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MEASUREMENTS OF ALBEDO VARIATION OVER NATURAL VEGETATION IN THE SAHEL

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ABSTRACT

This paper reports ground-based measurements of albedo at two different sites in south-western Niger: agricultural fallow at the ICRISAT Sahelian Center (ISC), Sadoré, and a type of open natural forest (tiger-bush), 6 km south-west of ISC. The vegetative cover at each site consisted of two clearly defined components, for which separate measurements were made. The four different component surfaces spanned the entire range of plant cover density normally occurring in the southern Sahel, ranging from zero (bare soil) to a dense, closed canopy of woody shrubs. Continuous automated observations of albedo were made over a period of 15 months, from July 1989 to September 1990, including both wet and dry seasons. The data are analysed on hourly, monthly, and annual time-scales in order to demonstrate how albedo varies in response to the density of plant cover, soil-surface moisture content, solar zenith angle, and the proportion of diffuse light in the incoming solar radiation. Large annual variation in monthly mean albedo was observed at both sites (increases from the wet to dry season of 0·065 and 0·057 for the fallow and tiger-bush, respectively). At the fallow site the annual variation in albedo resulted mainly from the wet to dry season cycle of leaf growth and loss. At the tiger-bush site the primary cause of annual variation in albedo was the frequent wetting of the extensive bare soil component that occurred during the rainy season. The significance of these results for global climate modelling is assessed briefly.

KEY WORDS Shortwave reflection coefficient Albedo Seasonal variation Sahel drought Climate modelling Savanna Tiger-bush Fallow

INTRODUCTION

Over the last 30 years the West African Sahel has suffered a persistent decrease in rainfall (Nicholson, 1989; Hulme, 1992), which has imposed serious stress on agricultural production in the sub-Saharan countries (Sivakumar, 1992). The possible causes of this apparent climate change have been widely debated. Charney (1975) suggested that the decline in rainfall could be caused by an increase in the albedo (shortwave reflection coefficient) of the land surface, resulting from the removal of vegetation cover through increased grazing, fuelwood collection, and cultivation of marginal land. Subsequent studies using general circulation models (GCMs) supported the existence of the bio-geophysical feedback proposed by Charney. Rowntree (1991) reviewed four of these numerical experiments, where GCMs were used to predict the change in rainfall over the Sahel that would occur if vegetation cover was removed. Increases in albedo of 0·12 to 0·22 were used to represent removal of vegetation, resulting in predicted rainfall decreases of 0·8 to 3·4 mm day^{-1}. Clearly the exact results of such sensitivity studies are dependent on the albedo values chosen, yet these are based on a rather limited number of published observations (Dickinson *et al.*, 1990). Despite the Sahel being a

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MATERIALS AND METHODS

Field sites

Measurements were made at two contrasting sites about 45 km south of Niamey, Ni
was a 0·8 × 2·0 km area of fallow land (13°14·62′ N, 2°14·70′ E), within the experime
International Crops Research Institute for the Semi-arid Tropics (ICRISAT) Sahelian
Sadoré. Before the establishment of ISC the land was managed by local farmers for
production. Since enclosure in 1983 the area has been left fallow and the natural vegetation
to regenerate. The resulting vegetation consisted of a ground layer of annual herbs and gras
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The second field site (13°11·91′ N, 2°14·37′ E) was located about 6 km south-west of
village of Damari, within an area of open natural forest occupying a flat, irregularly-shap
3 km across. This type of forest is known locally as 'tiger-bush', on account of its str
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4–8 m tall. Within the vegetation stripes the dominant woody species typically form a
canopy supported by a tangled mass of stems, casting too much shade to allow the grow
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Solarimeters (Kipp and Zonen, Delft, The Netherlands) were deployed at the fallow a
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focus for meteorological research through the last two decades, there is a surprising lack of albedo measurements. The majority of the few studies available rely on satellite data (Rockwood and Cox, 1978; Norton *et al.*, 1979; Courel *et al.*, 1984). Ground-based measurements of albedo over a range of different vegetation types throughout Nigeria have been provided by Oguntoyinbo (1970, 1974).

This paper reports an extensive series of ground-based measurements of albedo obtained during the Sahelian Energy Balance Experiment (SEBEX, see Wallace *et al.*, 1991). The albedo of two different vegetation types in south-western Niger was measured continuously over a 15-month period, allowing the effect of seasonal changes in the vegetation to be investigated. The vegetative cover at each site consisted of two clearly defined components, for which separate measurements were made. The four different component surfaces spanned the entire range of plant cover density normally occurring in the southern Sahel, ranging from zero (bare soil) to a dense, closed canopy of woody shrubs.

MATERIALS AND METHODS

Field sites

Measurements were made at two contrasting sites about 45 km south of Niamey, Niger. The first site was a 0·8 × 2·0 km area of fallow land (13°14·62′ N, 2°14·70′ E), within the experimental farm of the International Crops Research Institute for the Semi-arid Tropics (ICRISAT) Sahelian Center (ISC) at Sadoré. Before the establishment of ISC the land was managed by local farmers for subsistence millet production. Since enclosure in 1983 the area has been left fallow and the natural vegetation has been allowed to regenerate. The resulting vegetation consisted of a ground layer of annual herbs and grasses, with scattered shrubs (almost entirely *Guiera senegalensis*) 2–3 m tall and occasional trees 5–10 m tall (approximately 1·5 per ha). The bushes were even-aged, being 7–8 years old (determined from annual rings). This type of vegetation is similar to the fallow that develops as part of the normal agricultural practice, when land is left uncultivated for several years in order to regenerate its fertility. However, the site was subject to only occasional light grazing, by a small number of cattle, horses, and donkeys used for animal traction on the experimental farm. As a result, it showed better development of the herbaceous layer than a typical fallow outside of ISC. The vegetation at the site has been further described by Wallace *et al.* (1990) and photographs are given by Lloyd *et al.* (1992). The soil at the fallow site was a sand, overlying solid laterite at a depth of about 1 m. A more detailed description is given by West *et al.* (1984).

The second field site (13°11·91′ N, 2°14·37′ E) was located about 6 km south-west of ISC, close to the village of Damari, within an area of open natural forest occupying a flat, irregularly-shaped plateau, about 3 km across. This type of forest is known locally as 'tiger-bush', on account of its striped pattern. The vegetation is confined to dense bands about 10–30 m wide by 100–300 m long separated by extensive areas of completely bare crusted soil. The vegetation is dominated by two species of shrubs (*Combretum micranthum* and *Guiera senegalensis*) 2–4 m tall and a single tree species (*Combretum nigricans*), typically 4–8 m tall. Within the vegetation stripes the dominant woody species typically form a completely closed canopy supported by a tangled mass of stems, casting too much shade to allow the growth of a herbaceous understorey. At the periphery of the stripes, the bushes do not always form a closed canopy, and a sparse layer of annual herbs and grasses extend between them. An aerial photograph of the site is given by Culf *et al.* (1993) and a detailed map by Dolman *et al.* (1992). A general description of West African tiger-bush has been provided by White (1970). The soil on the site is thin and gravelly, with a matrix of fine to coarse sand. The soil profile is 0·4 to 0·8 m deep, overlying solid laterite.

Instrumentation

Solarimeters (Kipp and Zonen, Delft, The Netherlands) were deployed at the fallow and tiger-bush sites to measure incoming and reflected shortwave radiation. Prior to the field measurements all the sensors were intercalibrated with an internal standard (traceable to the UK Meteorological Office standard) at the Institute of Hydrology, and found to agree within ±2 per cent.

Table I. Mounting details for reflected shortwave radiation sensors

Site	Component surface	Vegetation height (m)	Sensor height (m)	Boom length (m)
Fallow	Herbs	0·6	6·5	4·7
	Bushes	2·5	3·4	2·3
Tiger-bush	Soil	0·0	1·4	1·6
'	Bushes	4·5	8·2	4·2

At each site a single upward-facing instrument mounted on top of a tower provided measurements of incoming radiation. The heights of these sensors were 9·2 m and 11·0 m for fallow and tiger-bush, respectively. Incoming diffuse shortwave radiation was measured only at the fallow site, using a solarimeter fitted with a shade-ring. This instrument was mounted at 0·6 m height in an area that was cleared of vegetation to ensure an unobscured view of the whole sky. The fluxes of reflected radiation from the two principal component surfaces at each site were measured separately, using downward-facing solarimeters. A single sensor was mounted above each of the surfaces on a horizontal boom, supported by a mast or tower. The booms were orientated to prevent shadowing of the surfaces under observation by the vertical support structures. Mounting heights are given in Table I. Instrument outputs were measured every 10 s with CR10 solid-state data loggers (Campbell Scientific Ltd, Shepshed, UK) and stored as hourly means.

Rainfall was measured at each site using a tipping bucket rain-gauge (Didcot Instrument Co. Ltd, Abingdon, UK), hourly rainfall totals being recorded with a CR10 logger. Measurements of both the shortwave radiation fluxes and rainfall were made continuously from July 1989 to September 1990, with the exception of a few periods when the instruments were not operating as a result of storm damage.

Fractional coverage of component surfaces

The areal fraction of the fallow covered by *Guiera* was determined by a survey done in September 1989. A series of five 120-m east–west transects, spaced 30 m apart, was laid out in an area close to the instruments. The total length of all portions of the transects that passed within the vertical projections of bush canopies on to the ground surface was measured. This was expressed as a fraction of the total length of the transects, and assumed to represent the fraction of the site covered by *Guiera* bushes. The remaining fraction was assumed to be completely occupied by annual herbs, although there were a few patches of bare soil.

The fractional coverage of the vegetated and bare soil areas of the tiger-bush site were determined from aerial photographs. During September 1990 a series of nadir-looking colour transparencies were taken from a light aircraft to form a mosaic covering the entire area of tiger-bush. These were digitized with a video camera, and a computerized image analysis system was used to measure the fractional coverage of the two components.

Vegetation measurements

Green-leaf areas were determined only at the fallow site. The leaf areas of the two different component surfaces, *Guiera* bushes and the herbaceous ground layer, were measured separately, at 2–3-week intervals during the 1990 rainy season.

At each sampling time, the green-leaf areas of 20 randomly selected *Guiera* stems were determined by harvesting. All the leaves were removed from each stem, and the area of a weighed subsample was measured with an LI-3100 leaf area meter (Li-Cor Inc., Lincoln, Nebraska, USA), allowing the calculation of total leaf area for each stem. These data were used to determine a linear regression between leaf area and stem cross-sectional area at each sampling time. The regressions were used in conjunction with the frequency distribution of *Guiera* stem diameter in a 0·25-ha plot (surveyed once at the start of the wet season) to estimate total *Guiera* green-leaf area. This was divided by the plot area to estimate mean green-leaf-area index of *Guiera* over the entire site.

The green-leaf area of the herbaceous component was also measured by harvesting. At each sampling time all plants in ten 0·25-m^2 quadrats, spaced at 5-m intervals along a randomly chosen transect, were clipped to ground level. All green leaf blades were removed, and their area determined with an LI-3100 leaf area meter.

No measurements of leaf-area index were made at the tiger-bush, because the density and heterogeneity of the vegetation would have necessitated an extensive sampling programme, beyond the available resources of time and labour. Throughout 1990, however, a qualitative record of the vegetation was maintained by taking colour photographs from a fixed point at intervals of several weeks.

Data analysis

The hourly albedo for each surface component was calculated as the radiation reflected from that surface, divided by the incoming radiation recorded at the appropriate site. Albedos were only calculated for hours when the incoming radiation was greater than 50 W m^{-2}. This was to prevent the calculation of spurious albedo values close to dawn and dusk, when the quantity of reflected radiation measured is near the limits of accuracy for the solarimeters. The hourly measurements of diffuse radiation were multiplied by 1·1 in order to account for that part of the sky obscured by the shade ring. Solar zenith angles for each hour were calculated using the standard equations given by Jones (1992).

Daily mean albedos were calculated by dividing the daily integral of radiation reflected from each component surface by the daily integral of the incoming radiation recorded at the appropriate site. Daily means were calculated only for complete days of data. Daily mean albedos for each site were calculated by multiplying the albedo for each component surface by its fractional coverage and summing the components. Monthly and annual mean albedos (and standard deviations) for all component surfaces and sites were computed from the appropriate daily means.

RESULTS AND DISCUSSION

Hourly mean albedo

The diurnal variation in hourly mean albedo over the four component surfaces is shown in Figure 1. Two typical days during the dry season have been chosen to exemplify variation under cloudy (30 December 1989) and clear (26 December 1989) sky conditions. Figure 1 also shows (fallow site only) the variation in diffuse and total incoming solar radiation together with the ratio of these quantities, R_{DT}. The ranking of the surfaces is the same on both days. The tiger-bush soil and bushes show, respectively, the highest and lowest albedos. The albedos of the fallow herbs and bushes are intermediate to those of the tiger-bush components. Although similar to one another, the fallow bush albedo is almost always slightly greater than the herb albedo. The ranking of the surfaces is a consequence of the differing quantity of plant material present to trap radiation by multiple reflection and absorption. The tiger-bush soil has no plant cover and thus the highest albedo. The tiger-bush bushes, although mostly leafless during December, present a dense mass of woody stems and branches. They exhibit the lowest albedo as a result of their high efficiency in trapping solar radiation. The fallow components are intermediate cases.

Under clear-sky conditions the differences between the surfaces are more pronounced. All surfaces show a tendency for the albedo to be greater at dawn and dusk (when solar zenith angle is high), and to have its minimum value at solar noon (minimum zenith angle). This pattern of variation has been commonly observed for a wide range of land cover types (Stewart, 1971; Nkemdirim, 1972; Oguntoyinbo, 1974; Pinker *et al.* 1980), and results from deeper penetration of the canopy by the solar beam at low zenith angles, causing more radiation to be trapped (Oke, 1987). The fallow bush and herb surfaces show very similar albedos at noon, but the increase at high solar zenith angles is more pronounced for the bushes. This probably results from the differences in the distribution of the reflecting elements of the two surfaces: the herbaceous layer (standing dead grasses and herbs) consists mainly of vertical elements, whereas the stems and branches of the bushes are orientated at a wide range of angles, from horizontal to vertical.

The variation in hourly albedo over the four surfaces for 3 days following a rainstorm is shown in Figure 2. The rainstorm occurred at both sites, between midnight and dawn on 2 September 1990, the total rainfall

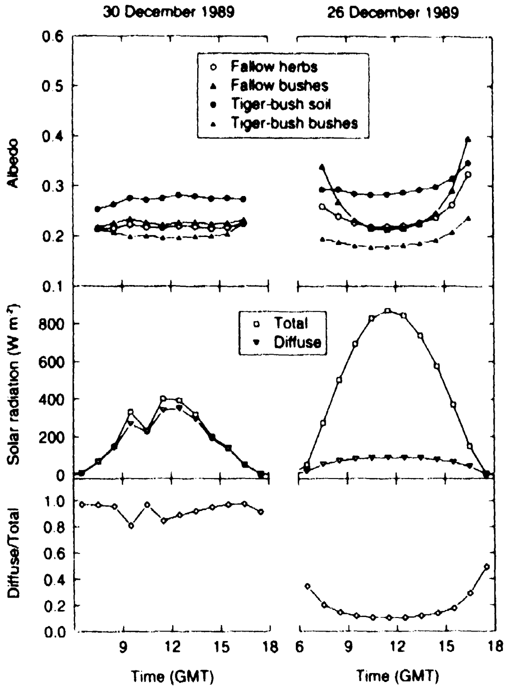

Figure 1. Diurnal variation in albedo over all surfaces for a typical cloudy day (30 December 1989) and a typical clear day (26 December 1989) during the dry season. Incoming shortwave radiation and diffuse/total shortwave ratio (fallow site only) also shown.

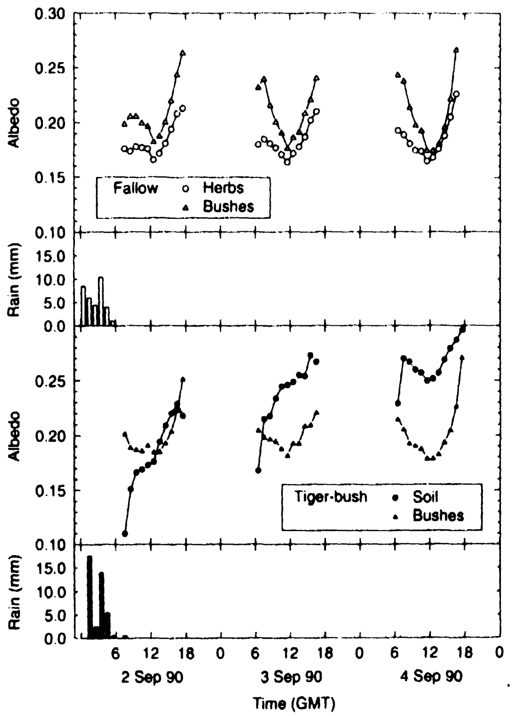

Figure 2. Variation in hourly mean albedo for the component surfaces at the fallow and tiger-bush sites over a 3-day period following a rainstorm (hourly rainfall totals also shown).

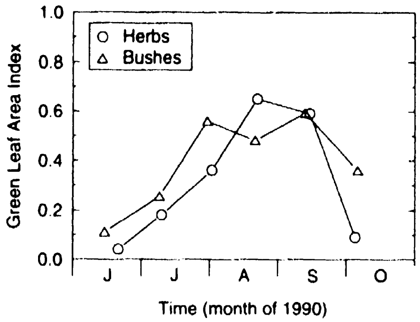

Figure 3. Green-leaf-area indices of fallow herbs and bushes through the 1990 wet season.

being 35 mm and 41 mm at the fallow and tiger-bush, respectively. Immediately after the storm, reduced albedos were observed for all surfaces, but by far the lowest was recorded for the bare soil at the tiger-bush. Previous studies (Idso *et al.*, 1975, Wallace *et al.*, 1990) have shown that the albedo of soil surfaces is very sensitive to moisture content, being lowest when the surface is most wet. This is because radiation is trapped mainly by internal reflection at air–water interfaces formed by the menisci in soil pores (Monteith and Unsworth, 1990).

The albedos of the three vegetated surfaces showed little response to the rainfall event. This was a consequence of the relatively small contribution of reflectance from the underlying soil to overall albedo, as leaf-area indices were close to their maximum values at this time (see Figure 3). However, a slight depression in albedo over the fallow component surfaces was observed during the morning of 2 September (Figure 2): this indicates that wetting did cause a significant decrease in the albedo of the soil, but it was partially masked by the overlying cover of leaves and stems. The smallest decrease in albedo was observed for the tiger-bush bushes, where the soil was almost completely obscured by the very dense canopy. It is also interesting to note in Figure 2 the slight decrease in albedo of the tiger-bush soil that was observed for the first hour of the day on 3 and 4 September, when no rainfall occurred. It was probably caused by increased soil moisture content, resulting from overnight rehydration of the surface layer by the upward movement of water. This water would have been rapidly lost as the day's evaporation commenced, thus explaining the short duration of decreased albedo. Similar effects can be seen in the data presented by Idso *et al.* (1975) and Wallace *et al.* (1990).

The variation of albedo with solar zenith angle over the four component surfaces is shown in Figure 4. March 1990 has been selected to exemplify the dry season and September the wet season, when leaf areas were maximal. To eliminate the effect of surface-soil moisture variation, all days commencing less than 48 h after the last rainfall were excluded. From each month, the four clearest and four cloudiest days of those remaining were chosen (on the basis of daily mean R_{DT} values), and for each zenith angle class the mean albedo across the 4 days was calculated. The objectives of this analysis were twofold.

First, by attempting to remove the confounding variations in other factors, the graphs allow the change in albedo due solely to the presence of leaves to be assessed. This can be achieved by comparing the albedos at a particular zenith angle in the March 1990 graphs with those at the same zenith angle in the September 1990 graphs. In fact, the confounding effect of zenith angle is small as there is little difference in solar declination between the two months. Second, by grouping clear and cloudy days, the effect of differing proportions of diffuse radiation in the incoming solar flux on the relationship between albedo and zenith angle can be examined.

Figure 4 shows a marked reduction in albedo over all component surfaces from the dry season to the wet season. For the vegetated surfaces, this reduction is caused by the development of leaves during the wet season. The explanation for the tiger-bush bare soil is less obvious. Possibly the dry season albedo may be elevated by the accumulation of a layer of fine, reflective dust deposited by the north-easterly harmattan winds which prevail in January and February (Hayward and Oguntoyinbo, 1987). This would be removed by surface run-off at the beginning of the wet season. Alternatively, the selection criterion used

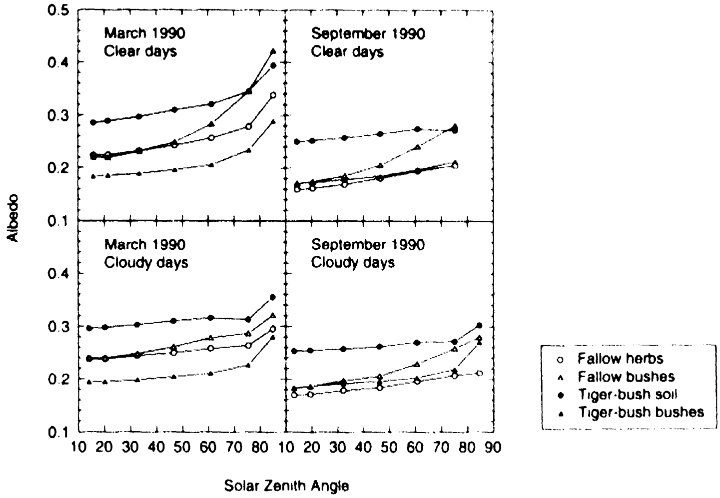

Figure 4. The relationship between albedo and solar zenith angle over the four surfaces as affected by cloudiness and time of year. Each graph shows mean albedo values calculated from four days' data (all selected days were at least 2 days after rain, to eliminate wet surface conditions).

for dry surface conditions may not have been rigorous enough, allowing some days when the soil surface was still partially moist (lower albedo) to be included in the analysis.

During the dry season (Figure 4, March 1990) the effect of variation in the diffuse component of incoming solar radiation on albedo is clearly shown. Under clear skies the relationship between albedo of all surfaces and zenith angle is markedly curved, the minimum values being at solar noon. The effect of overcast conditions is to flatten all the curves, slightly increasing albedo at solar noon, and decreasing it by a greater amount at high zenith angles. As the greater part of a day's solar radiation is received in a period of a few hours either side of noon, this means that the daily mean albedo increases slightly under overcast conditions.

During the wet season (Figure 4, September 1990) there is less difference between albedos on clear and cloudy days. This could be due to differences in the optical properties of a canopy of leaves, compared with a collection of leafless stems and branches. Alternatively, it could be the result of a smaller difference in mean R_{DT} of the 'clear' and 'cloudy' days selected from September 1990. This is an inevitable consequence of the rarity of really clear days in the wet season.

Monthly mean albedo

The trends in monthly mean albedo for the component surfaces of the fallow over the entire period of measurements are shown in Figure 5. The monthly albedos of the two surfaces were similar throughout, the albedo of the bushes always being slightly higher than for the herbs. This is in agreement with the observation of higher bush albedos near dawn and dusk that was noted in the diurnal trends. A strong seasonal variation in the albedo of both components is clearly apparent, closely mirroring the trends in the green-leaf-area index (Figure 3). The lowest albedos were recorded in the wet season months of August and September, when leaf areas were high, increasing the capacity of the vegetation to capture incident radiation by multiple reflection. The highest albedos were recorded during January to February, in the dry season, when green-leaf-area indices were zero. Figure 5 also shows error bars of ± 1 standard deviation for each monthly mean albedo. Over both surfaces there was little change in the variability of albedo through the year. This suggests that the repeated wetting and drying of the underlying soil was not the major cause of the lower albedos observed in the wet season.

A similar graphical analysis of the tiger-bush monthly mean albedo is presented in Figure 6. The soil component showed a strong seasonal variation, which was closely coupled with rainfall. This can be shown

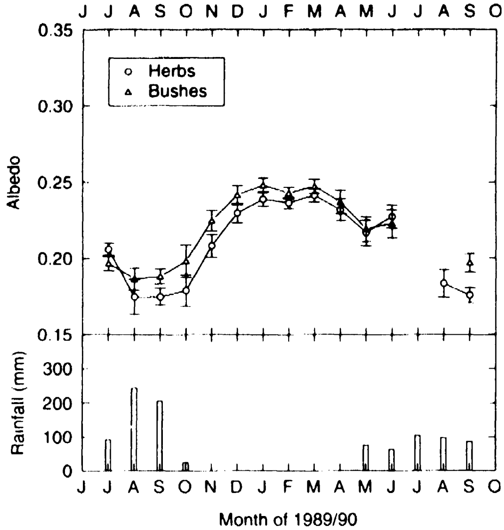

Figure 5. Variation in monthly mean albedo (error bars give standard deviations) for fallow herbs and bushes from July 1989 to September 1990. The monthly rainfall totals at the fallow site over the same time period are also shown.

by considering the 3 months with the largest rainfall totals. These were August 1989, September 1989, and July 1990, ranked in descending order. The soil albedo for these same months ranks in reverse order, the August 1989 albedo being the lowest recorded over the entire period of observations. The three high-rainfall months show great variability in albedo, resulting from repeated wetting and drying of the soil surface, as exemplified by Figure 2. The highest soil albedos were recorded in the dry season months of February and March. Here the variability was very low, due to the absence of rain events. The tiger-bush bushes showed the smallest seasonal change in albedo of the four surfaces studied, accompanied by the lowest variability. This behaviour was caused by two effects. Firstly, the loss of leaves during the dry season did not cause much reduction in the surface's ability to trap radiation, because of the close packing of the numerous

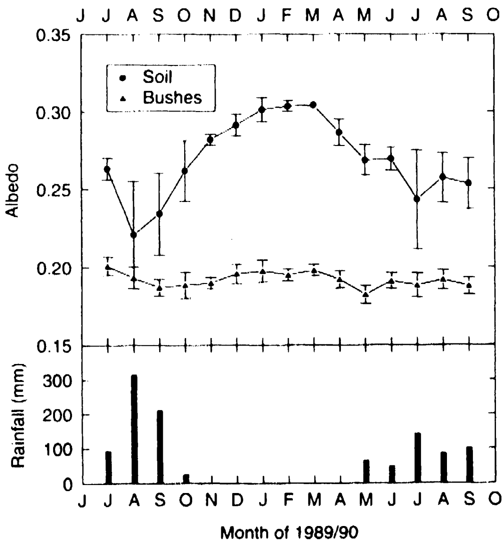

Figure 6. Variation in monthly mean albedo (error bars give standard deviations) for tiger-bush soil and bushes from July 1989 to September 1990. The monthly rainfall totals at the tiger-bush site over the same time period are also shown.

Table II. Minimum and maximum monthly mean albedos for the four individual component surfaces and the two sites, calculated as area-weighted means of the components

Site	Component surface	Fraction of area covered	Monthly mean albedo Minimum	Maximum	Difference
Fallow	Herbs	0·81	0·175	0·241	0·066
	Bushes	0·19	0·186	0·248	0·062
	Both	1·00	0·177	0·242	0·065
Tiger-bush	Soil	0·67	0·221	0·304	0·083
	Bushes	0·33	0·182	0·201	0·019
	Both	1·00	0·212	0·269	0·057

stems and branches remaining. Secondly, the canopy of leaves that developed during the wet season was dense enough to completely obscure the soil surface, therefore preventing changes in soil-surface moisture from reducing monthly mean albedo and increasing its variability.

The monthly mean albedos for the two sites, obtained by weighting the component surface albedos by their respective proportional coverages (given in Table II) are shown in Figure 7. The albedo of the tiger-bush was always greater than the fallow, because the more extensive bare soil component dominates the area-weighted mean. A marked seasonal cycle in albedo was observed at both sites. In the case of the fallow it was caused by changes in the vegetation, whereas for the tiger-bush it resulted mainly from the frequent variation in surface-soil moisture content that occurred during the wet season.

Table II gives the monthly minimum and maximum values, together with the differences between them. A difference of 0·06 between monthly minimum and maximum albedos was observed at both the fallow and tiger-bush sites. Because GCMs show that the typical impact of an 0·05 increase in albedo is a reduction in rainfall of between 5 per cent and 20 per cent (Henderson-Sellers, 1991), the use of a time-invariant albedo might be expected to introduce significant errors in GCM rainfall predictions.

Wilson and Henderson-Sellers (1985) compiled a global data set of land surface albedo, which is one of the main sources used to prescribe albedos in GCMs (Dorman and Sellers, 1989). Annual mean albedos are given for 24 land type components, from which the albedos of a wide range of land surfaces can be calculated as area-weighted averages of the component albedos. Summer and winter albedos are also given,

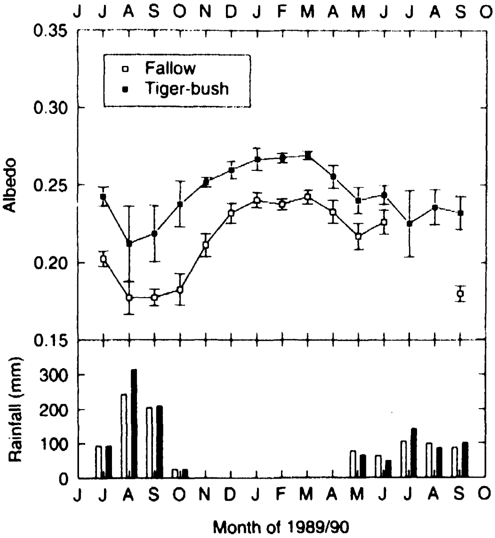

Figure 7. Variation in monthly mean albedo (error bars give standard deviations) for the fallow and tiger-bush sites from July 1989 to September 1990. The monthly rainfall totals at each site are also shown.

in acknowledgement of the possible requirement to include seasonality in GCM simulations. The summer-winter differences in albedo measured in the current study (Table II) for the vegetated surfaces are all greater than the differences given for the most directly comparable components by Wilson and Henderson-Sellers (1985). At the fallow site the difference for the herbaceous layer was 0·07, compared with 0·05 for 'tall grass', and for the *Guiera* bushes 0·06, compared with 0·02 for 'deciduous shrub'. The increase for the tiger-bush vegetation stripes was 0·02 compared with 0·01 for 'drought deciduous tree'. The minimum and maximum values of tiger-bush soil albedo are broadly in agreement with the 'wet' and 'dry' values given to define the response of albedo to surface moisture content for soil in the 'light' colour class.

Annual mean albedo

Mean albedos have been calculated over a year (1 July 1989 to 30 June 1990), rather than the whole 15-month data set, in order to avoid giving undue weighting to the wet season. These data are given in Table III.

The annual mean albedo of the tiger-bush (0·25) is only slightly higher than that of the fallow (0·22). This is because the reflectivity of the soil component was diminished by the frequent wetting in the rainy season, and balanced out by the persistently low albedo, even during the dry season, of the vegetated stripes. There are few ground-based measurements against which these data can be compared. Oguntoyinbo (1970) measured annual mean albedos of 0·20 and 0·21 for Sudanian and Sahelian savannas, respectively, in nearby Nigeria. These agree closely with the annual mean albedo of the fallow measured in this study. Sellers (1965) gives ranges of 0·15–0·20 and 0·25–0·30 for 'wet season' and 'dry season' savanna, respectively, suggesting an annual mean of between 0·20 and 0·25. The values found for the fallow and tiger-bush sites lie within this range.

In comparison with the annual mean albedos for the component surfaces reported in Table III, those given by Wilson and Henderson-Sellers (1985) for the most directly comparable land type components are rather low. The albedo measured for fallow herbs (0·21) agrees well with the value given for 'tall grass' (0·20), but the observed fallow bush albedo (0·22) is significantly higher than that given for 'deciduous shrub' (0·16). Similarly, higher albedos were measured for the tiger-bush bushes (0·19) and soil (0·28), than the values given for 'drought deciduous tree' (0·13) and 'light' soil (0·26). Clearly, further ground-based measurements of albedo in the Sahel would be of benefit to ensure that the values currently assumed in GCM experiments are correct.

The relatively short duration of the measurements reported here prevents much consideration of the patterns of inter-annual albedo variation that were addressed by the work of Norton *et al.* (1979) and Courel *et al.* (1984). However, it is possible in this study to compare July–September (JAS) means as a measure of the wet season albedo, for two years of differing rainfall. This can be done only for the tiger-bush site (see Figure 6) because some of the necessary fallow savannah data was lost through storm damage to the instruments. The year 1989 was much wetter than 1990, with a JAS rainfall total of 616 mm compared with 329 mm. Annual rainfall totals recorded at ISC were 623 mm (1989) and 400 mm (1990), compared

Table III. Annual means of daily albedo for the four individual component surfaces and the two sites, calculated as area-weighted means of the components. Standard deviations and number of days data used are also given

Site	Component surface	Fraction of area covered	Albedo (1 July 1989 to 30 June 1990)		
			Mean	Standard deviation	Number of days
Fallow	Herbs	0·81	0·213	0·026	341
	Bushes	0·19	0·223	0·023	331
	Both	1·00	0·215	0·025	331
Tiger-bush	Soil	0·67	0·275	0·029	336
	Bushes	0·33	0·192	0·007	342
	Both	1·00	0·248	0·021	336

with the long-term mean of 557 mm (Sivakumar, 1988). For the tiger-bush soil component, the 1989 and 1990 JAS mean albedos were 0·24 and 0·25, respectively. For the bushes, the corresponding figures were both 0·19. Thus for two years with annual rainfalls differing by almost a factor of two, there was virtually no difference in the wet season albedo of the tiger-bush soil and bushes.

CONCLUSIONS

The data presented show how land surface albedo varies in response to a number of different factors. On the time-scale of months, albedo appears to be most strongly affected by the amount of vegetation present and the moisture content of the soil surface. These factors account for the largest part of the differences observed between surfaces with differing covers and between the dry and wet seasons for a single surface. The variation in solar zenith angle and in R_{DT} probably also play a small part in the variation of albedo through the year, as they are both subject to seasonal variation. Their major influence, however, is over the time-scale of hours and days.

Clearly, the usefulness of albedo measurements to global climate modelling will depend on the areal extent of the surfaces that they characterize. The question of how well the sites used in this study represent the land cover of the Sahel has not been quantitatively addressed, but they appear to be common in south-western Niger. White (1970) states that there are numerous occurrences of tiger-bush in Niger, within a zone some 250 km wide, extending from approximately 15°N to 12°30′ N. Tiger-bush areas are easily distinguishable in satellite imagery (see Wallace *et al.*, 1991). Visual inspection of a SPOT image for the south-western quarter of the 1° square from 13°N 2°E to 14°N 3°E suggests that tiger-bush occupies the major part (at least 50 per cent) of the land surface. The next most extensive land cover type is millet, the dominant subsistence crop, occurring on the deep sands in the bottom of the valleys that separate the plateau areas occupied by tiger-bush. Some albedo measurements for this surface type have been presented by Kassam and Kowal (1975) and Allen *et al.* (1990). Fallow land is an integral part of the rotation practised by local farmers, but occupies a smaller area than the millet fields.

Besides adding to the available data on the albedo of Sahelian land surfaces, the measurements presented here highlight the variation that occurs from dry to wet seasons. This variation is not only observed for vegetated surfaces, where the annual growth and loss of leaves might be expected to affect albedo, but also for bare soil, as a result of frequent surface wetting during the rainy season. Considering the important role of albedo in determining the radiative balance of land surfaces it therefore seems inappropriate to prescribe a constant value for each land surface type if the climate of the Sahel is to be simulated accurately by GCMs. This justifies the move to more complex representations of the land surface, such as the Simple Biosphere model of Sellers *et al.* (1986), where the dependence of the albedo on seasonally varying vegetation cover and soil-surface moisture content is explicitly formulated.

Finally, this study has significant implications for the choice of albedo values to be used in GCM experiments, where the effect of vegetation removal on the Sahelian climate is assessed by increasing an invariant annual mean albedo. A hypothetical change in vegetation cover from tiger-bush bushes (a closed canopy of woody shrubs) to bare soil must be one of the most extreme reductions in vegetation that could be imagined for the Sahel. This would result in an increase in annual mean albedo of only 0·09, from 0·19 to 0·28 (see Table III). In the studies reviewed by Rowntree (1991), the imposed albedo increases ranged from 0·12 to 0·22. It is difficult to see how such large changes in albedo over the entire Sahel region could ever occur in practice. Such studies should thus be regarded as sensitivity analyses, rather than sources of quantitative predictions of realistic changes in climate that could occur through altered land use in the Sahel.

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