agricultural area, Williams (1991) also noted that rainfall had not decreased over the native vegetation beyond the rabbit-proof fence. This analysis combined with the observations presented here as well as those of Lyons *et al.* (1993) gives further evidence that changes in surface clearing could have contributed to the observed decrease in rainfall. Further analysis of the long-term satellite observations around the rabbit fence combined with mesoscale modelling are currently underway to address these issues.

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