Industrial Crops and Products 50 (2013) 203–211

Contents lists available at ScienceDirect

Industrial Crops and Products

journal homepage: www.elsevier.com/locate/indcrop

Seasonal and interannual variations of evapotranspiration, energy exchange, yield and water use efficiency of castor grown under rainfed conditions in northeastern Brazil

José Romualdo de Sousa Lima[a,*], Antonio Celso Dantas Antonino[b,1], Eduardo Soares de Souza[c,2], Carlos Alberto Brayner de Oliveira Lira[b,1], Ivandro de França da Silva[d,3]

[a] Universidade Federal Rural de Pernambuco, Unidade Acadêmica de Garanhuns, Avenida Bom Pastor, s/n, Boa Vista, 55292-270 Garanhuns, Pernambuco, Brazil
[b] Universidade Federal de Pernambuco, Departamento de Energia Nuclear, Avenida Prof. Luiz Freire, 1000 Cidade Universitária, 50740-540 Recife, Pernambuco, Brazil
[c] Universidade Federal Rural de Pernambuco, Unidade Acadêmica de Serra Talhada, Fazenda Saco, s/n, Zona Rural, 56900-000 Serra Talhada, Pernambuco, Brazil
[d] Universidade Federal da Paraíba, Centro de Ciências Agrárias, Campus II, 58397-000 Areia, Paraíba, Brazil

A R T I C L E I N F O

Article history:
Received 9 January 2013
Received in revised form 17 June 2013
Accepted 4 July 2013

Keywords:
Latent heat flux
Net radiation
Stored soil water
Bowen ratio
Oilseed

A B S T R A C T

Brazil is the world's third largest producer of castor. The crop is mainly cultivated in the northeastern region of the country, but little information is available concerning the diurnal, seasonal and interannual variability of evapotranspiration (ET) and energy exchange of castor crops grown in the region, as well as the water use efficiency and yield. To address this gap in knowledge, the Bowen ratio method was used to measure energy balance and ET in 2004, 2005 and 2007. The experiments were performed in a 4-ha area at the Centro de Ciências Agrárias, Federal University of Paraíba in Areia in the state of Paraiba, Brazil (6°58′ S, 35°41′ W, elevation 620 m). The study site had a micrometeorological tower with sensors for measuring air temperature and relative humidity located at two heights above castor canopy. Global and net radiation, rainfall, soil heat flux, and stored soil water at 0–1.0 m depth were also measured. Measurements from all of the sensors were recorded by a data logger every 60 s and mean/sum data were logged every 1800 s. Over 3 years, the net radiation (Rn) varied from 53.2 to 461.7 W m^{-2} and soil heat flux (G) varied from −10.5 to 58.9 W m^{-2}. Variation in energy partitioning into latent (LE) and sensible (H) heat fluxes was mainly associated with changes in stored soil water. H values were higher in 2004 and 2005 (35% and 37% of Rn, respectively) than in 2007 (25% of Rn). Daily ET was very similar in 2004 and 2005 (2.29 and 2.34 mm day^{-1}, respectively) but increased to 3.42 mm day^{-1} in 2007, mainly due to increased volume and more even rainfall distribution throughout the growing season. Total ET was 299.5, 334.3 and 656.6 mm in 2004, 2005 and 2007, respectively. Castor showed a low yield (60, 324 and 988.3 kg ha^{-1} in 2004, 2005 and 2007, respectively) and low water use efficiency (0.02, 0.10 and 0.15 kg m^{-3} in 2004, 2005 and 2007, respectively), especially in drier years, indicating that under short water supply the water use efficiency of castor plants was very low. The seed oil content varied from 33.6% to 49.2% by weight. There was also a strong correlation between castor yield and daily ET (R^2 = 0.9433, RMSE = 91.1 kg ha^{-1}), and between castor yield and rainfall (R^2 = 0.9902, RMSE = 30.6 kg ha^{-1}).

Abbreviations: ET, evapotranspiration; Rn, net radiation; G, soil heat flux; LE, latent heat flux; H, sensible heat flux; RMSE, root mean square error; BREB, Bowen ratio and energy balance method; L, heat of water vaporization; EF, evaporative fraction; WUE, water use efficiency; LAI, leaf area index; Y, yield.

* Corresponding author. Tel.: +55 87 3764 5529.
E-mail addresses: romualdo@uag.ufrpe.br, romualdo_solo@yahoo.com.br (J.R.d.S. Lima), acda@ufpe.br (A.C.D. Antonino), eduardosouza@uast.ufrpe.br (E.S.d. Souza), cabol@ufpe.br (C.A.B.d.O. Lira), ivandro@cca.ufpb.br (I.d.F.d. Silva).
[1] Tel.: +55 81 2126 7973.
[2] Tel.: +55 87 3929 3026.
[3] Tel.: +55 83 3362 2300.

0926-6690/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.indcrop.2013.07.012

1. Introduction

Castor (*Ricinus communis* L.) is an oilseed crop that has commercial value for use in the manufacturing of surfactants, coatings, greases, fungistats, pharmaceuticals, cosmetics and many other products. More recently in Brazil, castor oil has been used to produce biodiesel, a promising alternative fuel that can be mixed with petroleum diesel to reduce air pollution (Pinheiro et al., 2008).

In recent years, the federal government of Brazil has encouraged the regional cultivation of oilseed crops for the production of biodiesel through the Brazilian National Program for Production and Use of Biodiesel. According to César and Batalha (2010) this program is strongly based on social development through the inclusion of family farmers in projects integrated with biodiesel power plants. However, although promising, the mechanisms of the federal program are still insufficient to promote the effective participation of family farmers (César and Batalha, 2010).

Based on the climatic conditions in northeastern Brazil, castor was the crop chosen for biodiesel production in the region. In addition to the castor being adapted to regional climatic conditions, increases in castor production could potentially create new jobs and keep people in the countryside, slowing the rural exodus (Oliveira et al., 2009).

Profits from castor cultivation are dependent on economic factors such as domestic and international markets and marketing, in addition to soil and plant factors that must be controlled at appropriate levels to optimize crop production. Therefore, it is necessary to understand the factors that influence crop yield, which include breeding, nutrition, crop management and water use, among others. Among these factors, water use (evapotranspiration) by castor plants has rarely been studied (Silva et al., 2007).

The evapotranspiration (ET) process is governed by the exchange of energy at the vegetation surface and is limited by atmospheric demand, making it possible to estimate latent heat fluxes using the principles of energy conservation. Based on the concept of energy conservation, evapotranspiration is estimated by a simplified formula of energy balance using net radiation (Rn) and latent (LE), sensible (H) and soil heat fluxes (G). The equation can be solved by obtaining measurements of Rn and G and estimates of H and LE using the Bowen ratio method (Teixeira et al., 1999).

The Bowen ratio energy balance method has been widely used by many researchers (Azevedo et al., 2003, 2007; Jamiyansharav et al., 2011; Lima et al., 2005, 2011; Takagi et al., 2009; Zhang et al., 2010) for measuring ET and the energy partitioning of several major crops.

Long-term experiments are essential for improving our understanding of seasonal and interannual variations in energy partitioning and water consumption by crops. Future changes in climate will affect the exchange of energy between an ecosystem and the atmosphere (Gu et al., 2005). However, there is a lack of detailed information about the energy exchange between the atmosphere and castor crops in the international literature, mainly in long-term experiments.

In this paper, we report results for evapotranspiration and energy fluxes in addition to yield and water use efficiency from a field experiment conducted with castor under rainfed conditions in 2004, 2005 and 2007. Our main objective was to examine seasonal and interannual variability in evapotranspiration and energy exchange and relevant controlling factors (weather variables, soil moisture and leaf area), as well as yield and water use efficiency.

2. Materials and methods

2.1. Experimental site, climate and soil and the study period

The experiment was conducted at the "Chã do Jardim" experimental station at the Centro de Ciências Agrárias, Federal University of Paraíba in the municipality of Areia in the state of Paraiba (6°58′ S, 35°41′ W, elevation 620 m) in northeastern Brazil (Fig. 1).

According to the Köppen classification, the regional climate at the site is *As'* (*i.e.*, hot and humid with summer rains). The mean annual rainfall at the experimental site is approximately 1400 mm, the daily mean air temperature is 24.5 °C and the daily mean relative humidity is 80%. The rainy season includes the months of April, May, June and July, during which 62% of the annual precipitation occurs (Oliveira et al., 2009). The soil at the experimental site is classified as yellow Latosol (EMBRAPA, 2006), which corresponds to an Oxisol in the American Soil Taxonomy (Soil Survey Staff, 2006).

Measurements were made in a castor field approximately 200 m long and 200 m wide (4 ha). All plantings were made on the same field in all 3 years. In 2004, castor was planted on July 16–17, and the harvest occurred on November 15–17 (growing season was 123 days). In 2005, the sowing occurred on May 31–June 1, and the harvest was November 5–11 (growing season was 164 days). In 2007, the sowing occurred on April 25–26, and the harvest was November 1–2 (growing season was 191 days). In all 3 years, the variety BRS 149 Nordestina was used for the plantings, and the seeds were sown in a seeding depth of 0.05 m, with 2.0 m between the rows and 1.0 m between the plants (planting density of 5000 plants per hectare), according to Severino et al. (2006). Castor yield was measured in all the plants in six areas of 200 m^2. The seed moisture content at harvest was 12–13%.

Two hand weedings were performed during the cropping cycle of castor each year. No pests or symptoms of disease were observed. In 2005, fertilization was performed during planting with 300 kg ha^{-1} of ammonium sulfate, 100 kg ha^{-1} of potassium chloride and 178 kg ha^{-1} of triple superphosphate. According to the analysis of soil fertility, fertilization was not necessary in 2004 and 2007.

2.2. Stored soil water and energy fluxes

Soil moisture was measured at depths of 0.05, 0.20, 0.40, 0.60, 0.80 and 1.00 m using a water content reflectometer (model CS 615, Campbell Scientific Inc., Logan, UT, USA). Stored soil water was calculated for the 0–1.00 m soil layer by the trapezium method (Hillel, 1998; Libardi, 2005).

A micro-meteorological tower was set up in the center of the experimental field and sensors were installed to record measurements of energy fluxes at the interface between castor/soil system and the atmosphere during the study period. The location of the tower provided a mean fetch of 100–140 m in all directions. Dry and wet bulb temperatures were measured using two integrated temperature–humidity probes (model HMP45 C, Vaisala, Campbell Scientific Inc., Logan, UT, USA) at two heights above the crops. Wind speed (u) was monitored with cup anemometers (model 014A, Campbell Scientific Inc., Logan, UT, USA) at two heights. The measurements were collected at 0.35 and 1.05 m above the top of the crop canopy. The height of the sensors increased as castor plants grew taller over the study period, such that the distance between the sensors and the crops did not change.

Net radiation (Rn) was measured with a net radiometer (model Q7 net radiometer, REBS, Seattle, WA, USA) installed 1.5 m above the vegetation surface. Solar global radiation (Rs) was measured with a pyranometer (model LI-200X, LI-COR Inc., Lincoln, NE, USA). Total rainfall was measured with a tipping bucket rain gauge (model TE 525WS-L, Texas Electronics, Dallas, TX, USA). Soil heat flux (G) was measured using two soil heat flux plates (model HFT3, REBS, Seattle, WA, USA) inserted at 0.05 m below the soil surface. Two temperature sensors (model 108L, Campbell Scientific Inc., Logan, UT, USA) were also located at 0.02 m and 0.08 m below the soil surface to calculate the surface ground heat flux (Kustas et al., 2000). Measurements from all of the sensors were recorded by