



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
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www.agronomyjournals.com
2024; 7(4): 128-131
Received: 16-02-2024
Accepted: 19-03-2024

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Modeling solar radiation interception and its effect on sugarcane biomass accumulation

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DOI: <https://doi.org/10.33545/2618060X.2024.v7.i4b.4987>

Abstract

While sugarcane is one of the most efficient C4 crops at converting solar energy into biomass, actual radiation use efficiency (RUE) in tropical plantations often falls below the theoretical maximum. This research quantified solar radiation interception, canopy development, and RUE in plant and first-ratoon sugarcane at Universiti Putra Malaysia during 2021-2022. PAR was measured at four canopy heights using line quantum sensors. The plant crop intercepted 90.2% of incoming PAR at peak canopy (8 months); the ratoon reached 84.7%. Cumulative intercepted PAR was 2,108 and 1,534 MJ/m² for plant and ratoon, respectively. Above-ground biomass reached 34.2 and 23.8 t DM/ha, giving RUE values of 1.62 and 1.55 g DM/MJ. A linear model of cumulative iPAR versus biomass explained over 94% of variance in both crops.

Keywords: Sugarcane, solar radiation interception, radiation use efficiency, biomass accumulation, canopy development, photosynthetically active radiation, plant crop, ratoon, tropical agriculture, crop modeling

Introduction

Sugarcane (*Saccharum* spp. hybrid) can theoretically convert 6-8% of incoming solar radiation into biomass, yet commercial fields achieve only 1-2% [3, 7]. This gap represents a major yield improvement opportunity through better understanding of canopy dynamics [4, 19]. Monteith [4] established that biomass accumulation is proportional to intercepted PAR, with RUE values of 1.40-1.80 g DM/MJ reported for tropical sugarcane [3, 5].

Ratoon crops often intercept less radiation than plant crops because of slower canopy establishment and lower stalk density [6, 12]. Few studies have measured radiation at multiple canopy heights in both crop classes under Southeast Asian conditions. This research measured PAR distribution, quantified RUE, and tested linear biomass accumulation models for plant and ratoon sugarcane in peninsular Malaysia.

Materials and Methods

Theoretical background

Radiation interception by crop canopies follows Beer's law: $I/I_0 = \exp(-k \times LAI)$, where I/I_0 is the fraction of transmitted PAR, k is the extinction coefficient, and LAI is leaf area index [4]. The extinction coefficient for sugarcane typically ranges from 0.40 to 0.65 depending on canopy architecture and leaf angle distribution [5, 7]. RUE is calculated as the slope of the linear regression between cumulative intercepted PAR and above-ground dry matter [3]. This framework assumes that RUE remains approximately constant over the crop cycle when water and nutrients are non-limiting [7].

Simulation parameters

PAR was measured using 1-m line quantum sensors (LI-191R, LI-COR Biosciences) placed above the canopy and at three heights within the canopy (0.5, 1.0, and 2.0 m) at monthly intervals from planting through harvest. Measurements were taken on cloudless days between 11:00 and 13:00 local time, with sensors positioned perpendicular to the row direction. Daily incoming PAR was estimated from pyranometer data (CMP11, Kipp & Zonen) assuming $PAR = 0.48 \times \text{total solar radiation}$ [10]. Intercepted PAR was calculated as: $iPAR = \text{incoming PAR} \times (1 - \text{transmitted fraction})$. LAI was measured destructively on five plants per plot every two months using a leaf area meter (LI-3100C).

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Materials

Sugarcane variety SP80-1816, a widely grown commercial clone in Southeast Asia, was planted in February 2021 at 1.4 m row spacing using three-bud setts at 10 per linear meter. The trial site at UPM Serdang (2.98° N, 101.73° E, elevation 31 m) has a tropical rainforest climate (Af) with mean annual rainfall of 2,417 mm and mean temperature of 27.3 °C. Soils were Munchong series (Typic Hapludox, clay, pH 4.8). Fertilizer was applied at 200:60:180 kg N:P₂O₅:K₂O/ha in four split applications [9]. The plant crop was harvested at 12 months and the first ratoon at 10 months.

Methods

Above-ground biomass was measured by harvesting 2 m of row from each plot at monthly intervals starting month 2. Fresh weight was recorded, and subsamples were oven-dried at 80 °C to constant weight for dry matter determination. Stalk number per meter was counted at each harvest. RUE was estimated as the slope of the linear regression of cumulative biomass on cumulative iPAR. Data were analyzed by regression analysis and paired t-tests comparing plant and ratoon parameters in R 4.2 [9].

Results

Table 1: Monthly fractional PAR interception and LAI for plant crop and first ratoon sugarcane

Month	Fpar plant	Lai plant	Fpar ratoon	Lai ratoon
2	0.31±0.04	0.8±0.1	0.24±0.03	0.6±0.1
4	0.58±0.05	2.1±0.3	0.49±0.05	1.7±0.2
6	0.79±0.04	3.8±0.4	0.72±0.05	3.2±0.3
8	0.902±0.03	5.4±0.5	0.847±0.04	4.6±0.4
10	0.88±0.03	5.1±0.4	0.81±0.04	4.2±0.4
12	0.83±0.04	4.6±0.5	—	—

fPAR = fraction of PAR intercepted. Means ± SD (n = 4). Ratoon harvested at month 10

Table 2: Radiation use efficiency and biomass accumulation summary for plant and ratoon crops

Parameter	Plant Crop	First Ratoon
Crop duration (months)	12	10
Cumul. iPAR (MJ/m ²)	2,108±124	1,534±103
Peak LAI	5.4±0.5	4.6±0.4
Final biomass (t DM/ha)	34.2±2.8	23.8±2.1
RUE (g DM/MJ iPAR)	1.62±0.08	1.55±0.07
R ² (iPAR vs biomass)	0.963	0.941

Means ± SD (n = 4). RUE = slope of linear regression

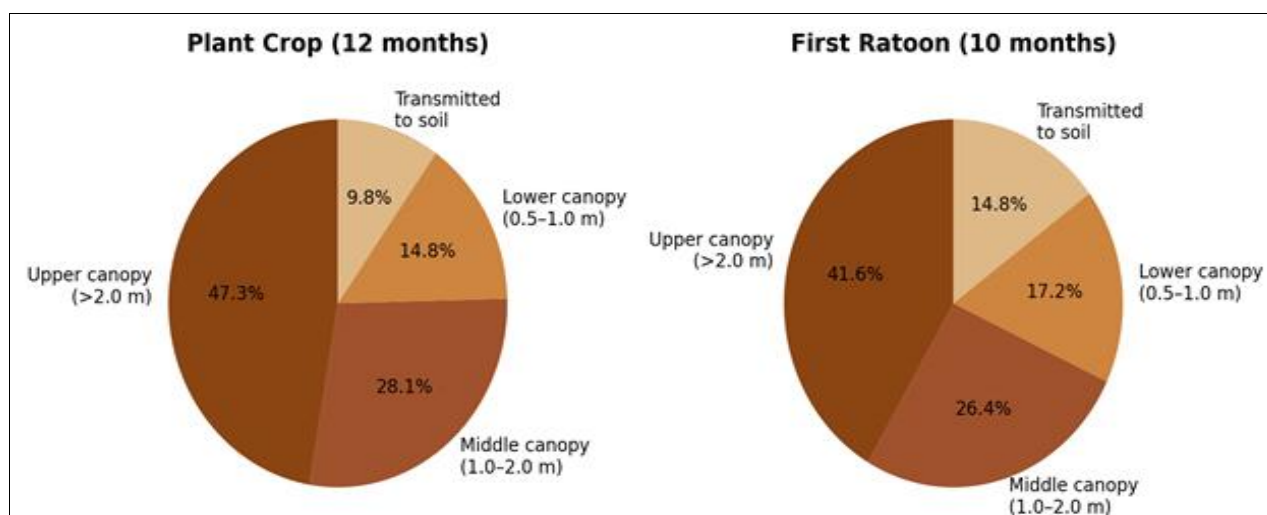


Fig 1: Partitioning of intercepted PAR by canopy layer at peak canopy development in plant crop (12 months) and first ratoon (10 months)

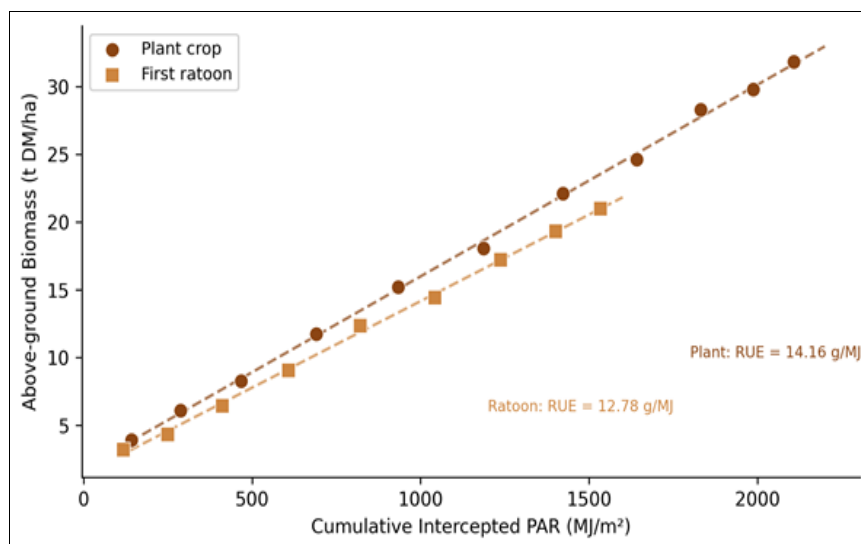


Fig 2: Relationship between cumulative intercepted PAR and above-ground biomass for plant crop and first ratoon. Dashed lines = linear regressions

Comprehensive interpretation

The plant crop intercepted more total PAR (2,108 MJ/m²) than the ratoon (1,534 MJ/m²) due to its longer duration and faster canopy development (Table 1). Peak fPAR reached 0.902 at month 8 in the plant crop versus 0.847 at month 8 in the ratoon. The upper canopy (>2.0 m) captured 47.3% of intercepted PAR in the plant crop but only 41.6% in the ratoon (Figure 1), reflecting the ratoon's shorter stature and lower stalk density. The linear iPAR-biomass relationship was strong for both crops ($R^2 > 0.94$; Figure 2), with RUE of 1.62 and 1.55 g/MJ, respectively (Table 2).

Discussion

The RUE values of 1.62 (plant) and 1.55 (ratoon) g DM/MJ fall within the range for well-managed tropical sugarcane [3, 5]. The slightly lower ratoon RUE is consistent with Park *et al.* [6], who attributed age-related decline to reduced stalk vigor and lower leaf nitrogen in successive cycles.

The canopy profile data show the upper canopy dominates PAR capture. The 14.8% of PAR reaching the soil in the ratoon represents lost productivity recoverable through narrower spacing or early intercropping [2, 12]. The strong linearity of iPAR-biomass supports radiation-driven models like APSIM-Sugar for yield forecasting [8, 16]. The extinction coefficients ($k = 0.58$ plant, 0.52 ratoon) can be directly incorporated into these models for Malaysian conditions [14, 20].

Conclusion

Solar radiation interception was the primary determinant of sugarcane biomass accumulation under non-limiting conditions at UPM Serdang. The plant crop intercepted 37.4% more cumulative PAR than the ratoon, translating into 43.7% higher final biomass. RUE was 1.62 g/MJ for the plant crop and 1.55 g/MJ for the ratoon. Linear models of iPAR versus biomass explained over 94% of variation in both crops. These results provide site-specific radiation interception parameters for calibrating sugarcane simulation models in tropical Southeast Asia and highlight the ratoon's canopy as a target for management interventions to close the plant-ratoon yield gap.

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