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EVAPOTRANSPIRATION FROM RICE FIELDS[1]

ABSTRACT

Evapotranspiration is a major factor affecting dry matter production, and hence, the agricultural production potential of a given region. Realistic evapotranspiration estimates are important to irrigation engineers, agronomists, and others involved in agricultural planning.

This paper deals with the recognition and description of evapotranspiration as a complex process affected primarily by climatic conditions. The literature and basic principles affecting transpiration, evapotranspiration, and the ratio of actual evapotranspiration to open-pan evaporation (ET-EP) in wetland rice culture of South and Southeast Asia are reviewed.

Large differences in daily as well as seasonal total transpiration and evapotranspiration values exist for various locations in South and Southeast Asia. Crop transpiration rate is low at the early stage of growth and increases almost linearly reaching 3-4 mm/day at maximum tiller number stage and 5-7 mm/day at heading time. Evapotranspiration also follows a similar trend for maximum rate. The seasonal average evapotranspiration in wetland rice fields is in the range of 4-7 mm/day. Evapotranspiration appears to vary with crop growth stage. The value of crop growth coefficient factor (ET-EP) is 1 at transplanting, reaching about 1.1 at maximum tiller number stage and about 1.2 or higher at flowering stage. A 1.15-1.2 ratio with pan evaporation can be used to estimate ET for a crop season. From this review of physical and empirical information a simple model is suggested to predict evapotranspiration from wetland rice.

The reader should be aware of the difficulty of interpreting the voluminous literature on the subject because of the interaction of varying seasonal climatic patterns (tropical monsoon or wet season, tropical dry season, temperate wet season), crop canopy development rates, and potential experimental and technical errors.

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EVAPOTRANSPIRATION FROM RICE FIELDS

Evaporation from soil and plant surfaces is a primary component of the energy exchange function determining the production potential of crop species and the distribution of natural vegetation. It is highly correlated with net productivity. Leith (1976) illustrates the global relationship between evapotranspiration and dry matter production.

Although abundant data have accumulated on evapotranspiration at different places in rice growing countries and the sciences of soil physics, plant physiology, and micrometeorology are becoming increasingly exact and quantitative, misunderstanding and misconceptions still abound. Accurate measurement, or estimation, of evapotranspiration will aid in:

- engineering, design, and management of irrigation facilities;
- developing sound practices by irrigation agronomists;
- determining the water balance of rainfed rice and estimating supplementary irrigation or water conservation goals to meet the crop's water requirement;
- evaluating cropping patterns' suitability based on the water balance estimate for a particular area, and
- classifying rice environments where genetic and agronomic technology may be transferable.

We review available information on evapotranspiration from the rice crop in South and Southeast Asia and discuss a simple and reasonably accurate method of computing evapotranspiration from wetland rice fields.

PHYSICS OF EVAPORATION FROM CROP COMMUNITIES

Growth and yield of the rice crop depend greatly on the water status and temperature of the plants, parameters largely governed by complex interactions between the energy and water balance in the environment. A large fraction of the solar radiation received on a crop area is used in the evaporation of water from plant and soil or water surfaces (Fig. 1).

Evaporation is the physical process by which a liquid or solid is transferred to the gaseous state. The evaporation of water that has passed through the plant is called *transpiration* (T). When evaporation from soil or water surfaces and transpiration occur simultaneously the term *evapotranspiration* (ET) describes the combined processes. Evapotranspiration provides an efficient mechanism for the dissipation of heat. We, therefore, first discuss heat and mass transfer in plant communities.

Energy balance

The crop and its immediate environment are coupled through the flow of energy. Radiation received by the crop canopy is dissipated by reradiation, convection, and transpiration. All radiant energy absorbed by a leaf must be accounted for and hence, the energy budget for a plant leaf must balance.

$$R_n = LE + H + G + P + M \qquad (1)$$

where R_n is the net radiation flux, LE is the flux of latent heat (L is the latent heat of vaporization and E is the quantity of water evaporated), H is the sensible heat flux above the surface, and G is the soil heat flux. P represents photosynthesis and M, miscellaneous exchanges. The sum of P and M is usually smaller than the experimental error in the measurement of major components; therefore, in an energy balance equation P and M can be ignored. Thus, Equation 1 will become

$$R_n = LE + H + G \qquad (2)$$

Equation 2 can adequately describe the energy budget of the plant community. Suomi and Tanner (1958), using this energy balance equation and the Bowen ratio $\beta = \frac{H}{LE}$ developed by Bowen (1926), solved for LE as follows:

$$Le = \frac{R_n - G}{1 + \beta} \qquad (3)$$

The greater the value of β the more energy lost as sensible heat transfer. If it is at or near zero, the energy budget reduces to

$$LE = R_n - G$$

or in certain conditions, when heat is drawn from air providing a second source of energy (advection) for evaporation, the value of β may be negative and

$$LE > R_n - G$$

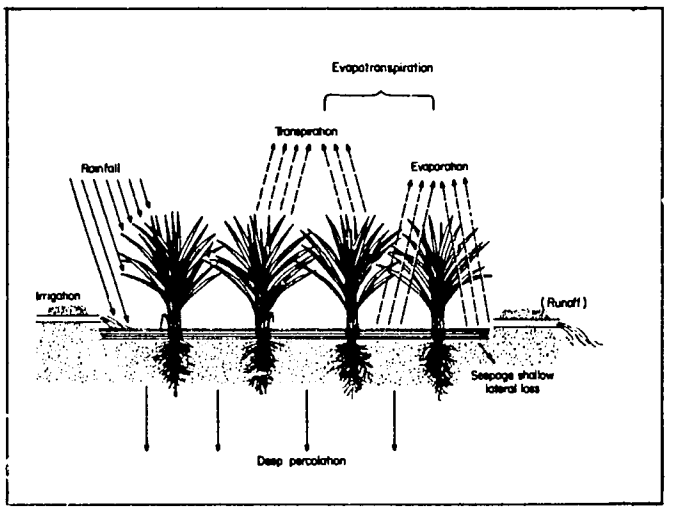


Fig. 1. Water balance in a wetland rice field.

The advection of sensible heat may be of great importance in rice fields in subhumid and arid regions. Lang et al (1974) suggested that the evapotranspiration due to advection, Et_{adv}, can be determined by subtracting the calculated equilibrium evapotranspiration from measured ET. The equilibrium evapotranspiration, ET_{eq}, is calculated as (Priestley and Taylor 1972)

$$ET_{eq} = \frac{1.26}{L} \left(\frac{s}{s + \gamma}\right) (R_n - G) \qquad (4)$$

where s is the slope of the saturated vapor pressure curve for water and γ the psychrometric constant, so that $s/(s + \gamma)$ is a function of the surface temperature.

Penman (1956) defined potential transpiration as "the amount of water transpired in unit time by a short green crop, completely shading the ground of uniform height and never short of water." Potential evaporation is normally considered to include both plant and soil evaporation. A more detailed discussion of the energy exchange process in the crop community follows.

Transpiration

Diffusion of water molecules out of the leaf -- the rate of transpiration E in g/cm^2 per sec -- is described analytically as

$$E = \frac{d_1^s (T_1) - rh \cdot d_a^s (T_a)}{r_1 + r_a} \qquad (5)$$

where $d_1^s (T_1)$ is the saturation water vapor density in the leaf and $d_a^s (T_a)$ is the saturation water vapor density in the air. They are each a function of the temperature, and rh is relative humidity. The diffusion pathway from the wet mesophyll cell walls within the leaf through the substomatal cavities and stomatal aperture to the leaf surface offers a resistance r_1 to the flow of water vapor molecules, and a boundary layer of viscous air adhering to the leaf surface offers an additional boundary layer resistance (r_a) to diffusion. The rice leaf's diffusive resistance (r_1) varies enormously from some minimum value such as 0.5 s/cm when the stomata are fully open to a maximum value of about 50 s/cm or even larger when the stomata are closed (Cruz and O'Toole 1978). The leaf resistance must be considered a dynamic quantity that, for a given leaf, may change constantly with environmental conditions -- light intensity, relative humidity, leaf temperature, leaf-water potential, and other factors.

The quantity of r_a also varies constantly with environmental conditions. Across the boundary layer, there are gradients of temperature, moisture, carbon dioxide, oxygen, and wind speed. The boundary layer is both laminar and turbulent depending on the wind conditions. The thickness of the boundary layer increases with leaf size and decreases with wind speed. The resistance to the water vapor diffusion r_a in crop communities of narrow leaves, such as those of rice, is described (Cowan and Milthorpe 1968) as

$$r_a = 1.3 \sqrt{\frac{W}{V}} \qquad (6)$$

where W is leaf width (cm) and V is wind speed (cm/s). From Equations 5 and 6, one can write

$$E = \frac{d_1^s (T_1) - rh \cdot d_a^s (T_a)}{r_1 + 1.3 \sqrt{\frac{W}{V}}} \qquad (7)$$

Equation 7 contains all environmental and plant factors that affect the rate of water loss from the plant leaf. At each specific leaf temperature, a leaf will have a particular transpiration rate dependent on its resistance and leaf size.

Using the energy balance concept (Equation 2), Blad and Rosenberg (1974) suggested a simple resistance model for the estimation of evaporation from large areas. Besides measuring R_n and G directly, they calculated sensible heat transfer, H, from the difference in crop canopy and air temperatures and by inferring r_a from wind speed information.

Leaf temperature and transpiration

Convection will change leaf temperature depending on air temperature. The transpiration rate depends on the amount of energy available after the net radiation is shared with convection. Hence, from Equation 2, considering the net soil heat flux to be negligible, one can write

$$L(T_1)E = R_n - H \qquad (8)$$

where $L(T_1)$ is the latent heat of water that is a function of leaf temperature (580 cal/g at 30°C). The convection term can be written as

$$H = K_1 \left(\frac{V}{D}\right) (T_1 - T_a) \qquad (9)$$

where K_1 is a constant that varies from about 10 to 16 x 10^{-3} and is such that with V in cm/s, D (leaf dimension in the direction of the wind) in cm, $T_1 - T_a$ in °C, the convection term is in cal/cm^2 per minute (Gates 1968, 1976).

If $T_1 > T_a$ in Equation 9 then an amount of energy less than R_n is available for the evaporation of liquid water to vapor. If $T_1 < T_a$, then the convection term is negative, heat is added to the leaf, and more energy is available for evaporation.

ESTIMATION OF EVAPOTRANSPIRATION

The estimation of actual and potential ET has wide utility and has been the subject of extensive research. However, it is recognized that available methods for measuring ET differ in short- and long-term accuracy and in convenience and cost. Thus, the choice of method depends on application.

The most commonly used methods are hydrologic (water balance, lysimetry), micrometeorological (mass transport, aerodynamic, eddy correlation, Bowen-ratio energy balance, resistance approach), and empirical. The most accurate is lysimetry which unfortunately is also an expensive method.

When determining ET from crops, the meteorological factors governing the process, as well as factors related to crop development and soil conditions, must be considered. To simplify the methodology, researchers have determined the crop coefficient factor (K_c) as a function of growth from the relationship: K_c = ET crop/ET_o, where ET_o is the reference crop evapotranspiration that covers the effect of meteorological factors. Some researchers have used open pan evaporation (EP) in place of ET_o to determine K_c. The Food and Agriculture Organization (Doorenbos and Pruitt 1977) recommends four methods of estimating ET_o: Blaney-criddle, radiation, Penman, and pan evaporation. But here we refer to EP to estimate K_c. Thus, under a given soil condition, if K_c is known, ET can be estimated from available meteorological data. The accuracy of this approach, however, strongly depends on knowledge of the effect of meteorological, plant physiological, and soil physical factors on ET.

As mentioned earlier, the energy balance equation can be used to derive precise estimates of ET. Here we discuss a simple form of energy balance equation (3) used to approximate ET from wetland paddy. The Research Group of Evapotranspiration (RGE 1967) reported that for the whole rice season, measured values of open pan evaporation (EP) are equivalent to net radiation.

$$EP = \frac{R_n}{L} = 0.0017\ R_n\ (\text{cm t}^{-1})$$

$$= 0.017\ R_n\ (\text{mm t}^{-1}) \qquad (10)$$

where R_n is the net radiation in cal/cm^2, L is the heat of vaporization of water (580 cal/g at 30°C), and t is the unit time for which R_n is considered. Continuous measurements of R_n of a paddy during the whole rice-growing period indicate that the ratio of R_n to total incoming solar radiation (R_s) varies from 0.70 at the early stage of growth to 0.55 at the ripening period with a mean value of 0.62 (RGE 1967).

$$R_n = 0.62\ Rs \qquad (11)$$

Thus, from Equations 10 and 11, and Rs in units of cal/cm^2 over a period t

$$EP = 0.017 \times 0.62\ Rs$$

$$= 0.01054\ Rs\ (\text{mm t}^{-1}) \qquad (12)$$

At IRRI, De Datta et al (1974) showed the following relationship between EP and Rs for the wet and dry seasons.

$$EP = 0.7546 + 0.0096\ Rs \qquad (13)$$

Equations 12 and 13 are about the same. From these equations, and the relationship between ET and EP, approximations of ET can be made.

EVAPOTRANSPIRATION STUDIES IN SOME ASIAN COUNTRIES

Irrigation systems were in use in ancient times. Basin irrigation was introduced in Egypt more than 5,000 years ago and *Atharva-veda*, the ancient Hindu scripture, describes canal and tank construction (Gulhati and Smith 1967). But an appreciation of the association between evapotranspiration and crop productivity and the start of research on that fundamental process are recent.

Transpiration and evapotranspiration

Reports on T and ET of rice are available for many countries and seasons. In Figures 2-5 examples of these reports illustrate the seasonal and growth-stage-dependent progression of T and ET.

Transpiration generally increases linearly from the early stage of growth, approaches 3-4 mm/day at the maximum tiller number stage, and attains a high value of 4-7 mm/day at heading time.

In Malaysia, a first peak of transpiration rate 3.5 mm/day is shown at the maximum tiller number

stage and the second, 5.5 mm/day, at heading (Fig. 2). However, at many locations in Thailand (Fig. 3), India (Fig. 4), and Japan (Fig. 5), transpiration rate increases consistently up to the heading stage and then declines. Its maximum value appears at about the heading stage. Deviations from this general trend have also been reported. For example, during the wet season in Thailand maximum transpiration was reported at the tillering stage followed by an almost constant but lower rate (Kung 1965). In general, transpiration rate increases with growth, reaches a maximum value at heading stage, and then declines.

Evapotranspiration follows a trend similar to that of T. In the *tarai* area at Pantnagar, India, ET values for IR8, which were around 4 mm/day in the beginning, have been reported to be 10-12 mm/day during 50 to 70 days after transplanting (DT) (G. B. Pantnagar University of Agriculture and Technology 1977). The slope of the curve relating ET to DT, however, may differ considerably depending on plant growth rate and atmospheric conditions. In addition, at certain locations, ET rate fluctuates in a short range over the season without following a definite trend (Fig. 5). Large variation in ET rate, which may be caused by atmospheric conditions, may also come from faulty methods of measurements and the contribution of unreported advective energy.

Daily transpiration and ET data for many countries are summarized in Table 1. The amount of transpiration, averaged over the season, varies from as low as 1.2 mm/day in Yunnan, China, to as high as 9.4 mm/day in Kushtia, Bangladesh. Normally transpiration rates range between 3 and 4.5 mm/day. Similarly, there is a great range of variation in ET depending on season, location, and presumably experimental methods.

Average ET values for the crop season range from as low as 4.4 mm/day in Kwantung, China; Orissa, India; and IRRI, Philippines, to as high as 14.3 mm/day in Kushtia, Bangladesh.

In general, the daily average ET in the tropics is about 5.0-7.0 mm, which is higher than temperate zone values of 4.4-5.5 mm in Japan and 4.2 mm in Korea. During the wet season, ET >5.5 mm/day is observed in Malaysia, southern Vietnam, Cambodia, and some parts of Thailand, India, Indonesia, China, northern Taiwan, and Kyushu district in Japan (Fig. 6). Generally, the values of ET throughout the temperate, subtropical, and tropical zones range from 4 to 6.5 mm/day. These values, however, are expected to vary depending on such location-specific factors as seasonal climatic interaction and varietal or cultural differences.

Seasonal variation in evapotranspiration

When a wet-season cultivation is compared with dry-season cultivation, daily, as well as total, transpiration and ET are higher in the dry than in the wet season. From available data (Table 1), it appears that daily ET is about 25% higher in the dry than in the wet season. However, little or no difference in transpiration and ET rates was reported at certain places in these two seasons (Figs. 2 and 4). These rates are primarily affected by climate and attain a maximum value when atmospheric evaporative demand is high such as a period from late July to mid-August in Japan (Fig. 5).

Water balance studies in farmers' fields in the Philippines have shown an average ET rate of 10.4 mm/day in the wet season and 11.6 mm/day in the dry (Alfonso and Catambay 1948). In those studies, however, seepage and percolation losses were considered negligible, which may not be true (Wickham and Singh 1978). Irrigation experiments at the University of the Philippines at Los Baños (UPLB), Philippines, have shown an average ET rate of 6.9 mm/day in the wet and 8.8 mm/day in the late dry and early wet seasons (Aglibut et al 1957). Lysimeter experiments at IRRI have shown ET rates of 6.2 mm/day (range 4.8 to 10.6 mm/day) during the dry season and 5.0 mm/day (range 1.9 to 7.8 mm/day) during the wet (Caoili 1963, IRRI 1963, Johnson 1963). However, Kampen (1970) estimated somewhat lower ET rates, which were 4.4 mm/day for the wet season and 5.5 mm/day for the dry. Although ET rate differed considerably, on the average it was in the range of 4 to 6 mm/day and was generally higher in the dry season.

Varietal differences in evapotranspiration

Irrigation experiments at UPLB have shown differences in evapotranspiration for Milfor 6-2 (av ET rate of 5.9 mm/day) and Tjeremas varieties (av of 6.9 mm/day) (Aglibut et al 1957). In our 1978 dry-season experiment at IRRI, transpiration and ET rates were higher for IR36 than for IR20, Ml-48, and Dular. It should be noted, however, that the leaf area index of IR36 was considerably higher than those of the other varieties. Sugimoto (1971), however, did not get any difference in daily average transpiration and ET among IR8 (Ria), a sister line of IR20 (Bahagia), and Radin Ebos-33. There are no sufficient data to show varietal differences in transpiration and ET rates. But a positive relationship is recognized between growth duration after transplanting and each cumulative value (Table 2) (Sugimoto 1971, Yadav 1973).

Relationship between evapotranspiration and pan evaporation

In several countries U.S. Weather Bureau Class A pan or sunken pan (installed in rice field) data have been correlated with actually measured evapotranspiration. Evaporation pans provide a measurement that integrates the effect of solar radiation, wind, temperature, and humidity on evaporation from a specific open-water surface. To eliminate the effect of these meteorological factors, the values of E, transpiration, and ET have been divided by the value of EP. These ratios can then be used to compare the difference between varieties, cropping seasons, and latitudes.

The ET-EP ratio may be used to determine water requirement of rice as ET from open-pan data if a satisfactory empirical relationship can be established over a crop season. Figure 7 shows, for exam-

ple, where the E-EP ratio in both wet and dry seasons decreases gradually from about 0.8 at transplanting to 0.5 at heading and to 0.2-0.3 at maturity. The variation is related to the change in water surface area shaded by growing plants. The transpiration ratio (T-EP) rises continuously after transplanting and attains a value of about 0.8 to 0.7 around the maximum tiller number stage. Then after about a 20-day period of little change, it shows the maximum value of 0.8 to 0.9 just after heading time and rapidly declines to about 0.5 at maturity (Sugimoto 1971). The occurrence of a bimodal relationship for the T-EP and ET-EP ratios (around maximum tillering and heading stages) has been reported in Malaysia by Sugimoto (1971) and Nishio (1972), in Thailand by Kung et al (1965), and in Laos by Kotter (1968). However, Murakami (1966) reported a monomodal pattern in Sri Lanka with the single peak at heading as did Pande and Mitra (1971) in India. For temperate countries like Japan, it is not evident whether the transpiration ratio shows a mono- or bimodal curve.

Our review of the ET-EP ratio also shows a growth stage relationship. Although the absolute values are variable it is interesting to note that this ratio is almost always greater than 1.0 but rarely exceeds 1.0 in irrigated dryland crops.

The ET-EP ratio in rice starts from around 1.0 after the transplanting, shows a first peak (1.1 to 1.3) at the maximum tillering stage, and a maximum value at around heading stage. The value at heading time became 1.4-1.5 in Malaysia (Fig. 7) and 1.7 in the Philippines (Krupp, IRRI, 1969, unpublished). On the average, for tropical countries this value is 1.43, for temperate (Japan) 1.33, and for Australia (Evans 1971) 1.37 (Fig. 8). Thus, on the average, this ratio is 1.0 at the time of transplanting, reaches 1.15 after 15-20 days, and attains a maximum of 1.3-1.4 at about heading.

The daily average of ET-EP in monsoonal Asian countries ranges from 1.1 to 1.6 (Table 1). Johnson (1965, c.f. Kampen 1970) developed the following linear regression between ET and EP (expressed in mm/day) at IRRI.

Vegetative stage	:	ET = 1.104 EP + 0.35
Reproductive stage	:	ET = 1.145 EP + 0.67
Ripening stage	:	ET = 0.88 EP + 0.807

Kampen (1970) developed a similar relationship between ET and Class A pan (EP) at IRRI for wetland rice with a crop coefficient factor less than 1 (0.84-0.94).

Ishikawa and Nishio (1959) reported a 1.1 ET-EP ratio in Japan but Nakagawa (1966), summarizing the results at 37 sites throughout Japan, found an average ratio of 1.3 (0.9-1.7) (Table 1). It is about 1.2 (1.1-1.3) throughout the temperate, subtropical, and tropical zones and does not show much difference by latitude or season. A simple regression equation between daily average ET and EP rates, passing through the zero, was developed for several places (Fig. 9) and shows an average seasonal ratio of 1.2.

Doorenbos and Pruitt (1977) estimated values of the crop coefficient (K_c) factor in different rice growing regions of the world. The values ranged from 1.1 to 1.15 during the first and second month of the crop to 1.05 to 1.35 during midseason and 0.95 to 1.05 during the last 4 weeks.

The advected energy that causes the ET-EP ratio to be more than 1.0 may be drawn from the air or transferred from areas where sensible heat has been generated. Slatyer and McIlroy (1961) suggested that even in the most homogeneous areas, large-scale or upper-level advection due to movement of weather systems may lead to latent heat consumption that exceeds average net radiation received, often for long periods of time. Examples of advection have been reported by van Bavel et al (1962) for sudan grass, Rosenberg (1969, 1972) for alfalfa, soybean, and sugar beets, and Evans (1971) and Lang et al (1974) for rice.

A simple model for the prediction of evapotranspiration

A generalized growth stage relationship derived from Figure 8 and other references is depicted in Figure 10. The ET-EP ratio increases from around 1.0 at transplanting to 1.15 at 20 to 30 DT, and, following a gradual increase, attains a value of 1.32 during

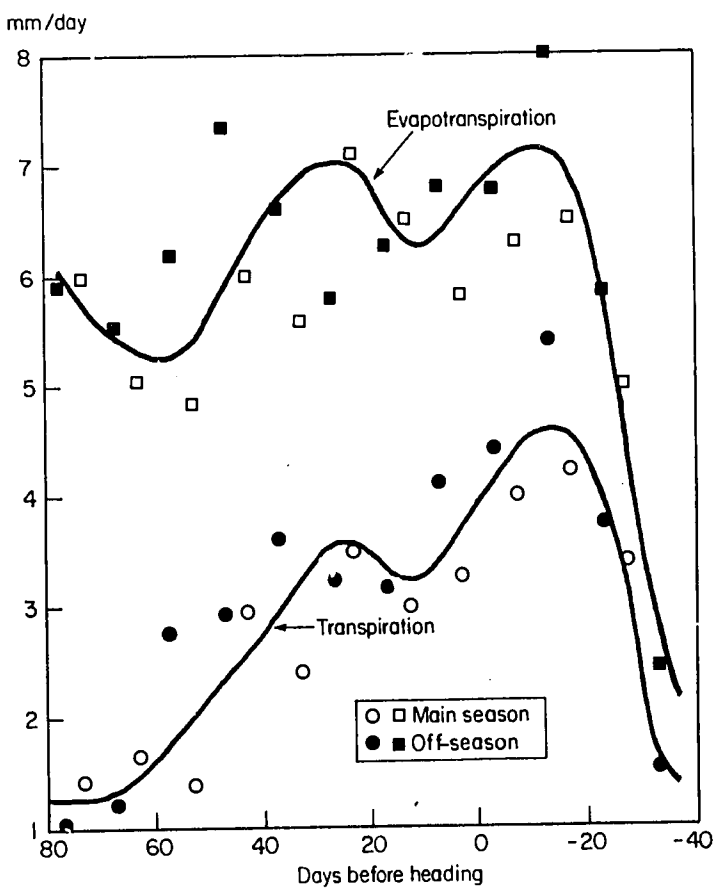
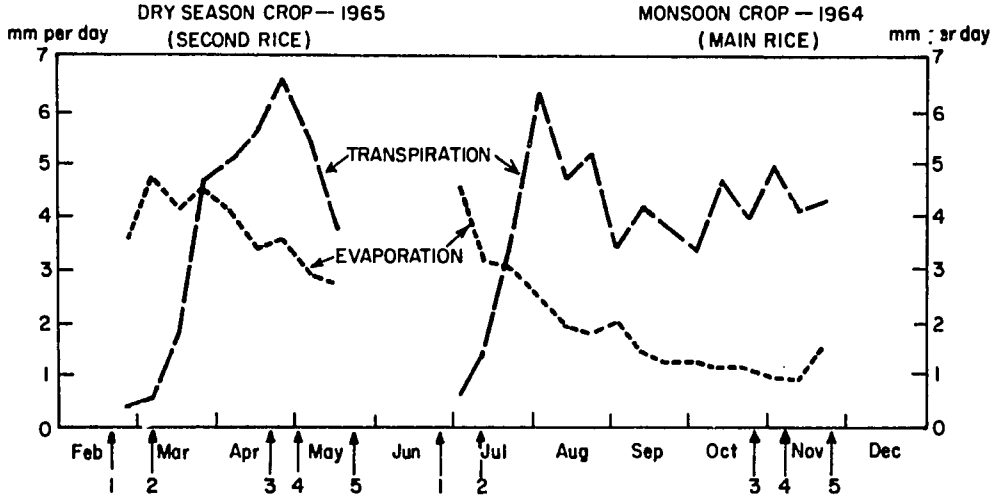


Fig. 2. Seasonal transpiration and evapotranspiration of rice cultivar Bahagia at Telok Chengai Padi Station, Malaysia (Adapted from Sugimoto 1971).



LEGEND:

1 = Date of transplanting, irrigation started

2 = Tillering period begins

3 = Booting period

4 = Heading period

5 = Dough ripening period, water drained

Fig. 3. Transpiration and evaporation rates in dry and wet seasons at Samchook, Thailand (Kung et al 1965).

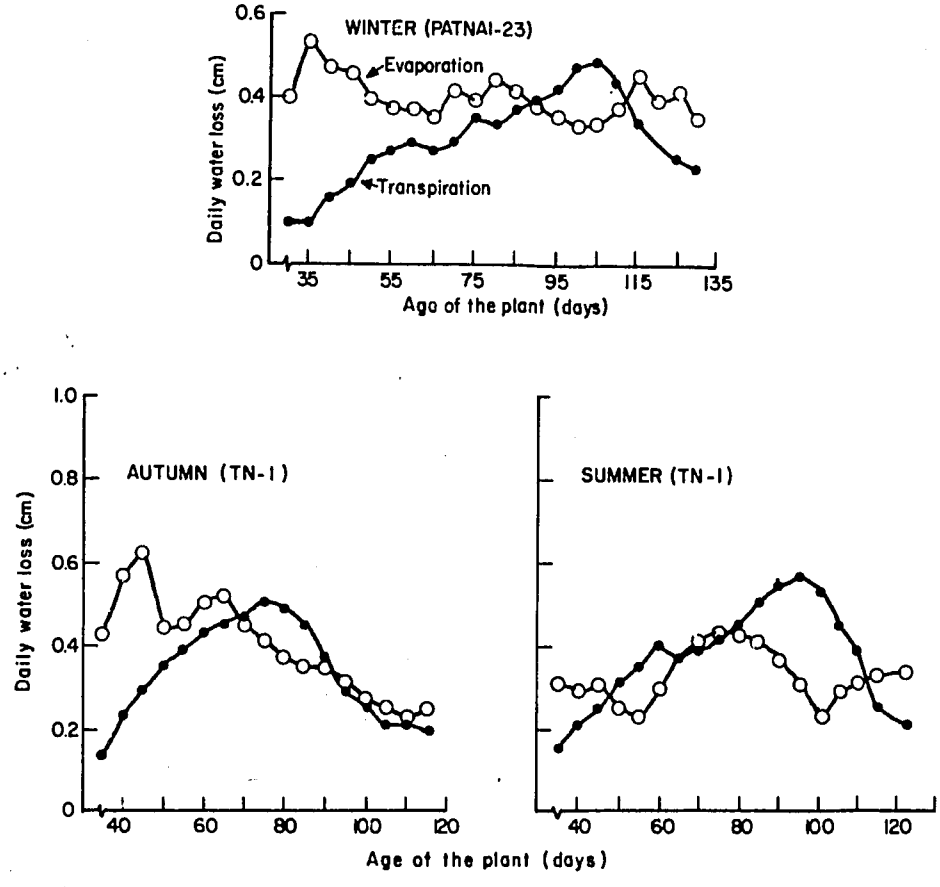


Fig. 4. Daily transpiration and evaporation from the rice field during winter, autumn, and summer in West Bengal (Pande and Mitra 1971).

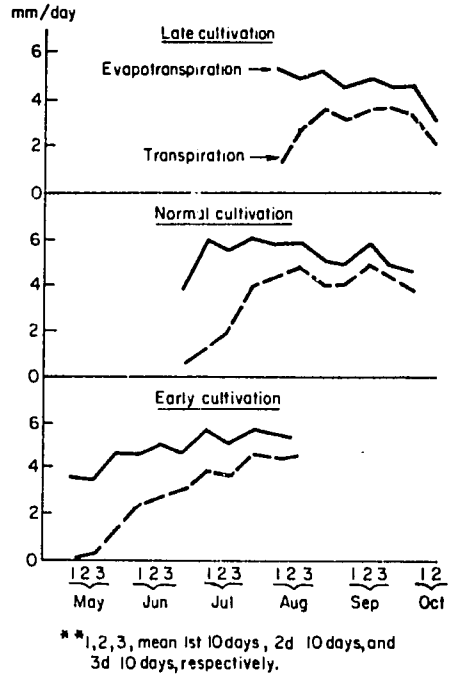


Fig. 5. Evaporation, transpiration, and evapotranspiration in Japan (Nakagawa 1976).

70 to 80 DT and declines. The two peaks in the ET-EP ratio coincide with the maximum tillering and flowering growth stages. The sharp decline after flowering is associated with grain filling and maturity, growth stages in which the leaves progressively undergo senescence.

As discussed earlier (Equation 13), EP can be estimated from solar radiation data. Considering the relationship between ET and EP (Fig. 10), approximations of ET can be made as a function of crop growth period. ET values for the wetland rice were calculated based on a daily solar radiation value of 400 cal/cm^2 per day (common in Asian countries) constant over the whole growth period and growth ET-EP relationship developed in Figure 10. The ET rate was about 4.4 mm/day at transplanting, 5.1-5.2 mm/day at tillering, and 5.7-5.8 mm/day at heading (Fig. 11). These values are close to those reported in the literature. Thus, Equation 13, with Figure 10, can be used with enough precision to estimate daily ET rates during the crop growth period.

Considering the weighted mean value of the ET-EP ratio from Figure 10 over the growth period, the following relationship was found.

$$ET = 1.2\ EP \qquad (14)$$

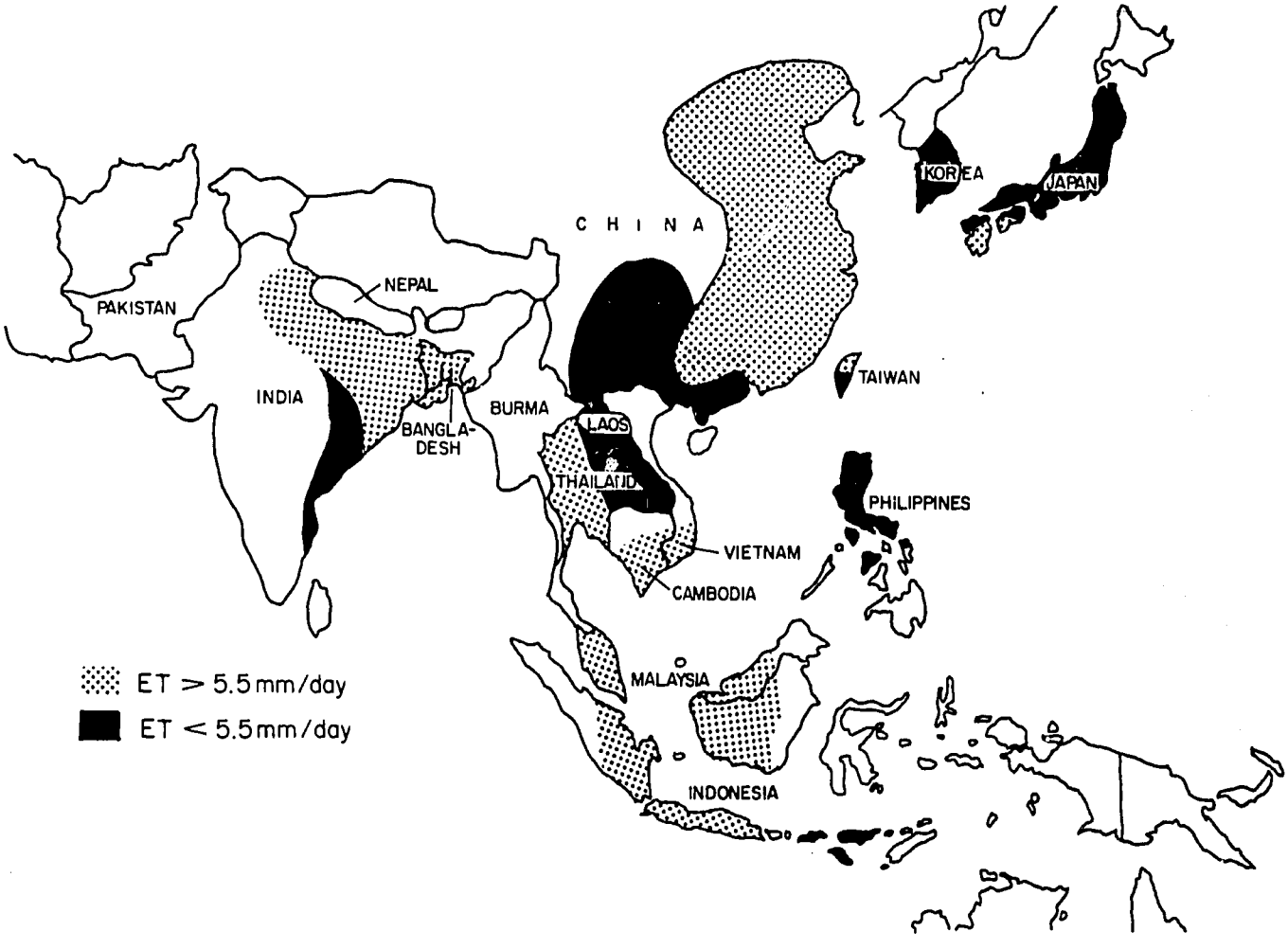


Fig. 6. Distribution of daily average evapotranspiration from wetland rice fields in Asia.

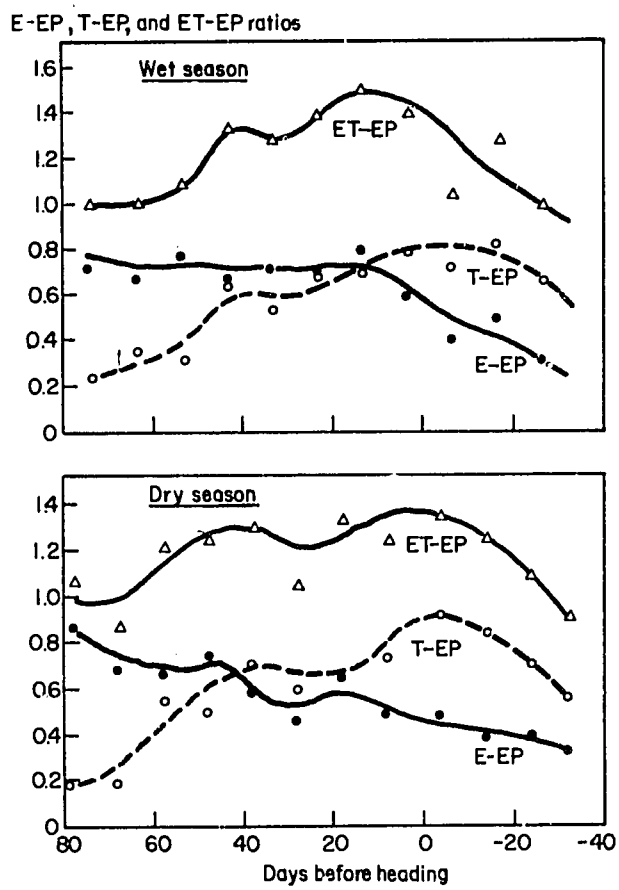


Fig. 7. Changes in ratios between evaporation (E), transpiration (T), evapotranspiration (ET), and pan evaporation (EP) for rice cultivar Bahagia in dry and wet seasons in Malaysia (Adapted from Sugimoto 1971).

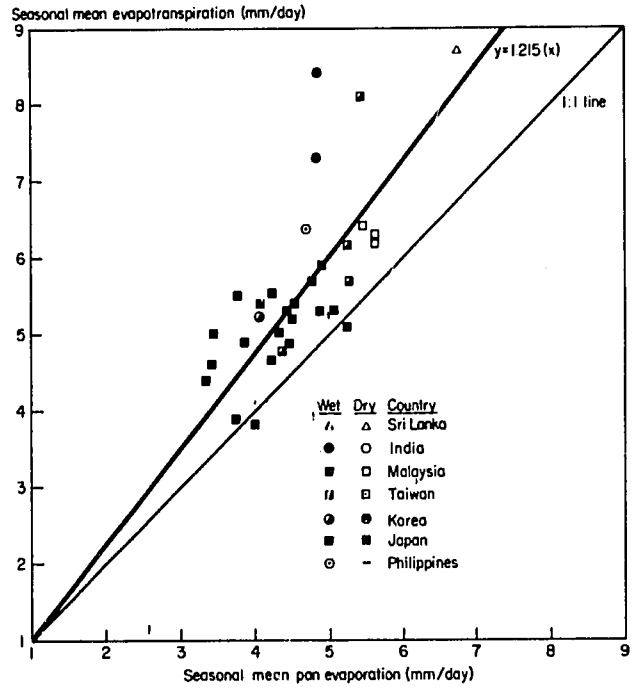


Fig. 9. Relationship between seasonal evapotranspiration and pan evaporation at different locations.

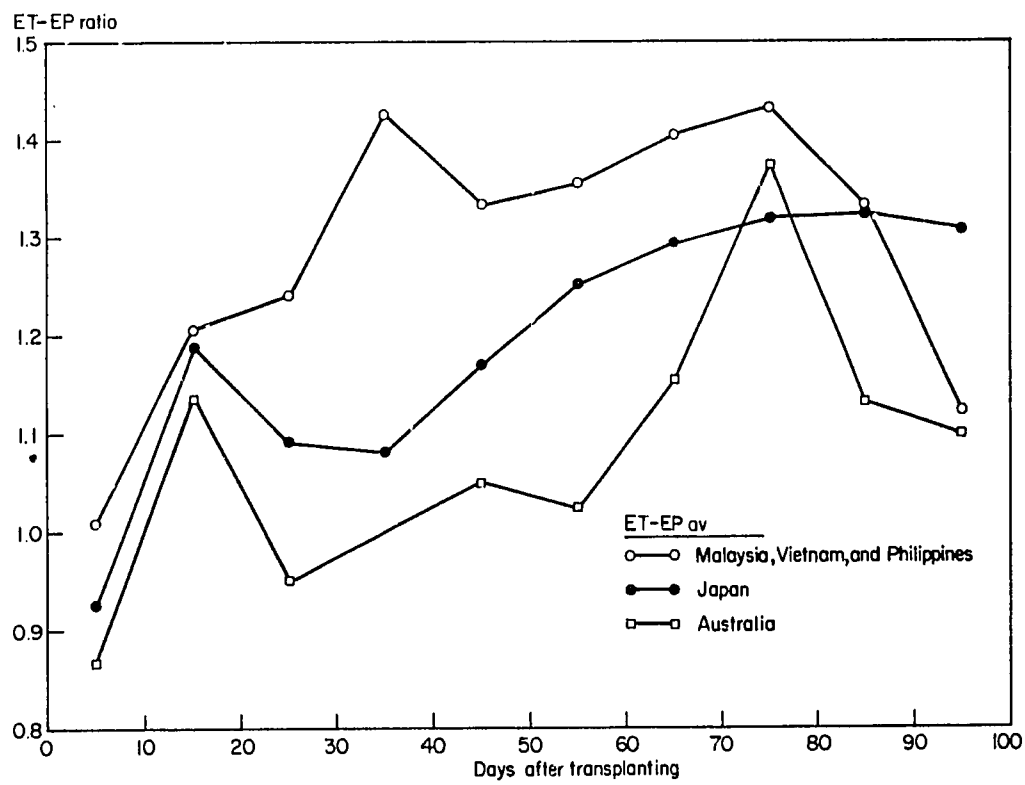


Fig. 8. Growth stage relationships of evapotranspiration (ET)-pan evaporation (EP) ratio for wetland rice in different countries.

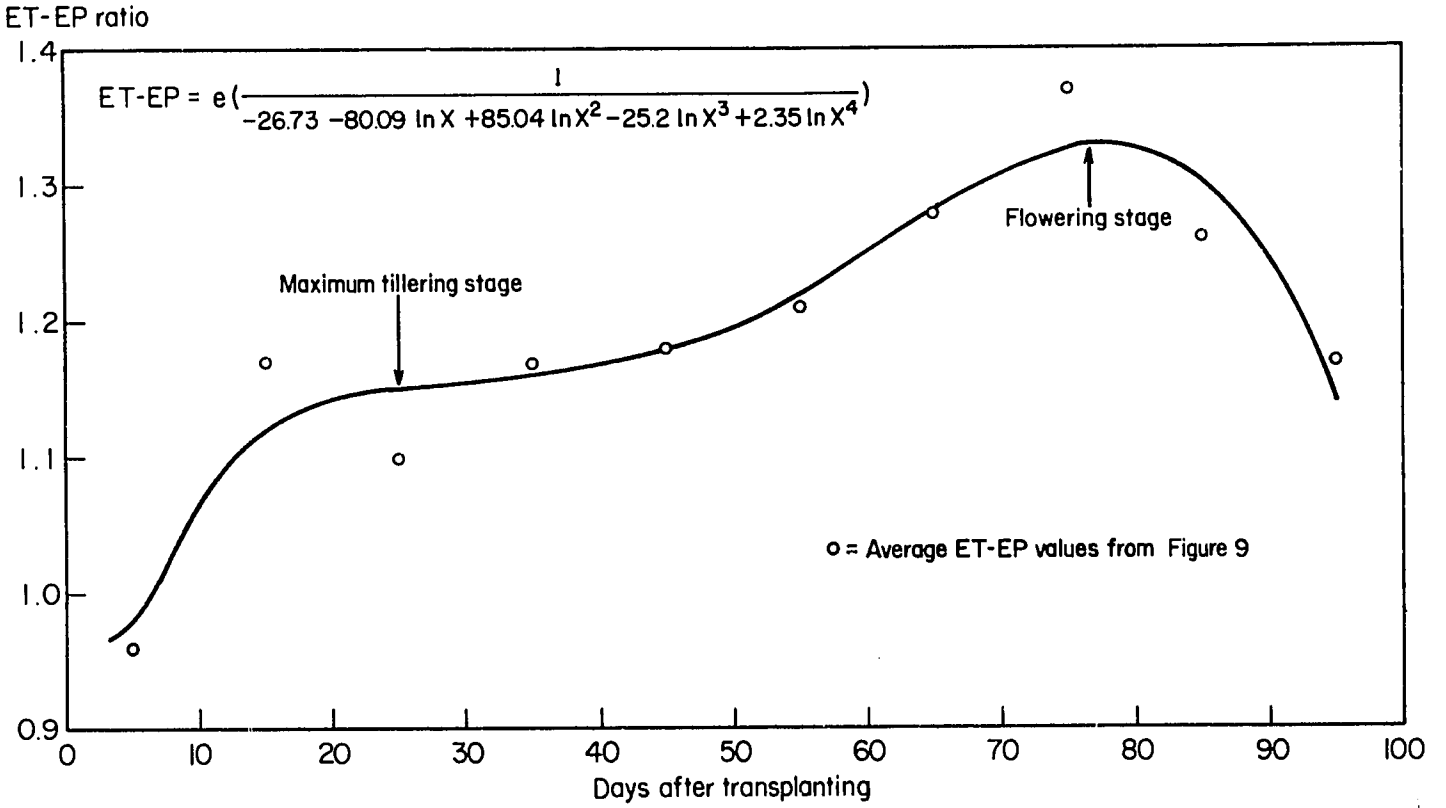


Fig. 10. A generalized growth stage relationship of evapotranspiration (ET)-pan evaporation (EP) ratio for wetland rice for Asian countries.

For Asian countries, we obtained a similar relationship between ET and EP over the whole growth period (Fig. 9).

From Equations 13 and 14, we obtain the following relationship:

$$ET = 1.2\ (0.7546 + 0.0096\ Rs)$$

$$= 0.90552 + 0.01152\ Rs$$

$$\text{or } ET = 0.9 + 0.0115\ Rs\ (\text{mm } t^{-1}) \qquad (15)$$

Equation 15 can serve as a model to estimate average ET values for the given crop season from Rs data alone. For example, for an average value of 400 cal/cm^2 per day of solar radiation over the crop season, the mean ET rate will be 5.5 mm/day. As seen earlier (Table 1 and Fig. 6), most of the seasonal average values of ET in Asian countries are close to this estimated value of ET over a crop season.

This review of rice evapotranspiration principles and literature provides the empirical and quantitative basis for development of the simple and effective relationship illustrated in Figure 11 and Equation 15. Accurate estimates of rice ET by more sophisticated methods require numerous data inputs that are not available in rice growing regions. The model we discuss requires only an estimate of solar radiation and relies heavily on the empirical results obtained across many locations and seasons in temperate and tropical environments. Although ET-EP ratios >1.0 are still debatable in many respects, and the change in crop water use at major growth stages raises questions for both the physiologist and physicist, these relationships have been incorporated into the model. The model's simplicity and depth of empirical background should allow more accurate estimates of ET across various conditions.

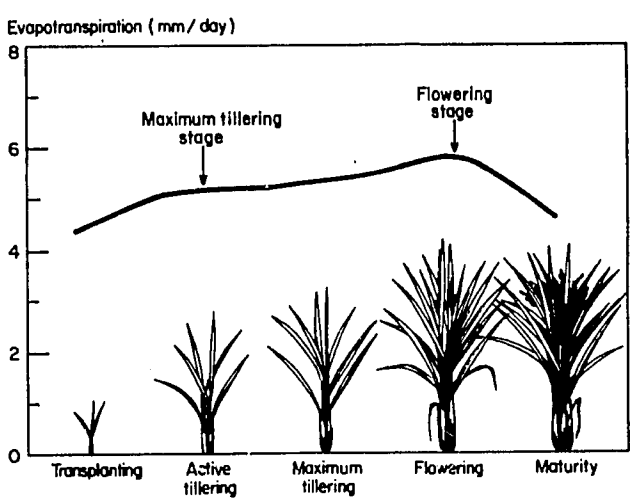


Fig. 11. Predicted evapotranspiration for wetland rice culture from constant solar radiation of 400 cal/cm^2 per day in the season.

Table 1. Transpiration (T) and evapotranspiration (ET) from rice fields in several Asian countries.

Country	Location	Season	Crop type or variety	Irrigation days	T (mm) Total	T (mm) Daily	ET (mm) Total	ET (mm) Daily	ET-EP ratio	Author
Bangladesh	Kushtia	Wet, 1959	Indica	78	733	9.4	1115	14.3		Kung 1961
		Dry, 1958-59	Indica	101	515	5.1	951	9.4		
Cambodia	Battambang	Dry, 1965-66		106	-	-	710	6.7	1.4	Hatta 1967
China	Liaoning	Normal, 1921-22	Japonica	83	376	4.5	706	8.5		
	Ning-sia	Normal, 1945	Japonica	94	340	3.6	637	6.8		
	Kiangsu	Medium, 1935	Indica	84	355	4.2	534	6.3		
	Hunan	Medium, 1940	Indica	92	576	6.3	830	9.1		
	Szechwan	Medium, 1937-38	Indica	79	230	2.9	406	5.1		
	Kwangtung	Early, 1926-28	Indica	85	167	1.9	394	4.6		
		Late, 1926-28	Indica	90	132	1.5	394	4.4		
	Yunnan	Medium, 1939	Indica	129	155	1.2	952	7.4		
India	Kharagpur	Autumn, 1967	TN-1	91	292	3.2	669	7.3		Pande and Mitra 1971
	W. Bengal	Wet, 1967	Patnai	111	325	2.9	793	7.1		
		Dry, 1968	TN-1	97	345	3.6	661	6.8		
	Pantnagar	Wet, 1968	IR8	126	-	-	994	7.9		Ghildyal and Tomar 1976
		Wet, 1971	Jaya	98	525	5.4	720	7.3	1.51	
		Wet, 1976	IR8	112	-	-	780	6.8	1.3	G.B. Pant Univ. of Agric. and Technol. 1977
	New Delhi	Wet, 1968	-	87	-	-	493	5.7		Vamadevan and Dastane 1968
	Orissa	Wet, 1968	-		-	-	-	4.4		Chaudhary 1966
Indonesia	Cianjur	Dry, 1972	Pelita I/1	100	-	-	631	6.3		Bratamidjaja 1976
	Sidrap	Dry, 1973	Pelita I/1	100	-	-	656	6.6		
	Nganjak	Dry, 1973	Pelita I/1	100	-	-	492	4.9		
Japan	37 places in the country	Normal, 1947-64	-	100	-	-	440-550	4.4-5.5	1.3 (0.9-1.7)	Nakagawa 1966
	Shikoku	Average, 1956-59	-	-	302	3.1	487	5.0	1.09 (0.97-1.19)	Ishikawa and Nishio 1959
	Kyushu	Late season	-	-	-	-	-	5.4	1.32 (1.0-1.4)	Nakagawa 1976
Korea	Central	Normal, 1931	Japonica	90	241	2.7	472	5.2	1.28	Tsubouti 1934
Laos	Vientian	Wet, 1967	-	102	245	2.4	515	5.1	1.2	Kotter 1968
Malaysia	Kedah	Main, 1967-68	IR8	97	262	2.7	527	5.4	1.21	Sugimoto 1971
		Off-season, 1968	Bahagia (sister line of IR20)	116	3 2	3.2	737	6.4	1.17	
		Main, 1968-69	Bahagia	110	312	2.8	649	5.9	1.2	
		Main, 1967-69	R. Ebos-33	156	417	2.7	878	5.5	1.13	
	P. Wellesley	Main, 1970-71	-	103	-	-	576	5.6	1.1	Nishio 1961
		Off-season, 1970	-	117	-	-	725	6.2	1.1	
Philippines	Los Baños (UPCA)	Wet	-	-	-	-	-	6.4		Aglibut et al 1957
		Dry	-	-	-	-	-	8.8	-	
	Los Baños (IRRI)	Wet, 1966	-	86	-	-	396	4.6	-	IRRI 1967
		Wet, 1968	-	97	-	-	430	4.4	1.6	IRRI 1969
		Dry, 1968	-	91	-	-	607	6.7	1.56	IRRI 1969
		Wet, 1968-69	-	-	-	-	-	4.4	0.87 + (.3)	Kampen 1970
		Dry, 1968-69	-	-	-	-	-	5.5	0.9 + (.5)	
		Dry, 1969	-	110	-	-	696	6.3	1.34	Krupp (IRRI 1969, unpubl.)
		Dry, 1963	-	-	-	-	-	6.2	1.04 + (.61)	Johnson 1963
Sri Lanka	Dry Zone	Dry, 1965	-	112	552	4.9	972	8.7	1.29	Murakami 1966
Taiwan	Central	Intermediate, 1923-26	-	103	323	3.3	675	6.2	1.17	King 1958 (*see* Kotter 1968)
	Southern	Intermediate, 1923-26	-	95	300	3.1	670	6.9	1.28	
Thailand	Central	Main, 1964	-	151	591	3.9	885	5.9	1.3	Kung et al 1965
		Off-season, 1965	-	91	348	3.8	695	7.6	1.2	Woud't 1965
	Northeast	Main	-	94	255	2.7	488	5.2		Sugimoto 1971
	Suphanburi	Main	-	150	-	-	898	5.9		Palaysoot 1965
Vietnam	Saigon	Main, 1961	Indica	66	-	-	648	9.8		King 1958 (*see* Kotter 1968)
	Cantho	Main	IR20	84	-	-	598	7.1	1.5 (1.12-1.88)	

Table 2. Water requirement of different-duration varieties in fully and partially irrigated conditions (Adapted from Yadav 1973).

Variety	Fully irrigated		Partially irrigated	
	Duration (days)	Water requirement (cm)	Duration (days)	Water requirement (cm)
Bala	96	82		
Cauveri	108	92		
Jaya	142	135	131	119
Jagannath	-	-	150	136

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