Observations of Albedo and Radiation Balance over Postforest Land Surfaces in the Eastern Amazon Basin

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ABSTRACT

Regional climatic change, including significant reductions in Amazon Basin evaporation and precipitation, has been predicted by numerical simulations of total tropical forest removal. These results have been shown to be very sensitive to the prescription of the albedo shift associated with conversion from forest to a replacement land cover. Modelers have so far chosen to use an "impoverished grassland" scenario to represent the postforest land surface. This choice maximizes the shifts in land surface parameters, especially albedo (fraction of incident shortwave radiation reflected by the surface). Recent surveys show secondary vegetation to be the dominant land cover for some deforested areas of the Amazon. The characteristics of secondary vegetation as well as agricultural land covers other than pasture have received little attention from field scientists in the region. This paper presents the results of field measurements of radiation flux over various deforested surfaces on a small farm in the eastern Amazonian state of Pará. The albedo of fields in active use was as high as 0.176, slightly less than the 0.180 recently determined for Amazonian pasture and substantially less than the 0.19 commonly used in GCM simulations of deforestation. For 10-yr-old secondary vegetation, albedo was 0.135, practically indistinguishable from the recently published mean primary forest albedo of 0.134. Measurements of surface temperature and net radiation show that, despite similarity in albedo, secondary vegetation differs from primary forest in energy and mass exchange. The elevation of midday surface temperature above air temperature was found to be greatest for actively and recently farmed land, declining with time since abandonment. Net radiation was correspondingly lower for fields in active or recent use. Using land cover analyses of the region surrounding the study area for 1984, 1988, and 1991, the pace of change in regional-mean albedo is estimated to have declined and appears to be leveling at a value less than 0.03 above that of the original forest cover.

1. Introduction

Regional, or even global, climatic change resulting from altered land surface characteristics is one of the potential serious consequences of large-scale tropical deforestation. General circulation model experiments using an extreme postforest scenario of impoverished grassland suggest that a reduction in Amazon Basin precipitation of 20% or more could result from complete forest removal (Henderson-Sellers et al. 1993; Henderson-Sellers et al. 1996; McGuffie et al. 1995; Sud et al. 1996). To simulate land cover change in the models, shifts are made in the values of land surface parameters such as albedo (the proportion of incident solar radiation reflected by the surface), aerodynamic roughness, leaf area, and soil moisture capacity. Dirmeyer and Shukla (1994) found simulated deforestation-induced changes in precipitation to be strongly dependent on the magnitude of albedo change. Average precipitation decreased as a result of deforestation in their study only if the increase in albedo was greater than 0.03; with lesser albedo increases, rainfall increased.

The magnitude of parameter shifts depends upon the

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assumed replacement land cover. GCM modelers have selected impoverished grassland (e.g., Henderson-Sellers et al. 1993; Henderson-Sellers et al. 1996; McGuffie et al. 1995; Sud et al. 1996) as the postforest scenario as a means of amplifying any possible deforestation effects. A characteristic feature of most deforestation experiments done to date is an increase in surface albedo from a forest value of about 0.12 to a grassland value of about 0.19. The choice of grassland represents the most extreme possible future for deforested land, which, the modelers reason, will indicate whether any significant regional or global climate change could result from tropical deforestation. The impoverished grassland scenario also stems from a general impression, especially in the Amazon Basin, of rapid conversion of tropical forest to agricultural land and ultimately to degraded pasture (e.g., Hecht 1993). However, forest clearing in the Amazon is partly offset by the rapid return of forest vegetation on abandoned fields (Turner et al. 1993). Uhl et al. (1988) found that for sites near Paragominas in northern Pará State, Brazil, Amazon forest ecosystems recovered after abandonment, except for the most intensively used sites, comprising less than 10% of pasture land. For sites along the Transamazon Highway near Altamira, Brazil, secondary vegetation experienced the largest absolute increase in area among all land cover categories, despite a quadrupling of pasture land (Moran et al. 1994). Watrin (1994) analyzed satellite imagery for the Igarapé-Açu, Brazil, area for 1984, 1988, and 1991 and found that secondary vegetation was by far the dominant land cover. These and other studies are beginning to bring into focus a picture of a future deforested Amazon that strongly contrasts with the homogeneous impoverished grassland scenario. That is, what comes after forest in the Amazon is a highly heterogeneous, dynamic land cover mosaic, including a variety of cultivated surfaces and significant areas undergoing secondary succession leading to forest regrowth. In the future, simulations of realistic deforestation scenarios must take into consideration the variety of land covers known to follow forest cutting, including secondary vegetation at various stages of maturity. The study presented here was undertaken to provide field observations of radiative exchange characteristics, especially albedo, of postforest land covers representative of the eastern part of the Amazon Basin.

2. Background

a. Radiative exchange

Radiant energy flux at the land surface can be described as

$$R_{net} = K\downarrow - K\uparrow + L\downarrow - L\uparrow, \quad (1)$$

where R_{net} is net radiation, $K\downarrow$ is downward shortwave radiation, $K\uparrow$ is shortwave radiation reflected by the surface, $L\downarrow$ is downward longwave radiation, and $L\uparrow$ is longwave radiation emitted by the surface (all terms are expressed in W m^{-2}). Here, R_{net} can be expressed, with emphasis on surface conditions, as

$$R_{net} = (1 - \alpha)K\downarrow + L\downarrow - \epsilon\sigma(T_s)^4, \quad (2)$$

where α is the surface albedo (ratio), ϵ is the emissivity (ratio), σ is the Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), and T_s is the surface temperature (K). The surface albedo is defined as

$$\alpha = \frac{K\uparrow}{K\downarrow}. \quad (3)$$

Albedo of a vegetated surface may be only half or less the reflectivity of its principal components, leaf surfaces, because of the trapping of light penetrating the upper canopy. This effect is generally considered to increase with vegetation height, giving forests the lowest albedo and grassland the highest of any class of vegetation. At high sun angles, light can penetrate to greater depths within a forest canopy. Annual and diurnal changes in sun angle, therefore, cause changes in albedo. For this reason and because of the annual cycle of foliage loss in deciduous forests, albedo is typically lowest in summer. In a tropical location with a significant annual rainfall cycle, albedo is generally observed to be highest during the dry season(s) because of foliage changes (Pinker et al. 1980; Barradas and Adém 1992). Diffuse light more effectively penetrates the vegetative canopy and is, therefore, absorbed more effectively than parallel beam radiation. When incident radiation has a high proportion of diffuse light, the sun angle effect on albedo is less important. For moist tropical regions such as the Amazon, albedo would not be expected to vary greatly during the year because annual changes in sun angle and foliage are relatively small and because a high proportion of incident radiation is diffuse under the cloudy skies of the equatorial region. However, Wright et al. (1996) observed significant annual albedo cycles in the Amazon, which appear to be related to fluctuation in soil moisture in forested areas and leaf-area variation in pasture. Nevertheless, sun-angle-related diurnal change is the most important source of temporal variation in albedo in the region.

b. Radiative exchange of tropical land areas

Albedo values measured over tropical evergreen forests are remarkably consistent (0.1225–0.134, Table 1). Shuttleworth (1989) recommended 0.12 as a large-scale average albedo for tropical and temperate evergreen forests for use in GCMs. Cleared areas have more variable radiative characteristics. Pinker (1982) found that albedo varied seasonally between 0.125 and 0.160 in a forest clearing in Thailand. Bastable et al. (1993) reported a mean albedo of 0.163 for a pasture near Manaus in central Amazonia, but they cautioned that albedo for deforested areas is likely to vary from place to place. They speculate that this unexpectedly low value may

TABLE 1. Albedo of tropical land surfaces.

Location	Surface	Source	Mean albedo
Amazon	Rainforest	Culf et al. (1995)	0.134
Amazon	Rainforest	Shuttleworth et al. (1984)	0.1225
Amazon	Rainforest	Bastable et al. (1993)	0.131
Nigeria	Rainforest	Oguntoyinbo (1970)	0.12
Thailand	Dry evergreen forest	Pinker (1982)	0.130
Tropical evergreen forest			0.12–0.134
Nigeria	Secondary vegetation	Oguntoyinbo (1970)	0.15
Nigeria	Savanna tall	Oguntoyinbo (1970)	0.19
Nigeria	Savanna short	Oguntoyinbo (1970)	0.15
Nigeria	Degraded savanna	Oguntoyinbo (1970)	0.16
Nigeria	Short grass	Oguntoyinbo (1970)	0.21
Thailand	Tall grass	Pinker (1982)	0.150
Amazon	Pasture	Bastable et al. (1993)	0.163
Amazon	Pasture	Fisch et al. (1994)	0.19
Amazon	Pasture	Culf et al. (1995)	0.18
Amazon	Burned pasture	Fisch et al. (1994)	0.08
Nigeria	Crops	Oguntoyinbo (1970)	0.17
Nigeria	Bare soil	Oguntoyinbo (1970)	0.14
Tropical nonforest			0.08–0.21

be due to darkening of the underlying soil by the ash from repeated burns at the site. In a large pasture at Marabá in the eastern part of the Brazilian Amazon, albedo dropped from 0.19 to 0.08 due to burning, then recovered to its preburn value within about 80 days. In a more recent summary of albedo measurements over Amazonian pasture, Culf et al. (1995) give monthly means ranging from 0.171 to 0.192 and an annual mean of 0.180.

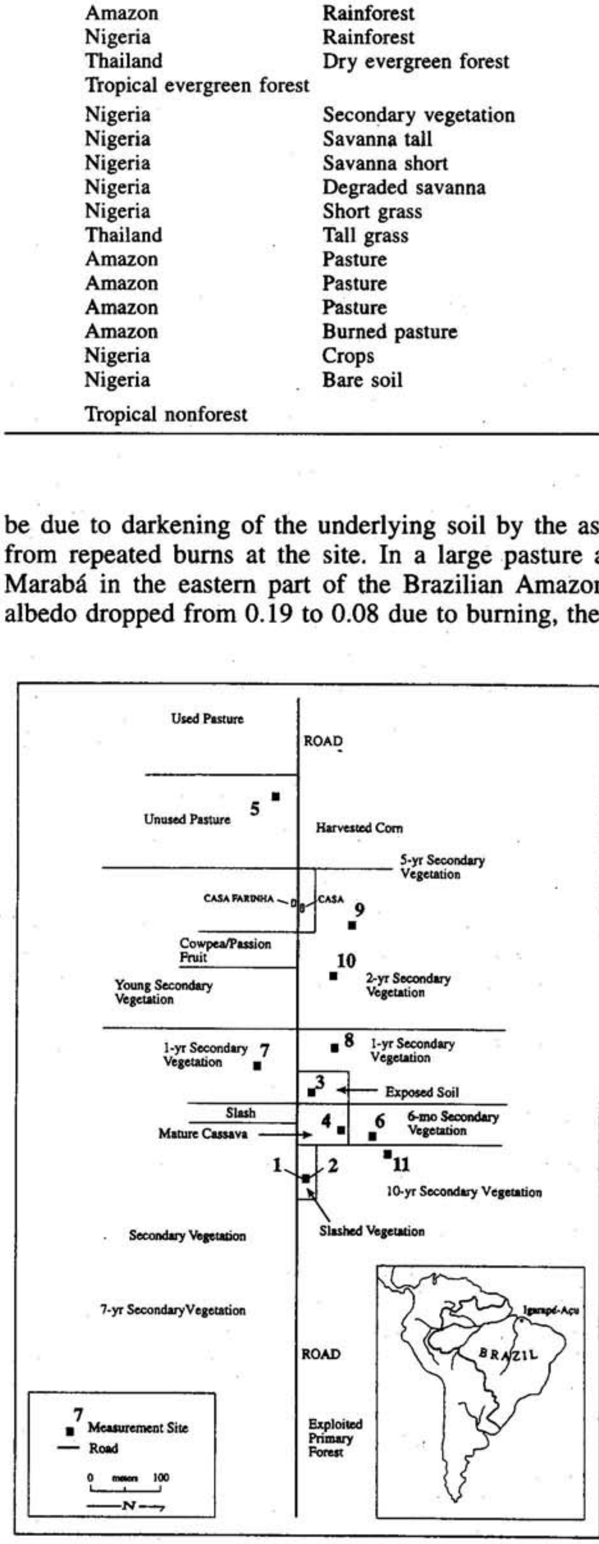

FIG. 1. Map of Igarapé-Açu study area.

Summarizing the various albedo measurements for deforested tropical areas, principally grassland, Gash and Shuttleworth (1991, 126) state that it is "likely that tropical deforestation will always result in a decrease in the energy absorbed by the surface equivalent to some 2–13% of the solar radiation before the change. A change of about 8% is probably a typical value . . ." On the basis of such statements from field scientists, climate modelers have prescribed an albedo of around 0.19. For seven recent GCM deforestation experiments examined by Culf et al. (1995), albedo settings averaged 0.124 for forest and 0.188 for the deforested surface.

3. Methods

Albedo and related measurements have been made and continue at several locations in the Amazon (Wright et al. 1996; Culf et al. 1995), but study sites have so far been limited to primary forest and pasture. Radiative characteristics of other forest replacement land covers, such as secondary vegetation, are as yet not well known. With this in mind, we took radiation measurements over a variety of land covers representative of forest replacement in the Amazon Basin. Measurement sites were all within a small farm near the village of Igarapé-Açu (1° 11.5′ S, 47° 35.8′ W), in the eastern Amazonian state of Pará (Fig. 1). This study differs from other field measurement programs in its emphasis on land-cover-related spatial variability of radiative exchange within a small area.

TABLE 2. Sensors and data recorders.

Instrument	Company	Location	Model
Shortwave radiation			
Downward	Eppley Laboratory	Newport, Rhode Island	8-48
Reflected	Eppley Laboratory	Newport, Rhode Island	PSP
Net all-wave radiation	REBS	Seattle, Washington	Q*6
Canopy temperature	Everest Interscience	Fullerton, California	4000ALCS
Air temperature	Vaisala	Helsinki, Finland	HMD30UYB
Rainfall rate	Campbell Scientific	Logan, Utah	TE525
Data loggers	Licor	Lincoln, Nebraska	LI-1000

a. Igarapé-Açu, Pará State

Agricultural practices in the village of Igarapé-Açu are typical of those in the deforested areas of the eastern Amazon Basin. Beginning in the early part of this century, the tropical rainforest in the area surrounding Igarapé-Açu has largely been replaced by secondary vegetation, areas cleared in preparation for planting, and crops. Secondary vegetation, known locally as *capoeira,* grows during multiyear fallow periods in the traditional slash-and-burn cropping system of the region (Denich and Kanashiro 1995). The species composition of the secondary vegetation in the region has been shown to include around 50 to 60 woody species in a sample area of 60 m^2. In total, more than 800 plant species have been found in the region (Barr 1995, personal communication). Cassava, corn, cowpea, and rice are the main crops (Kato and Denich 1993). Figure 1 shows the sites of radiation measurements at the Igarapé-Açu study area and the pattern of land use on the farm at the time of the measurements (October and November 1992). The equatorial climate of the region is characterized by a very small annual cycle of temperature, with an annual mean of about 26°C. About 2500 mm of rainfall is received annually, with the highest amounts during February through April and the minimum during September through November (Bastos et al. 1993). Soil at the site has been classified as *Typic Kandiudults* (Rego et al. 1993).

b. Measurement strategy

Meteorological measurements were taken using a single set of sensors (Table 2), which were moved from site to site, producing a sequence of observations for different covers. A larger temporal sample was sacrificed to obtain greater spatial variety. Measurement sites (Fig. 1) are described in Table 3. The "slashed vegetation" site refers to a field where 7-yr secondary successional vegetation had recently been cut. The slashed vegetation remained on the ground at the time of the observations. Later, after the vegetation had dried for several weeks, the field was burned. Measurements at the same site after the burn are listed under "burned slash." Ages of secondary vegetation are based on interviews with farmers and are considered to be only approximate.

c. Observations

Measurements were taken during the driest part of the year (October and November 1992). Because observations over different land covers were not made simultaneously, day-to-day variations in cloud cover, precipitable water, and atmospheric turbidity affected the measurements over each land cover differently. Direct comparisons among sites of measurements such as reflected shortwave radiation and net radiation are not meaningful because of day-to-day differences in solar radiation. However, when examining relatively time-invariant surface properties, such as albedo or net radiation as a fraction of incident solar radiation, comparison among sites is possible.

Concurrent incident ($K\downarrow$) and reflected ($K\uparrow$) shortwave radiation measurements were taken over multiple diurnal cycles at each site to capture the sun angle effect on albedo. Eppley model 8-48 and PSP measurements, sampled every 5 s and averaged and recorded each hour, were used to estimate the mean diurnal pattern of $K\downarrow$ and $K\uparrow$ over each land cover in the form of hourly means. Albedo values were computed for sunny and cloudy periods. Sky condition was determined on the basis of the ratio of $K\downarrow$ to estimated clear-day radiation (K_{cd}). The SPECTRAL2 model (Bird and Riordan 1986) was used to estimate K_{cd}. The cloudy condition was defined arbitrarily as periods during which $K\downarrow/K_{cd}$ was less than 0.5.

4. Results and discussion

a. Radiative characteristics of deforested sites at Igarapé-Açu

Figure 2 shows that most surfaces exhibit higher early morning albedo in accordance with expectations, but many show an albedo decline in late afternoon. Pinker (1982) reported similar asymmetry in measurements over forests in Thailand. We speculate that the observed pattern may be due to the clear conditions (high direct beam content) and dew-covered (more reflective) leaves in the early morning and cloudiness (higher diffuse light content) in the late afternoon.

The albedo site means at Igarapé-Açu (Table 4) reveal that 1) shortwave reflection from advanced secondary vegetation is very similar to that measured recently for

TABLE 3. Characteristics of measurement sites at Igarapé-Açu. Map code refers to Fig. 1.

Map code ↓	Land cover type	Vegetation: Height (m)	Age (years)	Representative species	Measurement period (1992)
1	Slashed vegetation	1.3	0.0	Prior cover 7-yr secondary vegetation	7–14 October
2	Burned slash	0.0	0.0	Prior cover 7-yr secondary vegetation	5–7 November
3	Bare soil (sparse vegetation)	0.3	0.1	*Phaseolus* sp.	7–9 November
4	Mature cassava	1.4	1.5	*Manihot esculenta* L. Crantz.; *Phenakospermum guyanensis* Endl.	14–16 October
5	Unused pasture	0.7	1.3	Piculho (local name for grass species)	28–30 October
6	Secondary vegetation	0.4	0.5	*Phenakospermum*; *Lacistema pubescens* Mart.	21–23 October
7	Secondary vegetation	0.3	1.0	*Cassia riparia* HBK; *Spermacoce verticillata* L. (*Borreria verticillata*)	16–19 October
8	Secondary vegetation	1.6	1.0	*Lacistema pubescens* Mart.; *Myrcea bracteata*	19–21 October
9	Secondary vegetation	1.8	2.0	*Banara guianensis* Aubl.; *Lacistema pubescens* Mart.; *Myrcea bracteata* DC	23–26 October
10	Secondary vegetation	1.8	2.0	*Banara guianensis* Aubl.; *Lacistema pubescens* Mart.; *Myrcea bracteata* DC	26–28 October
11	Secondary vegetation	4.8	10.0	*Phenakospermum guyanensis* Endl. (very few other species at this site)	30 October–5 November

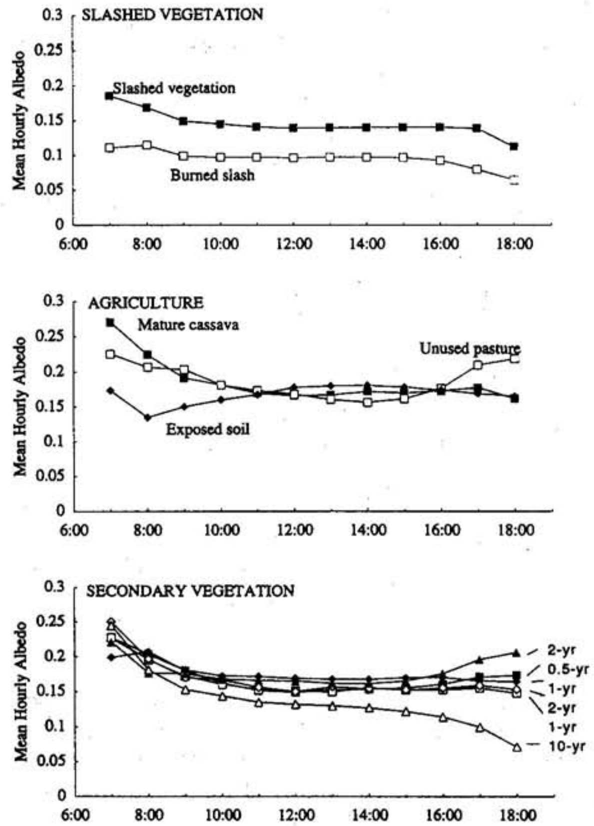

FIG. 2. Diurnal cycle of albedo for sites at Igarapé-Açu; curves for secondary vegetation sites are labeled by the age of vegetation.

primary tropical forest in the Amazon (see Table 1), 2) albedo of initial secondary vegetation is higher than that of advanced secondary vegetation by about 0.03, 3) three sites typical of the actively used farmland in the region have an albedo in the narrow range between 0.170 and 0.176, and 4) slashed vegetation and burned slash have respective albedo values slightly higher and significantly lower than the secondary vegetation previously covering the site.

The site means are based on relatively short observation periods and are, therefore, representative only of the season. Measurements at other times of the year would likely yield somewhat different values. Culf et al. (1995) found that forest albedo at their Amazonian sample sites varied from 0.121 in March to 0.144 in August. For October and November, corresponding to the observation period for our study, mean monthly forest albedo was 0.143 and 0.141, respectively (Culf et al. 1995), higher than our advanced secondary value (0.135). Ranch land albedo in the Culf et al. (1995) summary varied from 0.171 in February and September to 0.192 in July. The October and November ranch land albedos, 0.172 and 0.177, respectively, were very similar to our measurements for agricultural sites (Table 4).

The relative amount of sunlight reflected is expected to be greater during clear-sky periods when the fraction

TABLE 4. Summary of albedo measurements at Igarapé-Açu.

Land cover	Albedo		
	All	Clear	Cloudy
Slashed vegetation			
1 Slashed vegetation	0.142	0.141	0.139
2 Burned slash	0.097	0.098	0.089
Mean	0.120	0.120	0.114
Agriculture			
3 Bare soil	0.170	0.173	0.147
4 Mature cassava	0.176	0.174	0.185
5 Unused pasture	0.175	0.175	0.182
Mean	0.174	0.174	0.171
Initial secondary successional vegetation			
6 Secondary vegetation (0.5 yr)	0.173	0.172	0.175
7 Secondary vegetation (1 yr)	0.161	0.159	0.162
8 Secondary vegetation (1 yr)	0.157	0.156	0.163
9 Secondary vegetation (2 yr)	0.162	0.155	0.174
10 Secondary vegetation (2 yr)	0.172	0.173	0.167
Mean	0.165	0.163	0.168
Advanced secondary successional vegetation			
11 Secondary vegetation (10 yr)	0.135	0.132	0.140

of diffuse light is relatively low. Our observations, however, do not show this conclusively (Table 4). Albedo for cloudy periods was lower at the slashed vegetation and bare soil sites, but higher at the cropped field and secondary vegetation sites. Culf et al. (1995) were also unable to find a distinct relationship between Amazonian forest albedo and cloudiness. We believe that our observations, as well as those of Culf et al. (1995), may be due in part to the diurnal cycle in cloud cover and the resulting tendency to identify as "cloudy" the late afternoon period, a time during which the effect of low sun angle obscures the influence of higher diffuse light content.

TABLE 5. Ratios of net radiation to incident solar radiation for sites in Igarapé-Açu.

Land cover	$R_{net}/K\downarrow$
Prior measurement and model settings	
Amazon forest (based on data of Shuttleworth et al. 1984)	0.706
GCM forest (based on results of Nobre et al. 1991)	0.738
GCM pasture (based on results of Nobre et al. 1991)	0.616
New measurements	
Slashed vegetation	
1 Slashed vegetation	0.565
2 Burned slash	0.483
Mean	0.524
Agriculture	
3 Bare soil	0.526
4 Mature cassava	0.556
5 Unused pasture	0.545
Mean	0.542
Initial secondary successional vegetation	
6 Secondary vegetation (0.5 yr)	0.556
7 Secondary vegetation (1 yr)	0.529
8 Secondary vegetation (1 yr)	0.585
9 Secondary vegetation (2 yr)	0.545
10 Secondary vegetation (2 yr)	0.545
Mean	0.552
Advanced secondary successional vegetation	
11. Secondary vegetation (10 yr)	0.589

The result that all forest replacement covers measured in Igarapé-Açu had albedo values lower than those used in deforestation simulations indicates that radiant energy absorption over real deforested surfaces is greater than those simulated in GCM experiments. That advanced secondary vegetation and primary forest are similar in terms of shortwave reflection suggests that the radiative balance of the two land covers may be similar. The ratio of net radiation to incident solar radiation ($R_{net}/K\downarrow$) is expected to decrease as albedo increases. For tropical forest, the ratio may be as high as 0.7 (based on data of Shuttleworth et al. 1984). From our measurements (Table 5), $R_{net}/K\downarrow$ for advanced secondary vegetation is significantly lower than that of primary forest. Successively lower ratios are found for initial secondary vegetation, agriculture, and slashed vegetation. Despite the fact that these sites reflect less energy than the simulated deforested landscape, these ratios are significantly lower than that predicted by GCMs for deforested land. This implies greater-than-predicted net longwave emission from the surface—that is, higher surface (canopy) temperatures. The difference between surface temperature and air temperature ($T_s - T_a$) at midday is generally low, on the order of 1°C, for actively transpiring forests (Bastable et al. 1993). Table 6 shows that, for deforested land covers in Igarapé-Açu, large values of $T_s - T_a$ are observed, generally declining with increasing vegetation age and height. In all cases, the higher surface temperatures indicate inhibited turbulent energy ex-

TABLE 6. Midday surface temperature–air temperature differences for sites in Igarapé-Açu.

	Land cover	Midday $T_s - T_a$
	Slashed vegetation	
1	Slashed vegetation	9.9
2	Burned slash	22.3
	Mean	16.1
	Agriculture	
3	Bare soil	12.4
4	Mature cassava	8.3
5	Unused pasture	8.5
	Mean	9.7
	Initial secondary successional vegetation	
6	Secondary vegetation (0.5 yr)	14.0
7	Secondary vegetation (1 yr)	7.1
8	Secondary vegetation (1 yr)	7.9
9	Secondary vegetation (2 yr)	1.9
10	Secondary vegetation (2 yr)	0.9
	Mean	6.4
	Advanced secondary successional vegetation	
11	Secondary vegetation (10 yr)	2.9

change, a result, in part, of lower aerodynamic roughness (Giambelluca 1996).

b. *Temporal change in Igarapé-Açu regional-mean albedo*

Watrin (1994) used Landsat Thematic Mapper imagery to classify land cover distribution in the Igarapé-Açu region for 1984, 1988, and 1991. His results, summarized in Table 7, show that secondary vegetation is the dominant land cover of the region, pasture is the dominant active land-use type, and remaining primary forest is very small. By assigning albedo estimates to each land cover category, regional albedo can be estimated as a weighted average. Albedo values for advanced secondary vegetation, initial secondary vegetation, bare soil, and crop land were assigned on the basis of measurements reported in this study. Based on Culf et al. (1995), values of 0.134 and 0.180 were used for forest and pasture, respectively. We used the mean of measured initial and advanced secondary vegetation, 0.150, to represent intermediate secondary vegetation. Regional albedo estimated on this basis increases from 0.1531 in 1984 to 0.1556 in 1988 and 0.1562 in 1991 (Table 7). The rate of change in regional albedo during 1988–91 is estimated to be one-third of that during the 1984–88 period, reflecting stabilization of the pace of land cover change as the portion of land remaining in primary forest approaches zero.

Small farmers in Igarapé-Açu practice a form of shifting cultivation that is the dominant agricultural system in tropical America, including the Amazon Basin. The basic elements of shifting cultivation in this region (Nascimento and Homma 1984; Galvão et al. 1986; Szott and Palm 1986) are 1) forest felling and burning, 2) 1 to 4 yr of annual crop cultivation, 3) gradual or abrupt abandonment as the land reverts to secondary vegetation, and 4) the initiation of another felling–burning–cultivation–fallow cycle after a 3–25-yr fallow period. Using farmers accounts and the relative land area occupied by secondary vegetation of different ages and agricultural land, a typical crop–fallow rotation can be constructed for small farms in the eastern Amazon. Accounts and land cover distribution suggest that farmers in Igarapé-Açu clear and burn land for planting annual crops for 2 consecutive years, after which land is left in fallow for about 8 yr. Fields are typically prepared by cutting vegetation and allowing it to dry for about 1 month, burning it, and planting a field crop. Fisch et al. (1994) found that the albedo of burned land in the Amazon recovered preburn values within about 80 days of burning. We use this period as the time necessary to reach the pasture or crop albedo value. These assumptions lead to the land cover cycle summarized in Table 8. Albedo values, assigned on the basis of our measurements and published data, are also shown in Table 8. In Fig. 3 we have plotted the scenario of land cover

TABLE 7. Estimation of regional-mean albedo for 1984, 1988, and 1991, estimated as area-weighted mean of albedo values assigned to each land cover category; areas based on land cover data of Watrin (1994).

Land cover category	Assigned albedo	Land cover (Watrin 1994) 1984 sq km	1984 %	1988 sq km	1988 %	1991 sq km	1991 %
Dense forest	0.134	74.0	9.4	91.2	11.6	42.0	5.3
Advanced secondary vegetation	0.135	165.5	21.0	145.1	18.4	139.8	17.8
Intermediate secondary vegetation	0.150	254.7	32.4	187.3	23.8	247.4	31.5
Initial secondary vegetation	0.165	155.5	19.8	171.9	21.9	187.8	23.9
Exposed soil	0.170	24.3	3.1	13.0	1.7	10.8	1.4
Pasture *sujo* (dirty)	0.180	60.6	7.7	99.8	12.7	107.7	13.7
Pasture *limpo* (clean)	0.180	36.9	4.7	44.5	5.7	18.4	2.3
Perennial crops	0.176	0.8	0.1	3.7	0.5	6.4	0.8
Annual/semiannual crops	0.176	14.2	1.8	30.0	3.8	26.2	3.3
Land total		786.5	100.0	786.5	100.0	786.5	100.0
Regional-mean albedo		0.1531		0.1556		0.1562	

TABLE 8. Typical small farm land cover and albedo cycle in Igarapé-Açu.

Initiating event	Land cover	Period (years)	Albedo Start	Albedo End
Forest felling	Slashed vegetation	0.00–0.08	0.142	0.142
Burning/planting	Ash-covered soil; emerging vegetation	0.08–0.41	0.097	0.174
Attainment of vegetation cover	Crop (pasture)	0.41–2.00	0.174	0.174
Abandonment	Secondary vegetation	2.00–10.00	0.174	0.135

change and albedo given in Table 8 to illustrate the estimated temporal cycle in albedo for an actively farmed location in the eastern Amazon. To illustrate the effect of increasing land pressure, Fig. 3 also shows albedo change for 8- and 6-yr cycles. Mean albedo can be obtained for a site by integrating over a whole cycle. Assuming that the 10-yr cycle represents current practices in the region, mean albedo of land in the crop–fallow cycle is seen to be 0.16. Factoring in a 5% forest cover at an albedo of 0.134, the regional albedo becomes 0.1587, reasonably close to the estimate of 0.1562 made on the basis of relative land cover (Table 7).

5. Conclusions

The radiative characteristics of deforested land in active use in Igarapé-Açu are significantly different from those of primary forest. Higher albedo and higher daytime surface temperature result in significantly lower R_{net} [see Eq. (1)]. This implies a reduction in turbulent energy transfer—that is, lower evaporation and sensible energy flux—and an increase in radiative transfer—that is, a larger fraction of incident solar radiation at the surface is disposed of by reflection and emission. Evaporative flux from young secondary vegetation at the same study area was estimated to be 1364 mm yr^{-1} (Hölscher 1995), within the range of estimates of annual evaporation for Amazonian primary forest (Lesack 1993; Leopoldo et al. 1982a, Leopoldo et al. 1982b; Shuttleworth 1988) and close to the average of the most reliable estimates of tropical lowland forest evaporation, 1430 mm yr^{-1} (Bruijnzeel 1990). However, because R_{net} is higher in eastern than central Amazonia, where primary forest evaporation estimates were made (probably due to differences in cloudiness), these evaporation estimates likely represent a reduction in the fraction of net radiation used for evaporation: evaporation accounted for only 80% of R_{net} over young secondary vegetation at Igarapé-Açu in comparison with 90% of R_{net} for central Amazonian primary forest evaporation (Hölscher 1995). These changes in the disposition of incident radiative energy are likely to have important effects on local and regional atmospheric processes.

Secondary vegetation is the most extensive land cover in deforested areas of the Amazon Basin. Albedo of emerging secondary vegetation declines with age from as high as 0.173 to a value indistinguishable from that of the original forest within about 10 yr. Despite the relatively small difference between forest and secondary vegetation albedo, significant disruptions of energy and mass fluxes are indicated by changes in net radiation and surface temperature. For actively used land surfaces, such effects on energy and mass exchange are large and highly variable in time and space.

The highest albedo of deforested surfaces in Igarapé-Açu was 0.176 for mature cassava, with typical values about 0.160 to 0.170 for secondary vegetation. This represents a smaller shift than is commonly used to represent effects of deforestation in GCM experiments. Lowering the expected albedo increase by 3 to 4 percentage points is very significant in that it represents a reduction of 15% to 20% in the amount of simulated shortwave energy reflection from deforested areas. The estimated trend in regional-mean albedo indicates that deforestation-related albedo increase will level at a value less than 0.03 above the original forest value. Dirmeyer and Shukla (1994) found that an albedo increase of at least 0.03 was required to bring about precipitation reduction in simulations of tropical deforestation. According to their model results, a basinwide albedo change similar to that suggested by the Igarapé-Açu

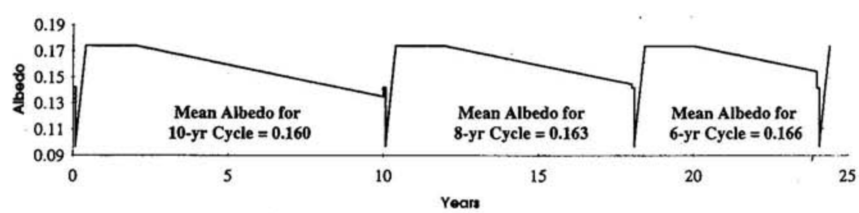

FIG. 3. Cycle of albedo for an actively farmed location in the eastern Amazon, based on a typical shifting cultivation pattern for small farms in the Igarapé-Açu region (see Table 8); 10-, 8-, and 6-yr cultivation cycles are shown to illustrate the effect of increasing land pressure on the regional-mean albedo; mean albedo is obtained by integrating the area under the curve for each cycle.

measurements would result in no significant change in regional precipitation.

Deforested land surfaces are represented in GCM deforestation experiments as uniform expanses of impoverished grassland. However, the dominant impression of the landscape in the Igarapé-Açu study area is one of great spatial diversity. Aggregation of surface properties necessary in GCMs is known to be a major source of uncertainty in model results. Failure to account for the effects of subgrid-scale landscape heterogeneity by prescribing a uniform deforested land cover may prevent future climatic impacts of deforestation from being predicted by the models. For example, mesoscale effects of land surface contrasts, as yet not treated in GCMs, have been shown to have significant influences on atmospheric dynamics (Anthes 1984; Yan and Anthes 1987; Segal et al. 1988; Giorgi 1989). Perhaps the focus of efforts to predict climatic impacts of deforestation should be on the effects of increasing land surface heterogeneity, rather than on a scenario of wholesale replacement of one homogenous surface by another.

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