A Semi-Empirical Model for Estimating Surface Albedo of Wetland Rice Field

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ABSTRACT

Surface albedo plays a vital role in the evapotranspiration component of the wetland rice water balance. This paper examines the influence of the phenological stages of rice (*Oriza sativa*) field on observed albedo at a tropical site (Ghana) during the year 2002, with a view to parametrizing a simple albedo model suitable for inclusion in models to estimate evapotranspiration in wetland rice cropping systems. Crop management was similar for the two planting dates used in this study. Measurements were taken from 10 m x 10 m plots within rice fields. Four phenological stages were distinguished: emergence, vegetative, flowering and physiological maturity. Surface albedo (α) was measured and simulated, using a calibrated semi-empirical model, at solar zenith angles of 15°, 30°, 45°, 60°, and 75°. Leaf area index (LAI) and crop height (h) were also monitored. Generally, albedo increases from emergence to flowering for both planting dates but slightly decreases after flowering. The correlation coefficient (r) between α and LAI equals 0.985 and the correlation coefficient between α and h equals 0.908. The composed albedo model adequately predicted the observed albedos with an overall $r = 0.946$ and mean bias error (*MBE*) of 0.002. The extinction coefficient of the rice crop albedo was estimated as 0.75. Data presented are valuable inputs in agricultural water management, rice production models, and especially as vital sub-routine inputs in calculating evaporation and transpiration from wetland rice.

Keywords: Surface albedo, rice field, regression model, water management, Ghana

1. INTRODUCTION

Rice, a staple food for rapidly growing population in sub-Saharan Africa, is the fourth most important cereal in terms of production (Rice Today, 2006). Rice grown on seasonally deep flooded areas is important in West Africa where rice is mostly grown under rainfed conditions. Wetland rice is the main water user in many developing countries (Jensen and Rahman, 1987). Irrigation engineers and water managers working in the West African countries need to have quantitative understanding of evaporation and transpiration of wetland rice system for efficient use of water resources and increased food production. The need of an evapotranspiration model for calculating water use and requirement at intervals of a few days, from early land preparation to harvest, has been advocated (Jensen and Rahman, 1987). However, net radiation and / or available energy, which largely depend on surface albedo, play a significant role in evapotranspiration in the tropics, especially when soil moisture is non-limiting making evaporation to be strongly correlated with available energy (Oguntunde, 2004). Furthermore, information on evapotranspiration is vital for estimating crop water requirement, planning of irrigation scheduling, irrigation systems design, hydrological and drainage studies and in the development of yield relations (Igbadun et al., 2006; Campos et al., 2003). The bulk of developed models to estimate this parameter, as found in the literature, are pointing to its relevance to many disciplines.

The albedo of a surface, defined as the fraction of incoming short-wave solar radiation (wavelength = 0.3-3.0 μm) that is reflected by the surface, is crucial in accounting for diverse physical, agronomic and biological processes including evaporation, photosynthesis and surface temperature changes (Yin, 1998; Giambelluca et al., 1999; Iziomon and Mayer, 2002). Errors in albedo directly lead to uncertainties in computed net radiation, energy fluxes and in simulated global surface temperature (Sellers et al., 1996; Yin, 1998). To overcome the limitation of using prescribed land-surface albedos in climate and hydrological simulations, models to account for the albedo variation caused by factors both internal to and external from the canopy are required.

Albedo tends to decrease with vegetation height and leaf wetness, whereas albedo increases with leaf area index (LAI) (Jacobs and van Pul, 1990; Cuf et al., 1995). Wind speed and direction have been shown to cause canopy re-inclination and hence lead to diurnal asymmetry in surface albedo, while dew could lead to a decrease in early morning albedo values (Song, 1998). The diurnal and seasonal courses of surface albedo have been studied, specifically for grasslands, forestlands, and crop fields (Pinker et al., 1980; Jacobs and van Pul, 1990; Song, 1999). From these studies, it appears that albedo is closely related to LAI and sun angle.

In situ albedo data, to aid research and modeling efforts by engineers and hydrologists, is not readily available in West African sub-region. Hence, field measurements were carried out to generate requisite albedo data especially at critical crop phenological or development stages during the growing season. The objective of this work was to investigate the effects of crop development and solar zenith angle on surface albedo in wetland rice production systems of West Africa. The paper also examines the prospect of parameterising a semi-empirical model useful in predicting wetland rice albedo and suitable for inclusion in models to estimate rice water use.

2. MATERIALS AND METHODS

2.1 Study Area

This study was conducted in Ejura, Ghana (Latitude 07° 20′ N, Longitude 01° 16′W). Ejura is a farming community with a population of about 200,000 people. Agricultural practices range from subsistence to large-scale commercial farming, maize, cowpea and rice being the main crops cultivated in this area. The climate is wet semi-equatorial with a long, bimodal, wet season lasting from April to October, which alternates with a relatively short dry season that lasts from November to March (Oguntunde et al., 2004). The vegetation type is derived transitional savannah. The major farming season begins in April and ends in July, while the minor season lasts from August to October. Mean annual rainfall and temperature, from 1973-1993, are 1264 mm and 26.6 ^{o}C, respectively (Adu and Mensah-Ansah, 1995). The geology of the study area is Voltaian Sandstone characterized by easily eroded flat-bedded sandstones, shales and mudstones. This has resulted in an almost flat and extensive plain between 60 and 300 meters above sea level (Dickson and Benneh, 1995).

2.2 Measurement Procedures

Measurements of albedo and other growth variables were carried out between the months of May and October 2002. One main plot per planting, measuring 10 m x 10 m in size was demarcated on farmers rice fields. Four mini-plots (3 m x 4 m) were further marked from the main plot for replication purposes. The four phenological stages distinguished (Table 1) were (1) emergence, (2) vegetative, (3) flowering and (4) maturity (Brouwer et al., 1989, Oguntunde, 2004). Incoming and reflected solar radiations were measured with a simple albedometer constructed from two pyranometers (model SP LITE, Kipp & Zonen, Delft, Netherlands) horizontally positioned about 1.5 m above the plant (canopy) surface. Leaf area index was measured with a SunScan canopy analysis system (Delta-T Devices, Cambridge, UK). Crop height (*h*), defined as the average of the heights from the ground to the top of the raised leaves of each plant, was measured non-destructively on six plants randomly sampled in each mini-plot. Surface albedo was measured at solar zenith angles of 15°, 30°, 45°, 60°, and 75° and the data used were generally for clear sky days. Measurements were made twice per growth stages on fields cropped during the first (6 May, 2002) and second (3 June, 2002) planting dates in 2002. Oryza sativa was planted on the flat by seeding at 10 cm by 20 cm. Manual weeding were used as necessary throughout the growing season and fertilizers were applied 2 and 8 weeks after planting (WAP). Similar crop management was maintained for both planting dates.

Table 1. Growth stages, description of phenological period and weeks after planting (WAP) when the measurements were taken in the rice fields

Growth stages	**Description of phenological stages**	**Measurements period**
Emergence or nursery	from sowing to transplanting; duration approximately one month.	3 WAP
Vegetative	from transplant to panicle initiation; duration varies from 1½ to 3 months. Vegetative stage includes the tillering.	8 WAP
Flowering or reproductive	from panicle initiation to flowering; duration approximately one month. This stage includes stem elongation, panicle extension and flowering.	12 WAP
Maturity or ripening	from flowering to full maturity; duration approximately one month.	14 WAP

Source: modified from Brouwer et al. (1989) and Oguntunde (2004).

2.3 Modeling of Surface Albedo

An existing albedo model was combined with empirical equations from the literature to simulate the rice fields' surface albedo at different phenological stages. Jensen and Rahman (1987) utilized the albedo model suggested by Uchijima (1976) in which the surface albedo (α) is given as:

$$\alpha = \alpha_c - (\alpha_c - \alpha_u)\exp(-\kappa L) \qquad (1)$$

where α_c is reflection coefficient of a fully developed crop canopy; α_u is reflection coefficient of the underlying soil surface; κ is extinction coefficient, and L is leaf area index.

The model above was developed for daily average albedo values and cannot be used to account for diurnal variations in the present form. Therefore, the parameters in the equation were estimated from other documented empirical relationships (Song, 1998; Ross, 1975; Monteith and Unsworth, 1990) in order to account for the diurnal dynamics of the overall surface albedo. Canopy albedo α_c is estimated as:

$$\alpha_c = f_c \alpha_{c\theta} + f_l \alpha_l \qquad (2)$$

where α_l is single leaf albedo, $\alpha_{c\theta}$ represents albedo of a semi-infinite canopy, f_c and f_l are weighting factors for canopy and single leaf, which are also dependent on leaf area index and solar zenith angle as follows:

$$f_l = \exp(-\beta L) \qquad (3)$$

$$f_c = 1 - f_l \qquad (4)$$

where β =0.5/cosθ (assuming spherical distribution of leaf angles) is the shadow area cast by a unit area of leaf that depends on zenith angle (θ). $\alpha_{c\theta}$ can be computed with two equations to account for the direct and the diffuse components of radiation. For the direct component, $\alpha_{c\theta 1}$ is computed as:

$$\alpha_{c\theta 1} = \frac{\beta\omega}{(\mu + \beta)(1 + \mu)} \qquad (5)$$

where ω is scattering coefficient (leaf transmissivity plus reflectivity coefficients) and $\mu=(1-\omega)^{1/2}$. The diffuse component, $\alpha_{c\theta 2}$, is computed by substituting β =1 in equation 5 (Song, 1998). $\alpha_{c\theta 1}$ and $\alpha_{c\theta 2}$ are substituted in Equation 2 in turn and the average α_c is used for the overall albedo computation (Equation 1).

The underlying soil albedo is also a variable parameter and is calculated as a function of soil wetness and the zenith angle of the sun according to

$$\alpha_u = \alpha_{uw} + \alpha_{u\theta} \qquad (6)$$

where α_{uw} represents effects of soil wetness and $\alpha_{u\theta}$ is a correction factor for albedo dependence on sun zenith angle (θ) and is defined as (Song, 1998):

$$\alpha_{u\theta} = 0.001\left[\exp\left(0.003358\theta^{1.5}\right) - 1\right] \qquad (7)$$

The shallow water albedo was measured and it ranged between 0.06 and 0.10 with average of 0.09. The average value was used in this model as the reflection coefficient of wet underlying surface.

The above equations were used to compute surface albedo at different sun angles and crop phenological stages. The mean values of the scattering coefficient used in equation (5) was $\omega=0.5$, and κ in equation (1) range from 0.3 to 1.5 (Ross, 1975), the higher value corresponding to large horizontal leaves and the lower values to vertical ones. A value of $\kappa = 0.56$, reported by Uchijima (1976), was used for the simulation initialization and, thereafter, optimized by minimizing the sum of the square of the residuals using the first planting data. Simulated albedo values, using the optimized parameters, were compared to observed albedo values from the independent second planting dataset. The goodness-of-fit statistics used in comparing the observed and the predicted values are correlation coefficient (r) and mean bias error (*MBE*). *MBE* quantifies the bias of the prediction and should be close to zero for unbiased predictions, while r explains the degree of associations between the observed and the simulated surface albedo. Correlation r ranges from 0 to 1 and the closer to unity the better.

3. RESULTS AND DISCUSSION

Average albedo values for five solar angles (five replicates), leaf area index (LAI) and crop heights (h) are presented in Table 2 for different phenological stages of rice fields during the first and second planting dates of 2002. Figure 1 shows the relationship between surface albedo and solar zenith angle in rice fields at Ejura, Ghana. There was an increase in albedo from emergence to flowering but slightly reduce at maturity. Albedo increased with mean LAI and h. LAI increased from 0.46 to 3.77 for the first planting and from 0.47 to 3.63 for the second. The values of α, LAI and h were not significantly different ($p>0.05$) for both plantings and during the corresponding growth stages. Both plantings showed similar trends of the measured parameters. The first and second planting data were therefore combined for mean comparison and least significant difference tests. From the analysis of variance (ANOVA), albedo values showed an overall significance ($p<0.01$) between the phenological groupings. This inter-comparison showed a very significant ($p<0.001$) difference between the emergence and other development stages. This implies that in the early stage of the crop growth, measured albedo during the emergence behaves similarly as bare soil since a large portion of the soil was exposed directly to solar radiation such that reflectance mainly influenced by soil optical properties and other soil surface conditions at the moment of measurement. The albedo of the crop fields changed considerably during the growing season. As the season progresses, the effects of the physical conditions of leaves and crop structures become more significant. This agrees with the findings of Ross (1975), Jacobs and van Pul (1990), Song (1998) and Oguntunde and van de Giesen (2004). The slightly lower albedo measured during the maturity, which appeared sharper for second planting date, may be due to senescence and change in leaf color, leading to lower leaf specular reflection. Moreso that the maturity stage for this planting occurred during the onset of dry season, leaves dryness becomes rapid compared to the first planting.

Table 2: Mean albedo values, leaf area index and crop height for rice fields during two planting dates in 2002

Phenological stage	Mean albedo (-)		Leaf area index (m^2 m^{-2})		Crop height (cm)	
	[a] 1st planting	2nd planting	1st planting	2nd planting	1st planting	2nd planting
Emergence	0.172±0.027	0.179±0.030	0.46±0.26	0.47±0.23	17.4±2.69	16.8±3.95
Vegetative	0.240±0.018	0.237±0.015	2.53±0.31	2.63±0.36	103.3±36.5	97.8±33.3
Flowering	0.247±0.016	0.246±0.016	3.77±0.57	3.63±0.33	121.7±22.5	112.7±40.0
Maturity	0.246±0.017	0.234±0.031	3.22±0.64	3.15±0.75	122.8±33.3	112.8±42.1

[a] 1st planting date is 6 May and 2nd planting date is 3 June, 2002.

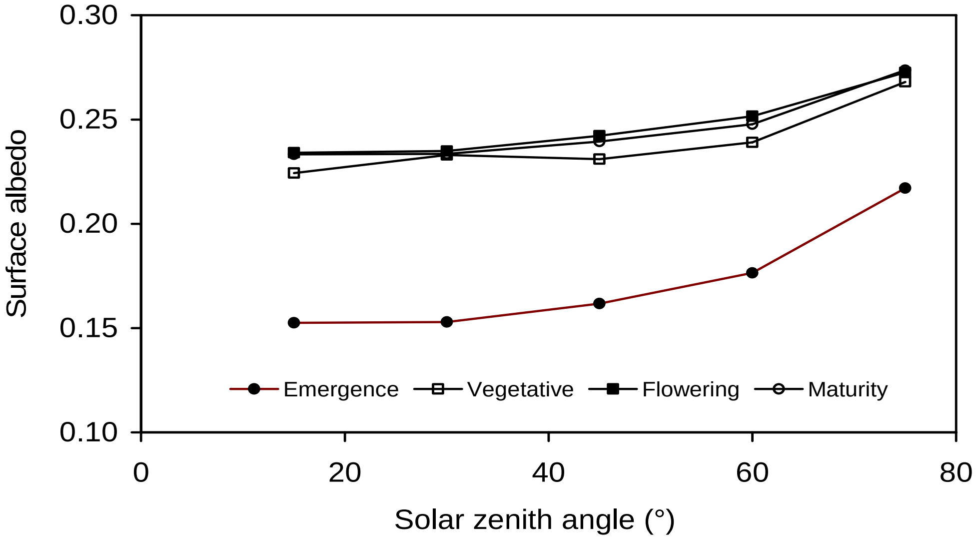

Figure 1. Variation of surface albedo with solar zenith angle in a rice field at Ejura, Ghana.

Paired comparisons between other groupings such as vegetative, flowering and maturity were not significant at the 5% level (Table 3). Correlating the albedo values with LAI and h shows the dependence of surface albedo on the crop phenology. The correlation coefficient between α and LAI equals 0.970, and between α and h equals 0.969. The result similar to that previous reported in maize and cowpea fields (e.g. Jacobs and van Pul, 1990; Oguntunde and van de Giesen, 2004)

Variations in observed and simulated albedo of rice field with solar zenith angle at different physiological stages are presented in Figure 2. Two goodness-of-fit statistics, correlation coefficient (r) and mean bias error (MBE) are presented in Table 3 for the comparison of model estimates and observed albedo values using first planting data. Correlation r varies between 0.953 for vegetative to 0.968 at physiological maturity and MBE ranges from –0.002 to 0.008. The negative sign indicates underprediction and the positive overprediction. The independent dataset for the second planting date was compared with the simulated values in Figure 3. The high value of r (0.946) obtained indicates the accuracy of the proposed model in predicting rice field albedo. Data points falling below the 1:1 line are the underestimated values while points above the line indicate overestimation.

The resulting κ, the extinction coefficient, was 0.75. Uchijima (1976) observed a κ value of 0.56 while Jensen and Rahman (1987) estimated a κ value of 0.62. Although these previous κ values were lower compared to the value in the present study, this value ($\kappa = 0.75$) is within the range reported by Ross (1975). Differences in variety and leaf architecture have been suggested as responsible for the observed variations in κ. In addition, previous albedo models mentioned above were for daily estimates while the diurnal dynamics of reflection coefficient were incorporated in the present study (model) making near real-time prediction possible. Furthermore, Jensen and Rahman (1987) introduced, successfully, a daily albedo model into an equation to estimate daily evapotranspiration in wetland rice. Thus, such ET models could be further improved to capture the diurnal dynamics using the model calibrated in this study.

Table 3. Multiple comparisons of mean albedo values at the four phenological stages

I	J	Md (IJ)	Sig.	Remark
1	2	-0.062	0.000	***
1	3	-0.071	0.000	***
1	4	-0.064	0.000	***
2	3	-0.009	0.359	ns
2	4	-0.002	0.859	ns
3	4	0.007	0.458	ns

Md(IJ) mean difference for I and J; I, J phenological stages (1= emergence, 2= vegetative, 3= flowering, and 4= maturity); Sig. is level of significance; *** mean difference is significant at the 0.001 level; ns mean difference is not significant at the 0.05 level

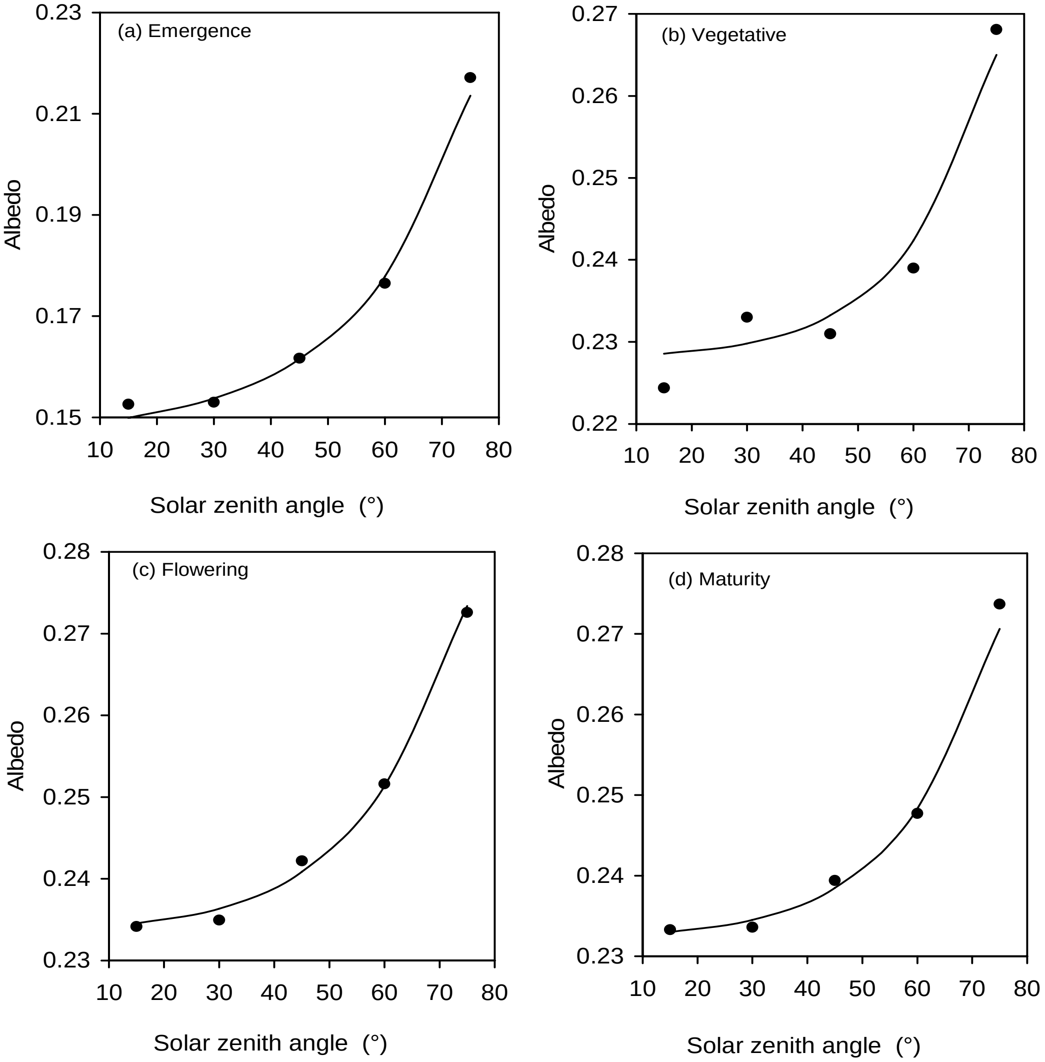

Figure 2. Observed (•) and simulated (-) albedo of rice field at different solar zenith angle and growth stages (a) Emergence (b) Vegetative, (c) Flowering, and (d) Maturity.

Table 4. Correlation coefficients (*r*) and mean bias error (*MBE*) to compare simulated and measured albedo values

Phenological Stages	Validation statistics	
	r	*MBE*
Emergence	0.967	0.008
Vegetative	0.953	-0.007
Flowering	0.968	-0.002
Maturity	0.968	0.006
Overall mean	0.964	0.001

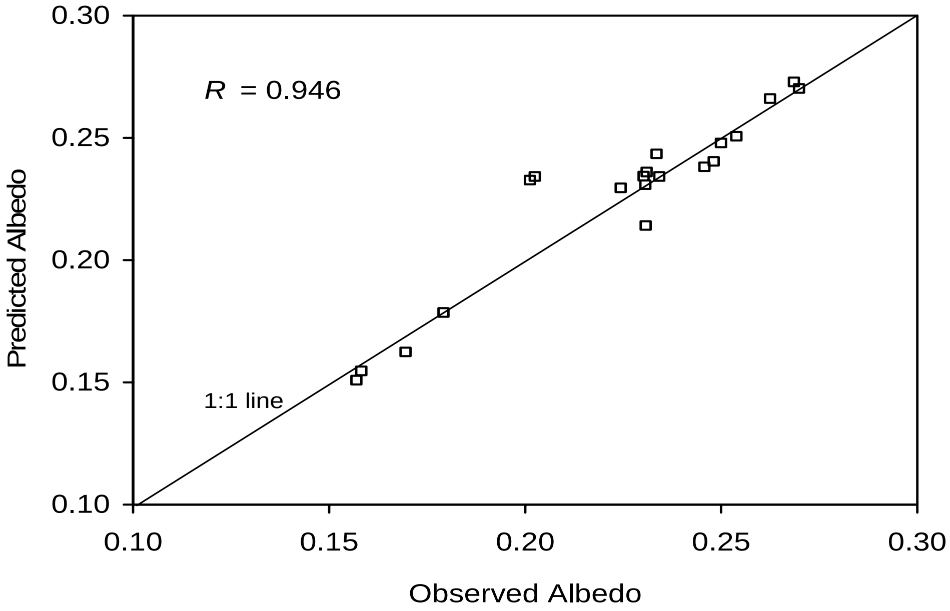

Figure 3. Comparison of the simulated and observed albedo values in rice field (second planting dataset).

4. CONCLUSION

Growth and development stages as well as solar zenith angle influence surface albedo of wetland rice field. Albedo increased up to the flowering stage and decreased thereafter. Albedo is positively correlated with both leaf area index and crop height. A simple model that could be used to simulate albedo values of wetland rice fields and account for the diurnal dynamics of the overall surface albedo was proposed, calibrated and validated. Data presented are expected to be a valuable input in crop water management and crop growth models especially for estimating ET, a very vital component of rice field water balance.

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