Potential Evapotranspiration and Crop Coefficient Estimates for Sugarcane in Okinawa

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Abstract

Seven empirical ET-calculation models (Penman Modified, FAO Penman-Monteith, Priestly-Taylor, Doorenbos-Pruit's Modified FAO Penman, FAO Blaney-Criddle, FAO 24 Radiation and Jensen-Haise) were evaluated from 1980-2003 to estimate the potential evapotranspiration (ET_p), crop coefficients (K_c) and crop water requirements (ET_c) for sugarcane grown in nine locations on Southwest Islands of Japan (Naha-Okinawa south, Nago-Okinawa north, Kume, Minami Daito, Ishigaki, Miyako, Yonaguni, Iriomote and Izena). The FAO Penman-Monteith model showed the most reliable estimates of ET_p . The mean of monthly ET_p , ET_c and K_c were higher in Ishigaki, Miyako, Minami Daito and Yonaguni compared to Naha, Kume, and Iriomote, while these were low for Nago and Izena. The values of ET_p , ET_c and K_c for all islands increased gradually from January (summer cane) and April (spring cane), reached the peak in July-October, and thereafter decreased gradually to February of the following year. The K_c values of summer and spring planted sugarcane reached a maximum during June to September (1.10-1.24) and July to October (1.17-1.41) respectively. Overall, the K_c values of spring cane were higher than the summer cane and the values declined around 0.50 (summer) and 0.54 (spring) at the end of growing season. A long-term analysis of effective rainfall revealed that 485 ± 125 mm annual water shortage prevails in these islands. Seasonal water demand in Ishigaki, Miyako, Minami Daito, and Naha was higher compared to other islands.

Key words: Crop coefficient, Crop water requirement, Effective rainfall, Water deficit.

1. Introduction

Sugarcane is a main crop in Okinawa. About 70% of farmers are engaged in its production. Annual productions of this crop have decreased from 2.43 million tons to less than 1.00 million tons in recent years since 1965. The present average yield of sugarcane is 58.3 t/ha (Annon, 2002-03). Drought in the summer season (July-October) is the major constraint in the production because the rainfall is mostly concentrated in the rainy season and in the typhoon season, which occurs in the dry summer period. Despite much rainfall (2200 ± 550 mm), there are no big rivers or reservoirs for water storage to meet the water demand in the dry periods.

Most of the sugarcane-growing islands in Okinawa, except Okinawa Main Island comprising Naha and Nago, have no proper irrigation schedules. Farmers in these islands practice irrigation based on their own experiences, which cause under or over-irrigation with potential effects on production cost. Therefore, information on evapotranspiration (ET) and crop coefficients (K_c) of sugarcane is important for irrigation scheduling through better utilization of the limited water resources in the dry period. In the absence of actual data on water requirements, there is no alternative to predict the accurate evapotranspiration of crops. The concept of a daily

potential evapotranspiration (ET_p) is widely used in the estimation of crop water requirements where studies on field water balance are lacking and meteorological data are adequate (Jensen *et al.* 1990).

A large number of models for ET -estimation have been developed elsewhere, which can be evaluated for the most suitable model in estimating ET_p in the sub-tropic humid climates of Okinawa, incorporating local meteorological data. The modified Penman-Monteith model (Allen *et al.* 1994) employed with adequate data on canopy and aerodynamic resistances could measure more accurate ET_p estimates than other methods. The long-term ET_p could be estimated using the most suited ET -estimation model, rather than the Penman-Monteith model (Allen *et al.* 1994), due to inadequacy of data on stomatal resistance, wind dynamics and surface roughness. The K_c is an important parameter, which can be estimated by dividing the daily crop water requirements (ET_c) obtained from lysimeter/ field water balance studies by the predicted ET_p . Therefore, the objectives of this study are to: (1) evaluate the most suitable ET -estimation model for the islands of Okinawa, (2) estimate the long-term average ET_p and K_c , which will provide a means for estimating actual crop evapotranspiration for summer and spring-planted sugarcane, and (3) analyze the effective rainfall and water deficits in the islands of Okinawa.

2. Materials and Methods

2.1 Study Areas and Investigation Period

This investigation was carried out for the allied islands of Okinawa Prefecture (24°19.9'–26°3.4'N). The nine locations on these southwest islands of Japan were Naha–Okinawa south, Nago–Okinawa north, Kume, Minami Daito, Ishigaki, Miyako, Yonaguni, Iriomote and Izena. Soils in these islands are locally classified as Shimajiri Maji and Kunigami Maji (Luvisols/Cambisols, FAO). The field capacity, wilting point and bulk density of these soils are $0.40 \pm 0.15 \text{ m}^3 \text{ m}^{-3}$, $0.20 \pm 0.05 \text{ m}^3 \text{ m}^{-3}$ and $1.14 \pm 0.45 \text{ kg m}^{-3}$. The investigation was conducted over 23 years (1980–2003) for summer (Jan.–Feb. of the following year) and spring (Apr.–Feb. of the following year) planted sugarcane.

2.2 Meteorological Data

The daily meteorological data on average temperature, solar radiation, relative humidity, vapor pressure, wind speed, and sunshine, were collected from automatic weather stations and the office of the Okinawa Met. Observatory.

2.3 Potential evapotranspiration

Seven energy balance *ET*-estimation equations such as: (1) Penman Model, 1956; (2) FAO Penman-Monteith (Allen *et al.* 1998); (3) Priestly-Taylor, 1972; (4) Doorenbos and Pruitt's Modified Penman, 1977; (5) FAO Blaney-Criddle (Allen & Pruitt, 1986); (6) FAO 24 Radiation; and (7) Jensen-Haise, 1963 (Penman, 1956; Reference Evapotranspiration Models [Online], 2004), have been evaluated to check the best-suited model for estimation of *ETp* of the study areas. The applicability of these equations was correlated with well-watered lysimeter *ET* of sugarcane to check the best-fitted model for Okinawa.

2.4 Actual Evapotranspiration & Crop Coefficient

Actual measured evapotranspiration data for summer and spring cane was available from field water balance lysimeter studies conducted in Naha for 1967–86 (Yamashiro, 1990) and 1999–02 (Yoshinaga and Hossain, 2003) respectively. Regression models for summer and spring cane were developed using the lysimeter measured *ETc* and locally available weather variables to calculate the long-term *ETc*. Further, the

predicted regression *ETc* was fitted with the Gauss method to calculate the missing values and to minimize the deviation in daily *ETc*. Crop coefficients (*Kc*) were computed as the ratio of daily *ETc* and *ETp* ($Kc = ETc/ETp$).

2.5 Effective rainfall and annual water shortage

Daily rainfall equal to or greater than 5 mm with 80 percent efficiency is considered to be effective rainfall, which was calculated as follows:

“*ER* (mm/day) = (Daily rainfall $\geq$ 5mm) $\times$ 0.8”. In Okinawa, soil water is usually depleted to critical level within 7 to 15 days after irrigation or rainfall (Yamashiro *et al.* 1994). Therefore, the criteria to estimate the effective rainfall and soil water deficits for every 10 days period were as follows:

- (1) If $\sum_{n=1}^{10} ER \geq \sum_{n=1}^{10} ET_c$, then irrigation (*I*) = 0 mm, and
- (2) If $\sum_{n=1}^{10} ER < \sum_{n=1}^{10} ET_c$, then $I = (\sum_{n=1}^{10} ET_c - \sum_{n=1}^{10} ER)$ mm.

Statistical analyses were done using the SPSS Package.

3. Results and Discussion

Seven energy balance *ET*-estimation models were evaluated for different islands to check the best-fitted model for estimation of *ETp*. The FAO Penman-Monteith model (Allen *et al.* 1998) showed the most reliable estimates of *ETp* (1342–1699 mm), as the closeness of fit ‘*R*²’ value of the model was comparatively higher than other models (Table 1). FAO Radiation and Jensen-Haise methods tended to overestimate the *ETp* rates during the peak growth period (July–October) and the annual estimates were high (1792–2472 mm) due to fluctuation of weather parameters. However, the FAO Blaney-Criddle method estimated an unexpected low annual *ETp* (750–981 mm) that occurred due to in adjustment of weather parameters in the model for these sub-tropic humid climates.

Depending upon the best fit, the FAO Penman-Monteith model (Allen *et al.* 1998) was used to estimate *ETp* in the islands of Okinawa (Fig. 1). Significantly high rates of *ETp* were recorded in Ishigaki followed by Miyako, Minami Daito, Naha

Table 1. Fitness of models: values are the seasonal potential evapotranspiration (mean of 1980–2003).

Study area	Modified PM	FAO PM-Monteith	Priestly-Taylor	Doorenb.-Pruitt	Blaney-Criddle	Radiation	Jensen-Haise
Naha	1699 (0.93*)	1468 (0.94)	1373 (0.88)	1328 (0.90)	891 (0.86)	1677 (0.90)	1988 (0.87)
Nago	1553 (0.92)	1342 (0.93)	1373 (0.88)	1307 (0.89)	778 (0.90)	1662 (0.90)	1943 (0.90)
Kume	1688 (0.93)	1458 (0.94)	1377 (0.88)	1328 (0.89)	778 (0.89)	1654 (0.90)	2136 (0.91)
Miyako	1705 (0.93)	1467 (0.94)	1486 (0.87)	1387 (0.89)	783 (0.89)	1749 (0.88)	2171 (0.91)
Minami Daito	1772 (0.90)	1511 (0.91)	1583 (0.86)	1470 (0.87)	915 (0.83)	1895 (0.86)	2214 (0.90)
Ishigaki	1873 (0.91)	1615 (0.93)	1503 (0.87)	1422 (0.88)	813 (0.85)	1773 (0.88)	2299 (0.89)
Yonaguni	2005 (0.91)	1699 (0.92)	1626 (0.85)	1518 (0.86)	750 (0.86)	1861 (0.86)	2472 (0.92)
Iriomote	1620 (0.89)	1380 (0.90)	1457 (0.84)	1421 (0.85)	789 (0.83)	1691 (0.85)	1792 (0.91)
Izena	1666 (0.89)	1421 (0.93)	1362 (0.85)	1294 (0.86)	798 (0.86)	1655 (0.86)	1984 (0.91)

*Parentheses are the closeness of fit ‘*R*’ values comparing with well-watered lysimeter *ET* of sugarcane.

Fig. 1. Potential evapotranspiration of crops in the islands of Okinawa (Penman Monteith model).

and Kume. Lower ET_p was recorded in Nago, Izena and Iriomote. The peak ET_p (5.07-6.19 mm/day) was observed during July-August. High temperature and radiation due to geographical position and comparatively low forest cover caused the high rate of ET_p of crops in Ishigaki, Miyako, Minami Daito, Naha and Kume. Moreover, analysis of 23 years weather data depicted $1 \pm 0.34^\circ\text{C}$ increment in annual air temperature that may have caused the increase in crop evapotranspiration.

The Gauss fitted long-term regional ET_c calculated by using the regression models are presented in Table 2. In the early and later seasons in the year, the ET_c was low compared to ET_p (Fig. 1 and Table 2). The growth rate, canopy dependant variable and K_c were responsible for minimizing the ET_c in early and later growth periods. However, ET_c peaked in July-October, which exceeded the ET_p values. High leaf area index and the function of stomata transpired much water in this stage. The Gauss fitted regression ET_c was in quite good agreement with the lysimeter measured ET_c , as the value of R^2 was 0.97 and there was standard error of estimates (SEE) of 0.31 mm per day at $P = 0.01$ (Fig. 2). Further, Fig. 2 reveals the lower value of $R^2 = 0.87$ ($SEE = 0.42$ mm per day), which shows the moderate relationship between model ET_p and lysimeter measured ET_c . The high values of ET_c

Fig. 2. Relationships of lysimeter ET_c between regression ET_c (Gauss fitted) and potential ET .

were found in Ishigaki, Minami Daito and Yonaguni Islands, which might be significantly influenced by the prevailing high temperature, wind speed and clear sunshine in these regions.

In irrigation scheduling, crop coefficient factors for different locations depending upon the growth stages are more effective to estimate ET_c of a special crop when multiplying with ET_p . Overall, K_c was lower in the early stage, gradually increased at the onset of increasing stem elongation, reached a peak in July-August, and decreased further retaining constant values during crop harvest (Table 3). As these results indicate, sugarcane consumes much water in the peak growth stage, with lower consumption in the early and later stages. The K_c values in the peak growth stages were higher for spring cane over summer cane. Further, the K_c values in Ishigaki, Minami Daito, Yonaguni and Miyako were higher than for the other islands (Table 3).

In common years, the sugarcane receives 816 ± 74 mm effective rainfall with annual water shortage of 483 ± 125 mm (Fig. 3). Yamashiro *et al.* (1994) reported 813 and 482 mm for annual average effective rainfall and water deficit, respectively in Naha and Miyako Island. The water deficits were very uncommon in the early and later-seasons because rainfall was more effective in meeting the water

Table 2. Crop water requirements (ET_c) for summer and spring (parentheses) sugarcane (mean of 1980-2003).

Months	Naha	Nago	Kume	Miyako	Minami Daito	Ishigaki	Yonaguni	Iriomote	Izena
Jan	1.5	1.2	1.3	1.5	1.5	1.5	1.3	1.3	1.2
Feb	1.9	1.5	1.8	1.9	1.9	1.9	1.7	1.7	1.6
Mar	2.5	2.1	2.3	2.4	2.6	2.6	2.4	2.3	2.2
Apr	3.3 (1.7)	2.8 (1.7)	3.2 (1.7)	3.3 (1.7)	3.4 (1.8)	3.5 (1.8)	3.2 (1.7)	3.2 (1.7)	3.1 (1.5)
May	4.2 (3.2)	3.7 (3.2)	4.1 (3.1)	4.1 (3.1)	4.3 (3.3)	4.4 (3.4)	4.1 (3.1)	4.0 (3.1)	3.7 (2.8)
Jun	5.5 (4.7)	4.8 (4.6)	5.3 (4.5)	5.5 (4.7)	5.6 (4.8)	6.0 (5.1)	5.5 (4.7)	5.4 (4.6)	4.7 (4.2)
Jul	6.7 (5.9)	5.9 (5.9)	6.7 (5.9)	6.7 (5.8)	6.8 (6.0)	7.2 (6.4)	6.8 (5.9)	6.3 (5.6)	5.8 (5.4)
Aug	6.3 (6.4)	5.8 (6.7)	6.6 (6.8)	6.4 (6.7)	6.5 (6.9)	6.9 (7.1)	6.5 (6.6)	6.1 (6.4)	5.5 (6.2)
Sep	5.5 (5.4)	5.1 (5.5)	5.5 (5.4)	5.5 (5.4)	5.6 (5.7)	5.8 (5.7)	5.4 (5.5)	5.1 (5.2)	4.8 (5.1)
Oct	4.1 (4.2)	3.7 (4.1)	4.0 (4.0)	4.1 (4.2)	4.0 (4.1)	4.2 (4.3)	3.9 (4.0)	3.7 (3.8)	3.9 (4.0)
Nov	2.8 (2.5)	2.4 (2.5)	2.7 (2.5)	2.8 (2.6)	2.7 (2.5)	2.9 (2.6)	2.6 (2.7)	2.5 (2.4)	2.7 (2.4)
Dec	1.9 (1.8)	1.6 (1.7)	1.8 (1.7)	2.0 (1.9)	1.9 (1.7)	2.0 (1.8)	1.8 (1.7)	1.7 (1.6)	2.0 (1.7)
Jan	1.4 (1.8)	1.2 (1.3)	1.4 (1.3)	1.5 (1.5)	1.4 (1.3)	1.5 (1.5)	1.3 (1.3)	1.2 (1.2)	1.4 (1.3)
Feb	1.3 (1.3)	1.0 (1.2)	1.2 (1.2)	1.3 (1.3)	1.2 (1.2)	1.3 (1.3)	1.2 (1.2)	1.1 (1.1)	1.3 (1.2)

Table 3. Crop coefficients of summer and spring (parentheses) planted sugarcane over 23 years (1980-2003).

Month	Naha	Nago	Kume	Miyako	MinamiDaito	Ishigaki	Yonaguni	Iriomote	Izena
Jan	0.60	0.61	0.60	0.60	0.60	0.60	0.61	0.60	0.50
Feb	0.70	0.71	0.70	0.68	0.72	0.70	0.69	0.70	0.68
Mar	0.80	0.81	0.80	0.75	0.86	0.80	0.80	0.80	0.83
Apr	0.90(0.48)	0.89(0.47)	0.87(0.49)	0.87(0.46)	0.93 (0.48)	0.91 (0.54)	0.90(0.49)	0.90(0.49)	0.96(0.45)
May	1.01(0.77)	1.02(0.77)	1.01(0.79)	0.97(0.75)	1.05 (0.78)	1.02 (0.86)	1.01(0.79)	1.01(0.78)	1.02(0.73)
Jun	1.13(1.02)	1.12(1.02)	1.11(1.03)	1.09(0.96)	1.13 (0.98)	1.11 (1.10)	1.12(1.00)	1.11(0.99)	1.05(0.91)
Jul	1.16(1.11)	1.17(1.10)	1.17(1.12)	1.14(1.09)	1.20 (1.12)	1.17 (1.22)	1.19(1.17)	1.17(1.10)	1.10(1.03)
Aug	1.18(1.24)	1.22(1.23)	1.21(1.22)	1.17(1.29)	1.24 (1.26)	1.21 (1.36)	1.25(1.31)	1.21(1.23)	1.12(1.16)
Sep	1.17(1.29)	1.19(1.31)	1.19(1.32)	1.14(1.30)	1.19 (1.32)	1.19 (1.41)	1.19(1.42)	1.18(1.34)	1.10(1.25)
Oct	1.05(1.20)	1.04(1.23)	1.05(1.24)	1.09(1.24)	1.01 (1.19)	1.05 (1.27)	1.05(1.34)	1.05(1.27)	1.06(1.18)
Nov	0.90(1.01)	0.91(1.04)	0.90(1.04)	0.94(1.03)	0.86 (0.99)	0.90 (1.08)	0.90(1.13)	0.90(1.07)	0.97(0.99)
Dec	0.76(0.81)	0.75(0.85)	0.74(0.86)	0.82(0.84)	0.69 (0.77)	0.75 (0.88)	0.75(0.91)	0.75(0.85)	0.82(0.78)
Jan	0.62(0.65)	0.62(0.69)	0.62(0.69)	0.68(0.68)	0.57 (0.62)	0.62 (0.70)	0.62(0.78)	0.62(0.70)	0.64(0.64)
Feb	0.50(0.53)	0.49(0.56)	0.51(0.56)	0.55(0.55)	0.46 (0.51)	0.50 (0.58)	0.50(0.61)	0.50(0.56)	0.57(0.52)

demand during these seasons. Low effective rainfall in the dry period (July-October) failed to meet the potential water demand (Table 2 and Fig. 3). The standard deviations (STD) of effective rainfall indicate a greater fluctuation in rainfall during July-October, which causes severe drought with a remarkable yield loss in the islands of Okinawa (Fig. 3). The high values of STD occurred in July to October due to low effective rainfall. This deviation in effective rainfall caused severe drought during 1963, 1971, 1994, and 1997 with yield losses of 60, 90, 50 and 45% respectively (Yamashiro *et al.* 1994; Anon, 2002-03). Overall, 350 ± 53 mm supplemental irrigation is needed during July-October to save sugarcane from drought damage and to optimize the yield in the islands of Okinawa (Fig. 3).

Fig. 3. Effective rainfall and water deficits in Okinawa (Ave. of all sites for 1980-03, Bar: STD of effect. rain).

Conclusions

- The simplified FAO Penman-Monteith model is the best-fitted model for Okinawa.
- In the dry period (July-October), irrigation could be applied at 10 day intervals as "Irrigation depth for 10 days (mm) = (Σ Actual *ET* for 10 days) - (Σ Effective rainfall for 10 days)".
- The database of this study, especially *ET* obtained from empirical models and meteorological data, would be worth comparing with the reflection based *ET* and *Kc* to be employed for Okinawa in the near future.

- Advanced technology "Remote sensing and GIS" would possibly be suitable in evaluating evapotranspiration in comparison with these findings and for growth analysis of sugarcane in the islands of Okinawa.

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References

- Allen, R.G., Pereira, L.S., Raes, D. and Smith, M., 1998: *Crop Evapotranspiration: Guidelines for computing crop water requirements*, FAO Irrig. and Drain. Paper No. 56, FAO, Rome, Italy.
- Allen, R.G., Smith, M., Pereira, L.S., and Perrier, A., 1994: An update for the calculation of reference evapotranspiration. *ICID Bull.* 43(2):35-92.
- Anonymous, 2002-03: Production report of sugarcane and sugar: Aug. 2003 (Japanese). Dept of Agril., Forestry and Fisheries, Okinawa, Japan, 55-60pp.
- Jensen, M.E., Burman, R.D., and Allen, R.G., 1990: Evapotranspiration and irrigation water requirements. *ASCE Manual & Reports on Engg. Practice*. No.70.
- Penman, H. L., 1956: Estimating evapotranspiration. *Trans. Geophys. Union*, 37:44-46.
- Reference Evapotranspiration Models, 2004: [Online] Available at: <http://etd.lsu/docs/available/etd-06302004-153939/unrestricted/Models.pdf>.
- Yoshinaga, A., and Hossain, M. A., 2003: Lysimeter study on sugarcane, Lab. of Water Use & Hydra. Stru. Engg., Univ. of the Ryukyus, Okinawa, (Un published).
- Yamashiro, S., 1990: Studies on some elements concerned with estimation of irrigation for sugarcane. *Bull. Univ. of the Ryukyus, Okinawa, Japan*, 12:209-219.
- Yamashiro, S., Onaga, K., and Yoshinaga, A., 1994: Problems on Agricultural Water Use in Miyako Island, Publication of Sesoko Marine Science Center, Univ. of the Ryukyus, Okinawa Japan, Vol. 12:209-219.