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Crop coefficients of Jatropha (Jatropha curcas) and Pongamia (Pongamia pinnata) using water balance approach

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Abstract

Jatropha and Pongamia are potential source of bio-diesel and grow in a wide range of agro climatic zones and soil conditions. Data and knowledge available on water requirement of Jatropha and Pongamia are very scarce. Crop coefficients are important parameters used for assessing water requirement and irrigation scheduling. In present study, crop coefficients of Jatropha and Pongamia were estimated using water balance approach. Temporal data on soil moisture at different depths in block plantations of Jatropha and Pongamia at ICRISAT farm, Patancheru in India were collected at 15 days interval between 2007 and 2010. Measured soil moisture data were analyzed using one dimensional water balance model. Results showed that annual water requirement of Jatropha is 750 mm and of Pongamia is about 950 mm in semi-arid tropics. Crop-coefficients of Jatropha ranged from 0.10 to 0.95 and of Pongamia from 0.30 to 1.10 depending on plant growth stage in different months. ICRISAT received 820 mm of rainfall in a normal year (data between 2001 and 2010) during the monsoon, of which 52 % (430 mm) contributed to evapo-transpiration, 34 % (280 mm) was stored in soil and, 14 % (110 mm) was lost through surface runoff. Stored soil moisture during monsoon season was subsequently utilized by the Jatropha and 270 mm converted into ET during non-monsoonal period. Pongamia utilized stored soil moisture more effectively than Jatropha as it could remove water from deeper soil layers even at high levels of soil moisture suction.

Key words: Bio-diesel, Jatropha, Pongamia, Green water, Semi arid tropics, Water Impact Calculator

INTRODUCTION

Food and energy security are becoming a major issue both for developing and developed countries all over the world. Biofuel such as ethanol and bio-diesel are considered as one of the potential alternatives to reduce fossil fuel dependency [1,2], also to reduce greenhouse gas emission and to sequester carbon [2,3,4]. In recent years, governments of many countries have targeted use of biofuel by blending it with conventional petroleum fuel and are promoted for wide industrial adaptability [1,5]. In contrary, it is also hypothesized that biofuel production at large scale may threaten the food security by competing with food crops and thus affecting the food supply and prices [6,7]. On the other hand, production of bio-diesel from plants grown in degraded lands offers opportunities to address the issues of environmental protection and provide options for improving rural livelihood especially in developing countries[3,8,9]. *Jatropha curcas* (Jatropha) and *Pongamia pinnata (*Pongamia) are identified as potential bio-diesel crops and may be grown in marginal and degraded lands with a wide range of rainfall and ecological conditions [4,10,11,12].

Although, the demand for bio-diesel is increasing, available data and knowledge on yield potential and water requirement of Jatropha and Pongamia are very limited and thus research efforts are required to address such issues[13]. However, few estimates on water requirements of Jatropha have been reported in literatures. For example, Rao *et al.*[14] reported that evapotranspiration (ET) from Jatropha plantation ranges from 1410 to 1538 mm in optimal conditions and 614-930 mm in field conditions in a semi-arid tropical location in India. They observed moisture extraction from soil layers 150 cm below from surface by five year old plants. Transpiration requirement of Jatropha was estimated as 300 mm and 500 mm at 4th and 12th year of growth stage at Owen Sithole College of Agriculture near Empangeni on the KZN north coast and Makhathini, Southern Africa, respectively [15]. Gush and Moodley[16] estimated total transpiration of 1983 ℓ (147 mm) for a 4-year-old *J. curcas* tree grown at a relatively wetter location, and 4884 ℓ (362 mm) for a 12-year-old *J. curcas* tree grown at a dry site of South Africa. Transpiration rate was found high during the warm wet summer months and negligible during winter due to the deciduous nature of the Jatropha species.

Water requirement of a plant may be estimated by multiplying crop coefficients (K_c) with atmospheric water demand (ET_0). In this method, effect of crop transpiration and evaporation are integrated by a single coefficient, which is known as crop coefficient[17]. The K_c-ET_0 approach provides a simple, convenient and reproducible way to estimate water requirement of crops in different climatic conditions[17,18]. Crop coefficient values have been reported for several crops [17] and tree plantations[19,20] and have been widely used for irrigation scheduling [17,21], simulation studies[22] and decision making process [17].

Several methodologies were developed for estimating K_c, for example, weighing lysimeter based techniques[23], agronomic measurements[18] and remote sensing-based techniques[24]. Irrespective to methodologies, basis for estimating K_c in all such techniques is common *i.e.*, computation of water and energy balance components. In the present study, we used soil moisture data collected at ICRISAT research station for analyzing water balance of Jatropha and Pongamia crops using one dimensional hydrological model. Specific objectives of the present study are: i) to estimate K_c for Jatropha and Pongamia crops and ii) to assess water requirements and analyzing field water balance of Jatropha and Pongamia crops in semi-arid tropics.

MATERALS AND METHODS

Experimental setup and data monitoring

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is located at 17° 53'N, 78° 27'E, and about 545 m above mean sea level in the Medak district of Andhra Pradesh, India. Climate of the study area is tropical monsoon. Long term (1974-2010) average annual rainfall is 898 mm (standard deviation, σ =225 mm), of which about 80-85% is received during June to October. Rainfall is highly erratic, both in terms of total amount and distribution over time. Monsoon is preceded by hot summers (minimum air temperature between 16^o and 29^{o}C and maximum air temperature between 30^o and 43^{o}C in May) and followed by cool winters (minimum air temperature in between 6^o and 20^{o}C and maximum air temperature between 23^o and 32^{o}C in December). Estimated potential Evapotranspiration (PET) of the study area is 1650 mm annually.

Two micro-watersheds each of 2 ha area were selected for cultivating Jatropha and Pongamia crops at ICRISAT research station, respectively. Soil of experimental site is classified as Vertisols having maximum depth up to 3 m. Topography of micro-watersheds is relatively flat with average slope between 1.0 and 2.0 %. Soil physical and chemical properties of experimental site e.g. bulk density, texture, organic carbon and soil water retention parameters were measured. Mean values of soil organic carbon was 0.65 % (standard deviation, σ=0.2) in 0-15 cm depth and 0.50 % (σ=0.10) in 15-30 cm soil depth. Soil bulk density of upper soil layers is relatively higher (1.4 g cm^{-3} up to 75 cm layer) compared to lower layers (1.2 g cm^{-3} between 120 and 150 cm). Bulk density of surface soil varied between 1.30 and 1.55 with average of 1.35 g cm^{-3} across the watersheds. Subsurface soils are high in clay content and hold more amount (soil moisture availability = 0.25 g/g) of soil moisture compared to shallow soils (soil moisture availability =0.14 g/g).

Jatropha (3 m × 2 m spacing) and Pongamia (5 m × 5 m spacing) seedlings were planted in year 2004. Crops were grown under rainfed conditions and chemical fertilizers were applied every year according to need of plants at its different growth stages. Nitrogen and phosphorus was applied @76 kg ha^{-1} and 10 kg ha^{-1}, respectively during 2006 and 2007. During subsequent growth stages, fertilizers dose was increased. Nitrogen and phosphorus was applied @ 92 kg ha^{-1} and 50 kg ha^{-1}, respectively during 2008 and 2009 Source of N and P in above fertilization was urea and single super phosphate, respectively[14]. Total 12 neutron probe tubes in each of Jatropha and Pongamia micro-watersheds were installed for monitoring soil moisture content. Schematic layout of the experimental setup is shown in **Figure 1** describing spacing and location of neutron probe tubes between the plants rows. Soil moisture content of each 15 cm thick layer was monitored from surface to 225 cm depth using calibrated neutron probe (Troxler 4302) at 15 days interval between 2007 and 2010. In addition, moisture in surface soils (0-15 and 15-30 cm) was also measured by gravimetric method. Daily weather data (rainfall, maximum temperature, minimum temperature, wind speed, solar radiation, relative humidity, and pan evaporation) of experimental site were collected from meteorological station located at 200 m distance from the micro-watersheds. Data on agronomic growth, seed yield and oil content were measured both from the Jatropha and Pongamia fields.

Description of simulation model

A simple and one dimensional hydrological model (Water Impact Calculator, WIC developed in ICRISAT) was used to analyze field water balance in the present study. WIC requires data on soil (soil depth and water retention), weather (reference evapotranspiration and rainfall), crop growth (biomass and root growth function), topography (land slope, land form conditions), *ex-situ* interventions (water harvesting capacity) and crop management (date of crop sowing and harvesting irrigation method) as an input. WIC analyzes water balance on daily time scale for each one cm soil layer (generate simulation matrix: time vs. soil depth). Rainfall, which is the only source of water for rainfed situation was partitioned into several hydrological components as defined by following mass balance equation:

Rainfall = Surface runoff + Deep percolation + Evapotranspiration (Evaporation + Transpiration) + Change in soil moisture storage Eq.1

Surface runoff is the flow of excess rainwater after soil becomes saturated and generally occurs either during or after the rainfall event. The SCS curve number technique[25] was used to estimate surface runoff in WIC. WIC calculates daily curves number value based on antecedent moisture content of surface soil layer (assumed for 15 cm depth in current analysis) and partition rainfall into surface runoff. Excess amount of infiltrated water after satisfying soil storage capacity is percolated below the crop root zone and is defined as deep percolation. Evapotranspiration comprises two basic hydrological processes: evaporation and transpiration. WIC calculates evaporation and transpiration based on imposed surface boundary conditions and moisture accessibility from surface soil layer and root zone. Water available in top 10 cm soil layer is contributed towards the evaporation demand, whereas, moisture available in root zone is used to meet crop water demand as defined by Allen et al.[17]. Crop water requirement (CWR) for a given crop is calculated such as:

$$CWR = K_C \times ET_0 \quad \text{Eq. 2}$$

$$\begin{aligned} &if:\ \sum_{i=1}^{rootzone} AWC > CWR \ \text{then}\ \mathrm{E}T = CWR \\ &\text{otherwise}\ \mathrm{E}T = \sum_{i=1}^{rootzone} AWC \end{aligned} \quad \text{Eq. 3}$$

where AWC is available water and *i* denotes each cm increment in soil layer reaching up to root zone. It was further assumed that evaporation from soil surface is inversely proportional to vegetative growth/stage. Thus, after achieving full vegetative crop growth (Kc ≥ 1.0), evaporation from the soil surface is considered almost negligible. Detailed description of WIC, model development, testing and validation procedure are shown by Garg *et al*. [26]

Estimation of crop coefficients

According to *FAO-56* nomenclature, *Kc* calculates water requirements under growing conditions having a high level of management and with little or no water stress[17]. Appropriate corrections need to be incorporated while estimating crop coefficients in case of water stress situation due to less water uptake. Allen et al. [17] described the effects of soil water stress on crop evapotranspiration (ETc) by multiplying the crop coefficient (*Kc*) and the water stress coefficient (Ks) with ET_0 such as: ETc = Ks x Kc x ETo Eq. 4

Soils of the experimental watershed are characterized by Vertisols which has medium to high water holding capacity and average depth of 2.5-3.0 m. In current study, *Kc* is estimated under the fully developed stage (between 2007 and 2011) and is expected to experience with minimal water stress situation. Despite this, whenever available soil moisture depleted below the threshold limit, stress adjustment in ETc was made as defined by Allen *et al* [17] and *Kc* was estimated using Eq. 4. Seventy per cent of total available water (soil moisture) is considered as readily available for crop uptake and further it declined linearly. Water stress coefficient (Ks in Eq.4) is assumed 0.7 for Jatropha and Pongamia as both are stress tolerant and deep rooted trees[17,27,28,29]. Crop coefficient of Jatropha and Pongamia crops were estimated using the inverse optimization technique. Solver is an optimization program built in Microsoft excel (developed for mixed integer nonlinear parameterization) was used for the current study. Based on field measurements, field capacity and permanent wilting point are defined for every 15 cm soil layer up to 300 cm depth. Maximum root zone depth for Jatropha and Pongamia plant is considered as 150 cm and 250 cm, respectively.[27,28,29] Model is set by assigning atmospheric boundary condition (rainfall and PET) on the soil surface as upper boundary and deep percolation from the bottom layer as the lower boundary. Simulation period is started after the four years of plant establishment. Total soil moisture status in root zone was used as the auxiliary variable in the objective function and crop coefficient at different crop growth stages were estimated using inverse optimization technique. WIC performance was assessed by comparing the simulated and measured soil moisture content using the root-mean-squared error (RMSE) of prediction:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \qquad \text{Eq. 5}$$

where n is the number of data points of measured (x_i) and simulated (y_i) profile soil moisture.

Estimation of crop water balance

The calibrated model set-up was used to simulate water balance of 10-year time period between 2001 and 2010 capturing large variability of rainfall. Water balance components (ET, runoff and soil moisture) are derived for dry, normal and wet years according to following classification (India Meteorological Department, Pune, India; http://www.imdpune.gov.in): Rainfall less than 20% of the long-term average = dry; Rainfall between –20% to +20% of the long-term average = normal; Rainfall greater than 20% of long-term average = wet.

Model further was used to estimate ET under non-limiting water stress situation both for Jatropha and Pongamia crops by applying auto irrigation setting in WIC between 2001 and 2010. Crop water stress was analyzed by considering difference between actual ET and ET under non-limiting water condition such as:

$$\text{Water Stress Factor (-)} = 1 - \frac{\text{ET actual}}{\text{ET under Non limiting water situtation}} \qquad \text{Eq. 6}$$

RESULTS AND DISCUSSION

Variation of soil moisture in Jatropha and Pongamia watersheds

Soil moisture variation in block plantations of Jatropha and Pongamia are depicted in **Figures 2a** and **2b**, respectively. Figures are divided into four panels and each one shows moisture profile of three consecutive months. In Jatropha field, new leaf flushes and biomass growth started by beginning of

April; flowering initiated by May/June; and pod formation and harvesting stage occurred between September and December[14]. Previous stored soil moisture into subsurface layers was used by Jatropha plants to fulfill water requirements during leaf sprouting. Thus, moisture level depleted significantly between April and June (**Figure 2a**). Large variation in moisture profile is observed between July and September, as this period coincided with peak vegetative growth and occurrence of monsoonal rainfall. Total soil moisture was found highest during September. Moisture in soil profile is depleted slightly during pod formation and harvesting stage during November/December. Variation in profile moisture was found minimal between January and March because crop entered into dormancy phase and leaf started falling down (**Figure 2a**). Soil moisture fluctuation generally was found up to 150 cm indicating maximum effective rooting depth for Jatropha crop.[27]

In Pongamia field, low variation in moisture profile was observed during April and June, indicating lesser water uptake (**Figure 2b**). Soil moisture content was increased during monsoon season and depleted subsequently in non-monsoonal period as expected. Data showed that Pongamia being a perennial crop could extract water from deeper and drier soil conditions. Several other studies indicated that Pongamia has an extensive lateral root system and thick-long tap root[28], which could be developed maximum up to 5-10 m length at fully matured stage[29]. Soil moisture level in Pongamia cultivated field is depleted much higher compared to Jatropha cultivated fields. For example, soil moisture content for Jatropha and Pongamia cultivated field in month of May-June was recorded as 0.2-0.3 $cm^3\ cm^{-3}$ and 0.03-0.15 $cm^3\ cm^{-3}$, respectively.

Model performance

Soil moisture measured in Jatropha and Pongamia fields is compared with model simulated moisture level between 2007 and 2011. Simulated soil moisture fluctuations are found comparable with observed numbers at most of the times both for Jatropha and Pongamia cultivated fields. Root mean square error in estimating profile moisture is 6.0 cm and 5.0 cm, which is equivalent to less than 10 % of total moisture in given soil profiles, thus model performance is considered acceptable.

Crop coefficients and crop water requirements

Crop coefficients estimated for Jatropha and Pongamia crops are summarized in **Table 1**. K_c for Jatropha and Pongamia are found in range between 0.10-0.95 and 0.30-1.10, respectively. Maximum K_c was found during August and September for both the crops.

Water balance components of Jatropha and Pongamia fields are summarized in **Table 2**. During normal years, rainfall recorded was 911 mm (820 mm in monsoon and 91 mm in non-monsoon) at experimental site. In these years, ET from Jatropha and Pongamia crop were estimated to be 685 and 830 mm year^{-1}, respectively. Surface runoff generated from both the crop lands is found almost similar, i.e., 130-135 mm (15 % of total rainfall). In Jatropha field, nearly 100 mm rainfall was harvested in terms of green water. In Pongamia fields, 35 mm of net deficit in green water storage was observed by end of the crop season in normal years.

ET from Jatropha and Pongamia field was found larger than the rainfall received during dry years. About, 130-150 mm harvested green water in previous years was utilized by crops during dry years as shown by negative balance (**Table 2**). Surface runoff and deep percolation volume were estimated to be 90-100 mm, i.e., 14% of rainfall received. Results showed that poor rainfall in dry years led to develop water shortage by 21 % (in terms of ET) than the required quantity for Pongamia crop (shown by water stress factor in Table 2). On the other hand, crop water demand and availability for Jatropha crop was found in comparable range.

To show a detail description of mass balance, the monthly water balance of Jatropha and Pongamia field is presented for one of the selected normal year (**Figure 3**). Total 850 mm of rainfall was received during monsoon in year 2003. Thirty four per cent of monsoonal rain was captured as soil moisture, 52 % (440 mm) contributed to ET and 14 % (120 mm) was exported as surface runoff. In non-monsoon period (Nov-May), harvested green water acted as source of water as shown in **Figure 3**. Results showed that water requirements of both the crops were nearly same during monsoon period (460 mm) but Pongamia required additional 200 mm water during non-monsoon season compared to Jatropha (240 mm). June is found the critical period for Jatropha growth and supplemental irrigation could be helpful in dry years.

Conclusions

Jatropha and Pongamia are potential bio-diesel crops and could be grown in wide range of agro-climatic and soil conditions. Water requirement of these two crops are estimated in the current study. Key findings of this study are:

1. Water requirements of Jatropha and Pongamia are estimated to be 750 and 950 mm in semi-arid tropics, respectively. Water balance showed that at ICRISAT out of 820 mm rainfall received

during monsoon period, 52 % was contributed to ET, 34 % stored as soil moisture and 14 % exported outside from watershed as surface runoff. Consumptive water use by Jatropha and Pongamia are found to be nearly same in monsoon, i.e., 460-500 mm. Water requirement (ET) of Jatropha during non-monsoon period is found as 265 mm. Pongamia required 200 mm additional water than Jatropha during non-monsoonal period.

2. Crop coefficients of Jatropha and Pongamia ranged from 0.10-0.95 and 0.30-1.1 depending on growth stage, respectively. Pongamia is found to utilize green water from deeper and drier soil layers compared to Jatropha crop.
3. Water availability for Pongamia crops was found adequate in wet years but slightly less (10% shortage) in normal year. Poor rainfall in dry years led to develop water shortage by 20 % than the required quantity in Pongamia field, whereas Jatropha experienced negligible water stress in all the years. *In-situ* moisture availability played an important role in supplying water both for Jatropha and Pongamia crops especially in non-monsoon period.

Crop coefficient estimated in current study could be useful to assess technical feasibility to grow Jatropha and Pongamia crops in different agro-ecological regions and soil conditions.

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Table 1: Crop coefficient for Jatropha and Pongamia tree crops on monthly time scale

Month	**K_c of Jatropha**	**K_c of Pongamia**
April	0.20	0.30
May	0.40	0.40
June	0.60	0.40
July	0.85	0.70
August	0.90	0.90
September	0.95	1.10
October	0.80	1.10
November	0.70	1.10
December	0.50	0.75
January	0.30	0.65
February	0.10	0.60
March	0.10	0.35

Table 2: Water balance of Jatropha and Pongamia cultivated fields at ICRISAT for 10 years simulation period

Crop cultivated	Year	No of year	Water balance components						Water stress factor (-)
			Rainfall (mm)			Surface runoff + Deep percolation (mm)	ET (mm)	Change in SMC (mm)	
			Jun-Oct	Oct-May	Annual rainfall				
Jatropha	Dry	2	612	40	652	90	690	-128	0.01
Jatropha	Normal	6	820	91	911	130	700	80	0.01
Jatropha	Wet	2	1179	71	1250	322	808	118	0.00
Pongamia	Dry	2	612	40	652	95	710	-153	0.21
Pongamia	Normal	6	820	91	911	115	830	-35	0.10
Pongamia	Wet	2	1179	71	1250	249	953	48	0.00

The calibrated model set-up is used to simulate water balance for a 10-year time period between 2001 and 2010. Water balance results are presented for dry, normal and wet years according to following classification (Indian Meteorological Department, Pune, India; http://www.imdpune.gov.in): Rainfall less than 20% of the long-term average = dry; Rainfall between –20% to +20% of the long-term average = normal; Rainfall greater than 20% of long-term average = wet;

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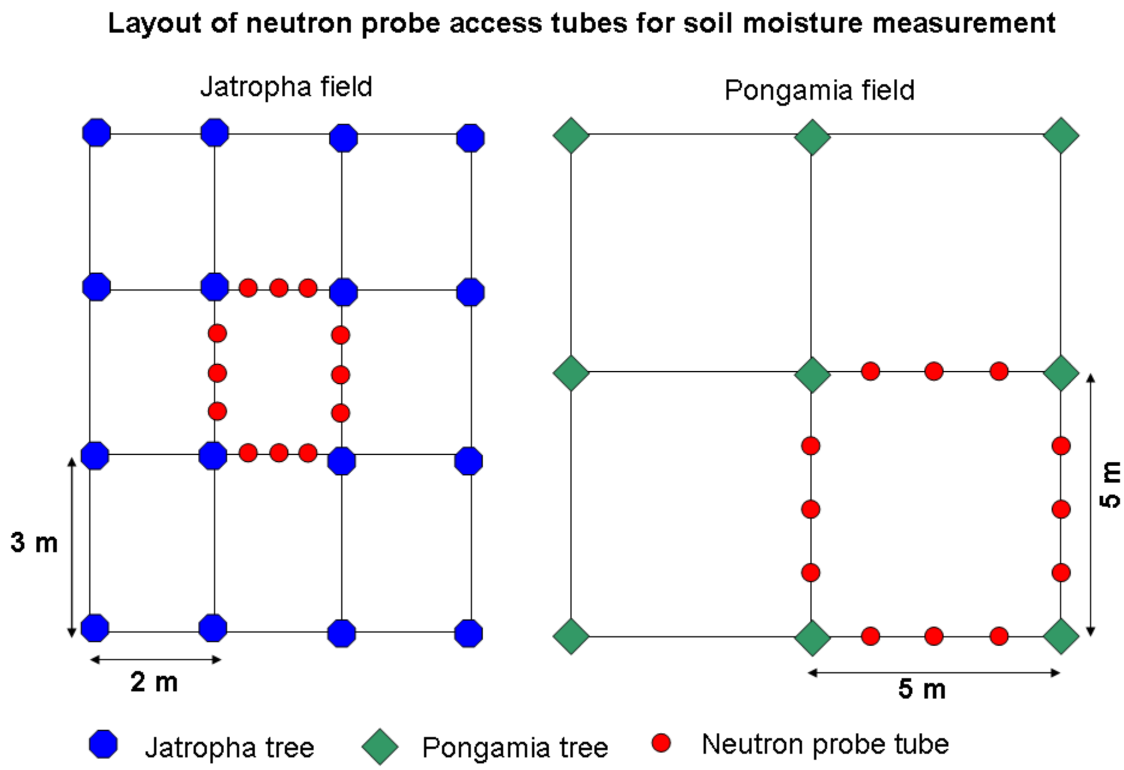

Figure 1: Layout of neutron probe access tubes for soil moisture measurement in Jatropha and Pongamia field at ICRISAT, Patancheru.

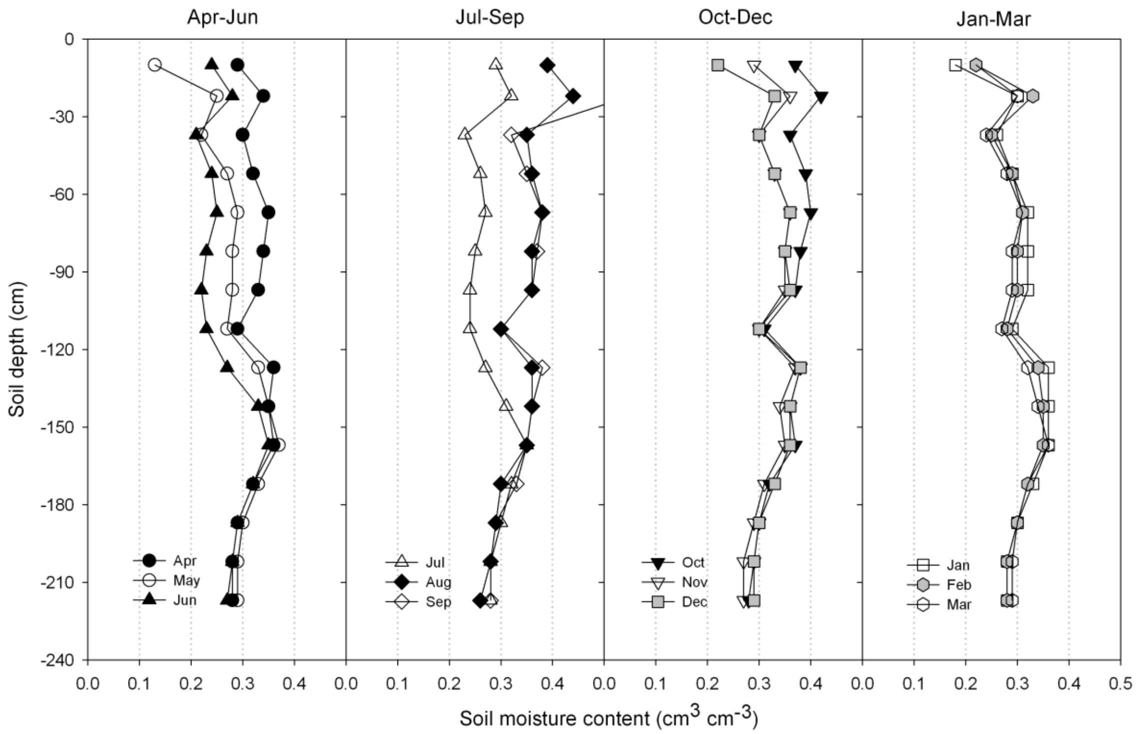

Figure 2a:

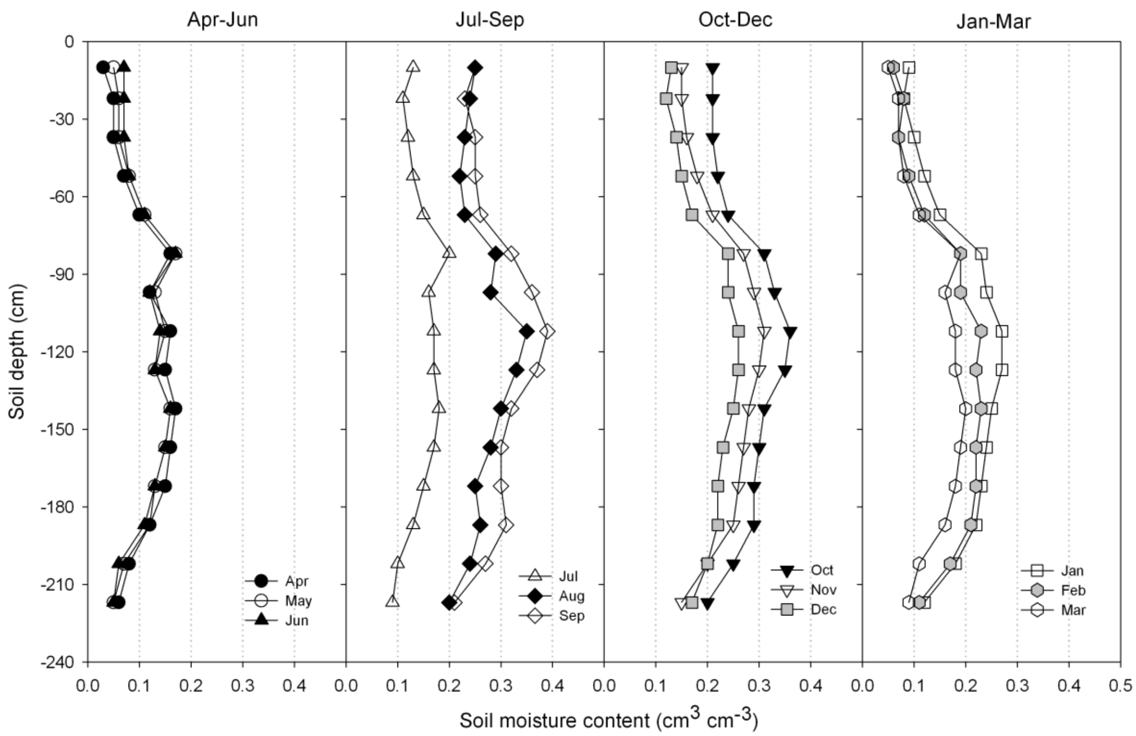

Figure 2b:

Figure 2a Depth wise soil moisture content during 12 months in Jatropha experimental field

Figure 2b Depth wise soil moisture content during 12 months in Pongamia experimental field

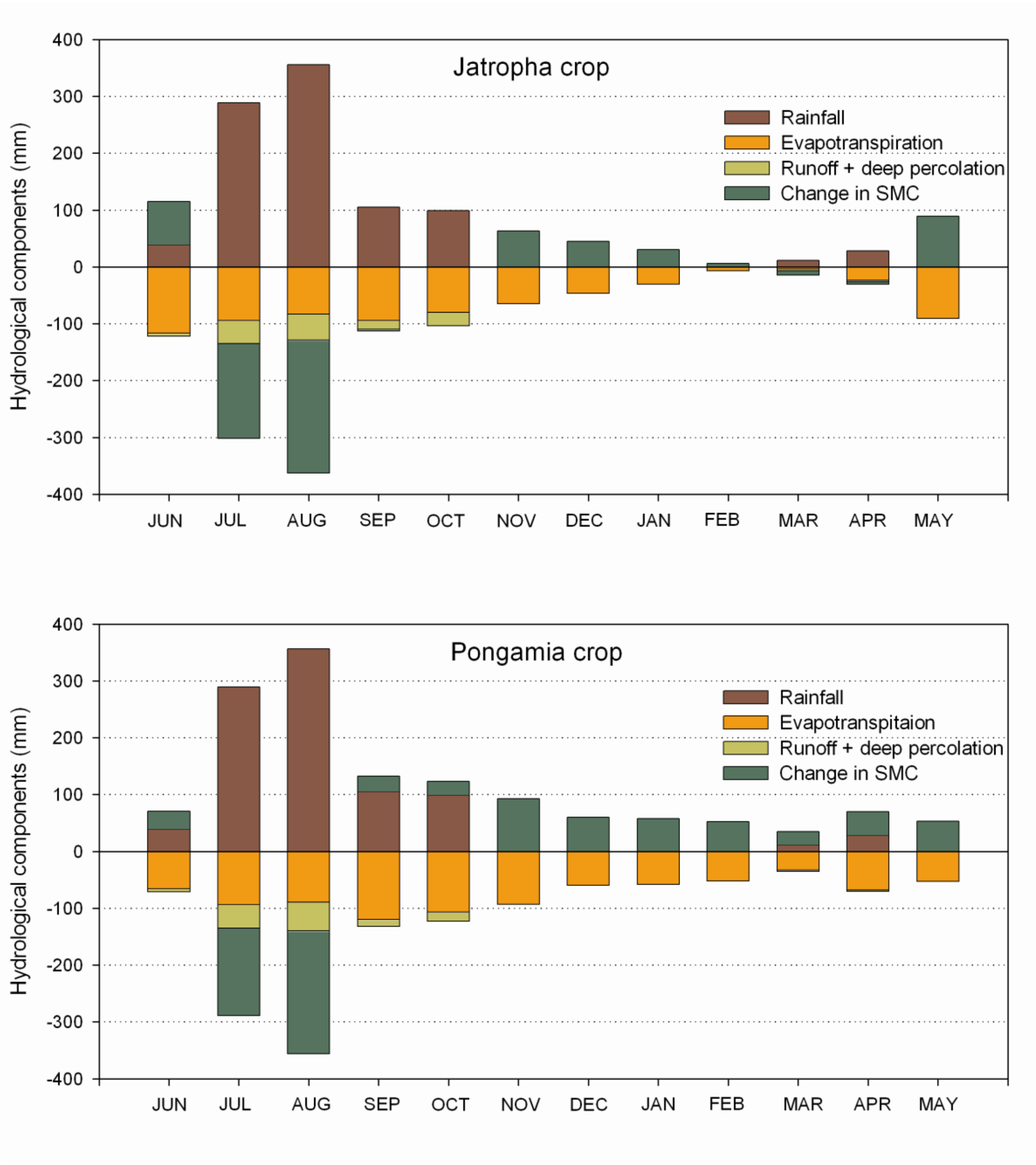

Figure 3 Monthly simulated water balance of Jatropha and Pongamia fields at ICRISAT for a selected normal year (2003-2004); the upper part of the graphs show the source of the water (rainfall and change in soil moisture content), and the lower part presents various sink components: ET, surface runoff, deep percolation, change in soil moisture content