Soil Water Relations and Yields of Upland Crops in an Upland Crop-Wetland Rice Sequence[1/]

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ABSTRACT

Food production in the tropics can be increased by expanding crop culture during the dry season, but soil water is a major constraint. Soil water dynamics under four crops -- cowpea [*Vigna unguiculata* (L.) Walp.], mungbean (*Phaseolus aureus* L.), sorghum [*Sorghum bicolor* (L.) Moench], and soybean [*Glycine max* (L.) Merrill] -- and fallow in an upland crop-rice (*Oryza sativa* L.) system in the Philippines was measured to determine soil-water-plant relationships and evaluate crop performance. Hydraulic properties, profile water content, and rainfall infiltration of the Typic Haplaquoll soil were calculated to determine actual evapotranspiration under crop covers and bare soil. Water uptake by crops or evaporation from bare soil continued at soil moisture contents below the lower limits of availability. Their short growth duration enabled mungbean and soybean to escape severe water stress, whereas cowpea and sorghum encountered severe water stress during the reproductive phase

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when exhaustion of soil profile moisture wilted crops and drastically reduced yields. Identical water losses from soil profile were observed for fallow, mungbean and soybean, which extracted 20.56, 19.81 and 20.6 cm water, respectively. Evapotranspiration losses under cowpea and sorghum were 37.52 and 39.26 cm, respectively. We concluded that short season crops with low water demand can be grown during the tropical dry season if soil moisture supports crop establishment.

Additional index words: Cowpea, Mungbean, Sorghum, Soybean, Fallow, Multiple cropping, Evapotranspiration

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INTRODUCTION

Inadequate rainfall and high evaporative demand limit crop production under non-irrigated conditions during the dry season in much of the humid tropics. Crop growth under such situations is governed by soil physical properties and crops' rooting depth and moisture extraction characteristics.

Various attempts were made to approximate water dynamics of tropical soils. Soil water was simulated from weekly rainfall and potential evaporation data for fallow-crop rotation systems in subhumid to semiarid regions in Australia (Fitzpatrick and Nix, 1969). Hasegawa, Parao, and Yoshida (1979) compared water depletion by upland rice and evaporation loss from fallow plots. Angus et al. (1979) used soil moisture changes and rooting configurations to estimate profile water withdrawal by six upland crops and two rice cultivars in the Philippines during the dry season. They showed that cowpea, mungbean, and soybean yielded equally well under non-irrigated and irrigated conditions, whereas rice failed to yield without irrigation. Most investigations, however, ignored flux beyond the root zone and the contribution of capillary rise to profile moisture. About 35% of profile water loss under sorghum, for instance, was by flux from the root zone (Stone, Horton, and Hsiao, 1973).

Much of the difficulty in describing water behavior in the upland soil plant environment occurs because the water is transmitted through the soil under unsaturated conditions. The extreme complexity of unsaturated flow makes the process difficult to describe mathematically (Feddes, Kowalik, and Zaradny, 1978). Advances in approximating unsaturated flow processes over the last two decades, however, resulted in several models for describing water uptake by crop plants (Gardner, 1960; Molz and Remson, 1970; Feddes and Rijtema, 1972; van Bavel and Ahmed, 1976). Those models differ widely in complexity, precision, and applicability under actual field situations(Taylor, Klepper, and Rickman, 1979). Soil water movement and its spatial variability were extensively reported (Nielsen, Biggar, and Erh, 1973), but little attention was devoted to actual field conditions under crop cover (Stone et al., 1973; Molz, 1981).

Expanding crop culture during the dry season is one of the most feasible ways of increasing food production in the tropics (Syarifuddin, 1979). Because soil water is a major constraint of crop growth under those conditions, information on water behavior in the upland soil-plant environment is needed to achieve that goal. Objectives of studies reported here were to determine soil water dynamics under four upland crops and fallow soil and to evaluate crop performance under limited soil moisture conditions.

MATERIALS AND METHODS

A field experiment was conducted at the International Rice Research Institute (Philippines) during the dry season of 1980. The soil was Typic Haplaquoll, fine loamy, mixed, isohyperthermic, shallow (R. Brinkman, University of Wageningen, the Netherlands, personal communication) developed on parent materials from hardened tuff deposited by lahar (mudstream of volcanic materials). The Ap horizon extended down to 0.22 m and was clay loam with common fine faint dark brown mottle overlaid on a gravelly clay Bg horizon extending to 0.43 m. The R horizon from 0.43 to over 1.00 m was weathered rock, light yellowish brown with common fine grey mineral grains. The soil below one meter (3C horizon) was layered, coarse-sandy clay tuff-like unconsolidated material. The water table was not present within 3 m of the soil surface throughout the dry season.

Undisturbed soil cores were removed from the soil profile at 0.1-m intervals down to 1.6 m in two pits; at least 20 samples -- 10 vertical and 10 horizontal -- at each depth were used. Bulk densities of the upper soil layer were determined at the beginning and at the end of the experiment but bulk densities of layers below 0.20 m were only obtained at the beginning. The method of McIntyre and Loveday (1974) was used. The same samples were used to determine maximum water holding capacity and soil moisture characteristics by the pressure plate outflow technique (Richards, 1948). After they were removed from the pressure plate, the samples were air-dried, ground and sieved (<2.00 mm) to determine particle density (Blake, 1965). Other subsamples were used to determine saturated hydraulic conductivity (Klute, 1965) and subsequently dried and ground for particle size analysis (Day, 1965). Hydraulic conductivity as a function of soil water content, $K(\theta)$, at 0.2-m intervals down to 1.6 m, was determined in the laboratory by the hot air flow method described by Arya, Farrell, and Blake (1975).

The experiment was initiated in early January 1980. Four upland crops -- cowpea [*Vigna unguiculata* (L.) Walp. cv. 'EG-2'], mungbean (*Phaseolus aureus* L. cv. 'CES 55'), sorghum [*Sorghum bicolor* (L.) Moench cv. 'COSOR 3'], and soybean [*Glycine max* (L.) Merrill cv. 'TK-5'] -- were planted in 0.1-m-deep furrows containing fertilizer covered by soil granules to a 0.05-m depth (Syarifuddin, 1979). The seeds were dibbled over the soil cover by the side of the furrow. Legumes received 20 kg N and 30 kg P per ha and sorghum received 80 kg N and 30 kg P per ha; the fertilizer sources were ammonium sulfate and superphosphate. Soybean and mungbean seeds were inoculated before planting. Approximate plant populations were 2.5×10^5 and 2.0×10^5 per ha for beans and sorghum, respectively. Standard practices were followed for pest management.

The experiment was laid out in a randomized complete block design with the four upland crop species and a fallow plot as treatment variables replicated four times. The experimental plots of 11-m x 7-m dimensions were separated by 1-m-wide borders. Irrigation water (0.044 m) was applied for uniform germination after seeding and 0.06 m more water was applied 33 days after seedling emergence to alleviate a prolonged drought of several weeks duration. The crops received 0.172 m rainfall during the growing season (Figure 1).

One 0.05-m-diameter aluminum access tube was installed at the center of each plot and the bottom of the tube was sealed. Soil water contents ($m^3 m^{-3}$) were determined from 0.2 m to 1.6 m below the surface weekly throughout the growing season. A neutron moisture meter (CPN model 503) calibrated _in situ_ (Greacen and Hignett, 1979) was used. Soil moisture in the surface layer was determined gravimetrically (McGowan and Williams, 1980) because of unavoidable error in the neutron moisture meter at shallow depths.

The change in soil moisture content was described by a volumetric sink term (Molz and Remson, 1970; Feddes et al., 1978) added to the continuity equation,

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} - S \qquad (1)$$

where θ is soil moisture content in $m^3 m^{-3}$, t is time in days, q is vertical water flux in $m^3 m^{-2} S^{-1}$, and z is the depth coordinate downward. The quantity S in the righthand side of Equation (1) represents uptake of water by roots as a sink term (m^3 water m^{-3} soil S^{-1}) depending on soil moisture content, θ. Evapotranspiration loss was thus calculated by integrating the sink term over the depth of the profile

$$E = \int_{z=0}^{z=1.60} S\,dz \qquad (2)$$

Components of Equation (1) for each individual plot were determined by procedures described by Allmaras et al. (1975) and Willat and Taylor (1978). Changes in moisture content were plotted as a function of time, the quantity ∂θ/∂t being the slope of the curve. Assuming a unique relationship between pressure head and soil moisture content obtained from soil moisture characteristic curves (neglecting hysteresis effect) and obtaining K(θ) separately, the depth dependent gradient in soil moisture flux can be obtained by Equation (3).

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta)\,\frac{\partial H}{\partial z}\right) \qquad (3)$$

where K(θ) is hydraulic conductivity as a function of moisture content, θ, ∂H/∂z is hydraulic head gradient over depth, and hydraulic head H, is the sum of matric potential (ψ) and gravitational potential (z). Values of matric potential (ψ) were inferred from the measured moisture content for appropriate depth and time using the ψ(θ) relationship obtained from the desorption curve (Figure 1). Evaluated hydraulic head, H = ψ+z, was plotted against corresponding depth intervals each day to get ∂H/∂z. Negative values of ∂H/∂z corresponded to upward flux. Hydraulic conductivity functions, K(θ), were obtained separately and water flux (q) at different depth intervals was computed using K(θ) relationships. Flux values were plotted against corresponding depths and ∂q/∂z of Equation (3) was determined. The quantity S in Equation (1) was obtained and total water depletion was approximated by integrating the sink term over the profile (Equation 2).

The climate of the experimental area is hot humid tropics characterized by a distinct wet season with surplus water from June to November and a dry season with water deficits from January to May. Mean annual precipitation is 2.03 m (2.356 X 10^{-5} m S^{-1}), mean daily solar radiation is 1.7849 J m^{-2} S^{-1} (426 cal cm^{-2} d^{-1}), mean daily temperature is 302 K (29 C), and mean monthly open pan evaporation is 0.154 m (5.94 X 10^{-8} m S^{-1}) (Angus and Manalo, 1979). During the dry season from January to April, precipitation, solar radiation, open pan evaporation, and mean daily temperature are 1.16 X 10^{-8} m 3^{-1}, 232 J m^{-2} S^{-1}, 7.07 X 10^{-8} m S^{-1}, and 299 K, respectively.

Mungbeans and soybeans were harvested March 25, 1980. Cowpea and sorghum were harvested before they were completely mature April 12 because of hastened senescence due to droughty weather. Yields and dry matter production for each crop were obtained at maturity from an area 5.0 m^2 about 2 m away from the center of the plot previously demarcated as the harvest area.

RESULTS AND DISCUSSION

Physical characteristics and some hydraulic properties of the experimental soil are presented in Table 1. Bulk density, which ranged from 0.93 to 1.09 Mg m^{-3}, only slightly differed within the soil profile. It was lower in the soil layers from 0.4 to 1.0 m than in the other soil layers, which had identical bulk density values. The clay fraction decreased and silt content increased with increasing depth, whereas sand content changed little in the profile except in the top 0 to 0.2 m and intermediate 0.6 to 1.2 m layers. The high saturated soil moisture content, ranging from 0.54 to 0.69 m^3m^{-3}, likely was associated with the soil's longtime use for lowland rice before it was converted to upland crops (Croney and Coleman, 1954). Extremely low rates of saturated hydraulic conductivity (Table 1) were similarly attributed to structural degradation by wet puddling as well as to the clay and silty clay composition of the soil.

Soil moisture characteristic curves from 0.01 MPa to 1.5 MPa for different soil horizons were constructed from pressure plate outflow data (Figure 1). The highest moisture retention was in the 0.2 to 0.4 m soil layer. The top layer and the layers from 0.4 to 1.0 m and 1.2 to 1.6 m had nearly similar water retention. Low water retention in the 1.0 to 1.2 m layer was probably caused by the high fraction of silt and sand.

Estimating available soil water as the amount between field capacity and permanent wilting point, generally considered to be 0.03 MPa and 1.5 MPa, respectively, is of questionable value (Ritchie, 1981). Water withdrawal by transpiring plants is a function of root systems, soil hydraulic properties, and soil moisture and pressure characteristics (Hillel, 1971). Plants take up water above 0.01 MPa or field capacity (Lal, 1979) and soil is seldom isotropic; water retention under field conditions is largely regulated by underlying fine-texture soil of relatively low hydraulic conductivity (Hillel, 1971). Assuming the concept of 'available water' is valid and a root zone of 1.0 m, however, transmissible water content was within the neighborhood of 0.2 m. Available water should be less than 0.2 m for mungbean and soybean because their root systems hardly penetrated deeper than 0.8 m under similar conditions (Angus et al., 1979).

Most of the season's rainfall came as typhoons on two occasions (Figure 2). Efficiency of rainfall on crops depends primarily on the infiltration capacity (INCAP), which is determined by soil physical properties and soil moisture status, toposequence of the land, and crop cover (Hillel, 1977). A prolonged dry spell immediately preceding the second typhoon probably meant that rainfall infiltration from the second storm was equal to maximum infiltration capacity (MAXCAP). MAXCAP and intake rates over time were determined in a separate study (data not shown) and rainfall and other meteorological parameters were recorded on daily basis, but the duration and intensity of rainfall were not available. Assuming that the maximum daily rainfall duration during the dry season did not exceed 4 h and following procedures analogous to Berndt and White (1976), MAXCAP $\leq$ 0.04672 m. Based on those assumptions, it is probable that the effective rainfall on March 23 was 0.04672 m. But assuming rainfall duration 4 h and rain (R) > 0.04672 m, runoff (Q) can be calculated as

$$Q = R - I \tanh (R/I) \qquad (4)$$

where Q = runoff (10^{-3}m), R = rainfall (10^{-3} m), I = cumulative infiltration previously determined as a function of time, I = 11.8667 $t^{0.25}$, and t = time (min). Assuming a rainfall duration of 6 h and quantity of 0.0925 m March 23, over 0.04362 m rain was lost from runoff. In that case MAXCAP was $<$ 0.05 m. The rainfall was considered to be effective on other occasions when rain $<$ MAXCAP.

Periodic changes in profile soil water content under four different crops and fallow are compared in Figure 3. Loss of profile soil moisture in all plots was identical and mostly from the upper part of the profile at the beginning of the experiment. It is evident in Figure 3, however, that profile moisture content varied considerably at the beginning of the experiment. The fallow soil and that under cowpea had relatively uniform moisture contents in the beginning, but the upper layers of the profiles under sorghum and soybean had relatively low moisture contents. Initial differences in soil moisture were probably caused by spatial variation in soil structure or, more likely, by differential infiltration in soil layers or runoff.

Water extraction did not markedly vary among crop species or between cropped and fallow plots in the beginning. Five weeks after crop emergence, however, water content in the top soil layer (0 to 0.2 m) decreased to the permanent wilting point (Figure 3). The drying front subsequently advanced quite rapidly into deeper layers under sorghum and cowpea. Irrigation applied February 10 to prevent loss of the experiment and rainfall on February 13 greatly recharged the upper layers of the profile but did not saturate the soil or even restore moisture to levels at the beginning of the study. The profile moisture content apparently was adequate to supply the water demand of soybean and mungbean during reproductive stage or at least to forestall severe moisture stress. Subsequent prolonged drought lowered the top soil moisture content below the permanent wilting point for four to five weeks. Cowpea and sorghum relied heavily on water extracted from deeper soil layers and the drying front gradually extended to 1.2 m by the third week of March. Rapid rates of root extension (Angus et al., 1979) enabled cowpea to exhaust nearly all the available water from the profile before the second typhoon March 23. However, water withdrawal diminished to such an extent that cowpea showed clear symptoms of wilting before the second typhoon. Wilting was probably caused by death of inactivation of roots from soil moisture deficits. It is unlikely that the roots penetrated the hardened tuff below 1.0 m (R. Brinkman, personal communication).

Because root growth in the lower and upper soil layers is independent (Portas and Taylor, 1976), growth likely continued until moisture extraction from the lower layers was complete. When that happened, root activity was disrupted and the plants eventually senesced.

Sorghum had a pattern of water extraction similar to that of cowpea but did not show wilting symptoms until late March. The crop experienced severe moisture stress during booting and flowering stages and the subesquent rain failed to stimulate growth. The plants started wilting approximately two weeks after the rain, although soil moisture in all except the top of the root zone was at or above field capacity. The severe moisture stress apparently caused blasting and poor head filling (Vanderlip, 1979) and hastened senescence of the plants.

Soil moisture uptake by plants or evaporation from the soil surface apparently continued, albeit at diminishing rates, at moisture contents below the lower limits of availability (Figure 3). Those results agreed with Angus et al. (1980), who showed that the volume of extracted water below 1.5 MPa tension by wheat was sufficient to keep the crop alive.

Soil water flux through the root zone layers is illustrated in Figure 4. Initial soil moisture together with irrigation water caused internal drainage which continued throughout January in all plots (negative Y axis). Drainage and flux rates varied considerably, perhaps due to differences in starting soil moisture and uptake by crops, but the trend reversed by mid-February except under mungbean and fallow. Soil layers 1.6 m below the surface apparently contributed to recharging the root zone, at least under sorghum and cowpea, even in the absence of a phreatic level in the bottom layer. In contrast, downward water flux continued under fallow until mid-March (Figure 4) and reversal of the trend did not markedly alter the profile moisture status. Upward soil water flux through the 1.2 to 1.6 m layer reached a maximum of about 9.26×10^{-8} m s^{-1} under sorghum 66 days after emergence March 14 and gradually diminished to 1.16×10^{-8} m s^{-1} April 12. Maximum upward flux of 1.97×10^{-8} m s^{-1} under cowpea occurred March 14 and the value declined to below detectable limits by April 1. Upward flux under the other treatments was negligible. Considerable upward flux into the root zone was also reported by van Bavel et al. (1968) and Stone et al. (1973) for sorghum and by Willat and Taylor (1978) for soybeans.

Potential evapotranspiration rates for individual crops were determined following Doorenbos and Kassam (1979). Reference evapotranspiration (ETo) was computed for each 10-day period using standard open pan evaporation and pan coefficient. Crop coefficients (Kc) for each crop at different growth stages were selected from the values given by Doorenbos and Kassam (1979). Potential evapotranspiration values were taken as the product of ETo and Kc. Actual evapotranspiration (ETa) under crop cover calculated from profile moisture loss minus downward flux (Figure 4) was compared with potential evapotranspiration (ETp).

Runoff was considered negligibly small except on two occasions when rainfall exceeded MAXCAP as described earlier and horizontal flow below the soil surface was considered nonexistent. Cumulative evapotranspiration for different cropping systems against time is plotted in Figure 5 and should be viewed in conjunction with Figures 3 and 4. The surface soil was never saturated except briefly during irrigation or heavy downpours. Therefore, the evaporation rate never equalled potential evaporation and hence was limited by soil profile hydraulics, not by evaporativity (Hillel, 1977). At early stage, when crop cover was too sparse to influence evaporation or surface drying, water loss was largely due to evaporation as reflected by almost uniform evapotranspiration rates under different treatments until mid-February.

Two distinctly different trends in evapotranspiration developed after late February: rates from cowpea and sorghum exceeded rates from soybean and mungbean, which did not differ markedly in actual evapotranspiration (ETa) from fallow plots. Soybean and mungbean were similar to fallow because fallow plots had higher evaporation loss immediately after rainfall or irrigation probably because of surface crust and higher runoff which caused overestimation of evaporation loss. Soybean and mungbean extracted 0.21 m and 0.20 m of water, respectively, from the root zone compared to 0.21 m evaporation loss under fallow till March 25. Total water uptake recorded for cowpea and sorghum at harvest (April 12) was 0.38 m and 0.39 m, respectively.

The ratio ETa/ETp, an index of water deficits, is plotted against time for different crops for a selected period in Figure 6. Figures 3 and 6 reveal that actual ET ratio was a function of relative water content in the profile and declined progressively with depletion of profile soil moisture. Cowpea, however, maintained vigorous growth until flowering. Severe water deficits indicated by the ETa/ETp ratio 0.30 restricted pod formation and development and caused early senescence and poor yields of cowpea. The results compared favorably with those of Labanauskas, House, and Stolzy (1981), who found yields of field-grown cowpea decreased 67% when the crop was subjected to moisture stress during flowering and pod filling stages.

Total water use and water use efficiencies of four different crop species are given in Table 2. Sorghum and cowpea used more water than the other crops because of their longer growth duration and water extraction from deeper layers. The high biomass production of sorghum, however, caused it to have the greatest water use efficiency, whereas the low economic yield greatly decreased water use efficiency of sorghum. The dichotomy likely was caused by the moisture stress the crops encountered during the reproductive stage. Results reported here and earlier (Angus et al., 1979; Hasegawa et al., 1979) indicated that short season crops with low water demand like mungbean and soybean can be grown during the tropical dry season provided soil moisture supports crop establishment. The findings are based on one season's field experiments, however, and need revalidation before firm conclusions can be drawn.

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Table 1. Physical characteristics and hydraulic properties of the experimental soil profile used for upland crops at IRRI, Philippines, during 1980.

Soil depth	Bulk density	Particle size analysis Clay	Silt	Sand	Saturated moisture content	Saturated hydraulic conductivity
m	Mg m^{-3}	------ % ------			m^3m^{-3}	m s^{-1}
0.0-0.2	1.09*	46	14	40	0.59	2.48×10^{-7}
0.2-0.4	1.08	55	20	25	0.64	3.50×10^{-8}
0.4-0.6	0.97	19	54	27	0.63	1.44×10^{-7}
0.6-1.0	0.93	11	53	36	0.69	1.47×10^{-7}
1.0-1.2	1.06	13	49	38	0.54	2.39×10^{-7}
1.2-1.6	1.08	19	60	21	0.62	1.99×10^{-7}

*Bulk density values shown for surface soil were obtained at the beginning of the experiment. Values for the subsequent samplings are not shown here.

Table 2. Dry matter production, yield, water uptake, and water use efficiencies for four upland crops at IRRI, Philippines, during 1980.

Crop species	Total ET_a	Total DM at maturity	Ratio DM/ET_a	Economic yield	Ratio $yield/ET_a$
	m	$g\ m^{-2}$	$g\ m^{-2}m^{-1}$	$g\ m^{-2}$	$g\ m^{-2}m^{-1}$
Cowpea	0.375	340	907	130[1/]	347
Mungbean	0.198	124	626	73	369
Sorghum	0.393	635	1 616	154	392
Soybean	0.206	220	1 068	108	524

[1/] Yield of cowpea was taken as green pod weight.

Figure 1. Moisture retention curves of undisturbed samples of the experimental soil profile used for upland crops at IRRI, Philippines, during 1980.

Figure 2. Rainfall, open pan evaporation, solar radiation, relative humidity and temperature during the growing season of upland crops at IRRI, Philippines, during 1980.

Figure 3. Successive soil water content profiles for cropped and fallow plots at IRRI, Philippines, during 1980.

Figure 4. Soil water fluxes at four depths under four upland crops and fallow at IRRI, Philippines, during 1980.

Figure 5. Cumulative evaporation/evapotranspiration loss by four upland crops and fallow at IRRI, Philippines, during 1980.

Figure 6. Potential and actual evapotranspiration functions for four upland crops at IRRI, Philippines, during 1980.