Modeling and Analysis

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Water needs and productivity of *Jatropha curcas* in India: myths and facts

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Abstract: *Jatropha curcas* referred as a 'wonder plant' with low water requirement, which can be cultivated on wastelands in dry tropical conditions to provide oil seeds for biodiesel without competing for prime cropland. However, results from experiments and case studies in semi-arid tropical locations in India indicated that evapotranspiration (ET) demand for Jatropha ranges between 750 and 1000 mm under optimal conditions. Jatropha extracted water from soil layer 150 cm below with transpiration requirements of 600–800 mm with increasing age. The yield potential of current genotypes is low (2–3 ton/ha) for realizing the potential of Jatropha cultivation on wastelands subject to limited availability of nutrients and water. *Jatropha curcas* is drought tolerant, but contrary to belief, it is not a crop that requires less water: in fact, it requires 750–1000 mm water to achieve economic production. However, *Jatropha curcas* demonstrated good potential for enhancing green water use efficiency without adversely affecting the blue water component, and for promoting crop management options facilitating carbon sequestration and nutrient recycling when grown on degraded lands. Improved cultivars of *Jatropha curcas* with synchronized flowering to enable mechanical harvesting, along with improved land and water management, are needed for harnessing the potential of Jatropha as a commercially viable biofuel crop. © 2016 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: energy security; feedstock; biofuel; biodiesel; water balance; wasteland

Introduction

Demand and energy security

Food and energy security are major concerns for developing and developed countries all over the world. India is the fifth largest primary energy consumer and the fourth largest petroleum consumer in the world.[1] With increasing energy demand, the import of crude oil in India has increased from 39.8 million metric tons in 1998 to 184.8 million metric tons in 2012/2013 and this has raised oil import expenditure US$144.3 billion in 2012/2013.[1] In recent years, governments of many countries including India have targeted the use biofuel by blending it with conventional petroleum fuel and have promoted its use at industrial scale.[2–4] Biofuels such as ethanol and biodiesel are considered potential alternatives to reduce crude oil

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dependency[4–6] and also promising measures to mitigate climate change effect as they can reduce or offset greenhouse gas (GHG) emissions by directly removing carbon dioxide from the air as they grow and store it in crop biomass and soil.[5–8]

Generated biodiesel in India is currently used for industrial furnaces and the textile industry, and is being exported rather than used in vehicles. The government of India approved the national policy on biofuels in 2009 targeting a 20% blend of biofuels with gasoline and diesel by 2017. Diverting agricultural area for biofuel production is not feasible due to increasing food demand; but there is a large area of degraded lands offering opportunities to grow biofuel plantations as well as increase green cover to minimize further degradation of land with investment in land management, community participation, and converging various state and national schemes/programs together. Land use assessment made by National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), reported that nearly 120.4 million ha land in India is available under the wasteland category. These lands generally are not suitable for agricultural production due to excessive soil erosion, pH, salinity, alkalinity, water logging, and high land slope. However, wasteland/rangeland is being used as common property resources largely for animal grazing and collecting fuel wood but also contributes to supplying regulating and supporting ecosystem services (e.g. run-off generation, groundwater recharge). Managing wasteland for biofuel production is further considered for protecting environmental degradation and strengthening ecosystem services (e.g. reduced soil loss, increased carbon sequestration) and also providing options for improving the livelihoods of the rural community by creating employment opportunities.[8–12]

Jatropha

Jatropha (*Jatropha curcas L.*), commonly known as 'purging nut' or 'physic nut', is a perennial deciduous, multipurpose shrub belonging to the family *Euphorbiaceae.*[13,14] *Jatropha curcas* (Jatropha) is identified as a biodiesel crop and has potential to grow in marginal and degraded land with a wide range of rainfall from 300 to 3000 mm, either on farms as a commercial crop or on the boundaries as a hedge to protect fields from grazing animals and to prevent erosion.[8,10,15–21] Extracted Jatropha oils have been reported as being used directly in high rpm diesel engines for power generation as well as for pumping water.[20] The use of blended fossil fuels with biofuels results in substantial reduction of unburnt hydrocarbons by about 30%, carbon monoxide by about 20%, and particulate matters by about 25%. Moreover, sulfur content in the emissions from the use of blended fuels is almost negligible.[22] These crops can not only meet the oil demand for biofuel production but also rejuvenate wastelands without sacrificing the food and fodder security and improve the livelihoods of rural poor.[20]

A large variation in the seed yield of Jatropha is reported from different field and research experimental trials. The seed yield of Jatropha depends on rainfall amount, soil moisture availability, and fertility;[18,19,22,23] plant age;[24] genetics;[14,25,26] and management factors like fertilization application, pruning and disease control.[16,19, 25,27,28] Annual yield levels of Jatropha at 2-3 tons dry seeds per ha have been proposed as achievable in semi-arid areas and also on wastelands, while 5 tons can be obtained with good management on good soils receiving 900-1200 mm average annual rainfall.[21,22,24,29]

Policy support and demand for biodiesel, however, is increasing but insufficient knowledge of technical and economic suitability of Jatropha in various agro-ecological regions, limited knowledge on water requirement, lack of organized breeding programs, and limited agronomic and input response studies are the main limiting factors for inadequate investments by developing and private agencies. In the absence of such data and knowledge, hypothetical claims about Jatropha in terms of yield potential, water and nutrient requirements, and tolerance to pests and diseases were made which misled stakeholders and raised uncertainty of expected returns.

Scope and aim of study

In this paper we report the findings of our strategic and development research conducted over the last eight years. The study analyzed water requirements and yield potential of Jatropha at field, watershed, and national scale. It also discusses various challenges and opportunities to harness the potential of biodiesel plantations for protecting the environment while improving rural livelihoods. Specific objectives of the current study are: (i) comparing crop yields of various genotypes obtained from field experiment and its response to rainfall variability; (ii) analyzing water balance of Jatropha, and (iii) analyzing technical feasibility of Jatropha in wastelands located at different rainfall levels and ecological zones.

Material and methods

Field experiment at ICRISAT

Genotype evaluation using field experiment

A total of 124 accessions of Jatropha were evaluated at ICRISAT headquarters at Patancheru, Telangana, India. Out

Table 1. Fertilizer scheduling details of different Jatropha accessions/collections evaluated.

Age of plan	Accessions/collections		
(years)	IJC	CSMCRI	NBPGR
	Urea (g/plant)		
1	50	33	75
2	50	33	75
3	72	48	108
4	80	53	120
5	120	80	180
	Triple super phosphate (g/plant)		
1	55	37	82
2	55	37	82
3	77	51	115
4	85	57	127
5	127	85	190

of these, 97 were accessed from the National Bureau of Plant Genetic Resources (NBPGR), Rajendranagar, Hyderabad, Telangana; 12 from Central Salts and Marine Chemicals Research Institute (CSMCRI), Bhavanagar, Gujarat; and 15 from across different places in India referred as to as the ICRISAT Jatropha Collection (IJC). IJC collections were planted during 2004 and 2005 in ICRISAT fields, namely BL3 (N 17^0 30' 06.5" and E 078^0 16' 11.1") and BL5 (N 17^0 29' 56.9" and E 078^0 16' 02.5") at 3 m × 2 m spacing. NBPGR and CSMCRI accessions were planted during 2006 in ICRISAT field namely BW8 (N 17^0 30' 10.8" and E 078^0 15' 42.4"). The spacing for plantations was 3 m × 3 m in case of NBPGR accessions and 2 m × 2 m in case of CSMCRI accessions. Plant density obtained in case of IJC was 1667 ha^{-1}; 1111 ha^{-1} for NBPGR accessions and 2500 ha^{-1} for CSMCRI accessions. The plants were established in a rectangular/square pattern. Jatropha seedlings were raised in nurseries, followed by their transplantation during the rainy season (June-July) in pits measuring of 0.3 m × 0.3 m × 0.3 m.

Nitrogen (N) and phosphorus (P) fertilizers were applied during beginning of monsoon (Table 1). Replanting in some of the patches was done in the second year to fill the gaps (5 to 10%). Pruning excess to 1.5–2.0 m plant height was also done in post-rainy winter season (January-February) to maintain required canopy and promoting secondary branching for more fruiting from the second year of plant establishment. Manual weeding was done during June/July prior to fertilizer application. During weeding, soil across the plant is tilled to create congenial environment for plant growth. Harvesting of pods started from the second year onwards. Harvesting of seed was done manually between September and December. Numbers of agronomic parameters (plant height, stem diameter, crown area, number of branches, and seed yield) were measured for all the accessions from 2008 onwards.

Moreover soil moisture at every 15-day interval is recorded in one of the experimental site (BW8 watershed) using neutron-probe (Troxler 4302) moisture meter up to 225 cm soil depth. 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 the experimental site were collected.

Modeling water requirement and yield potential of Jatropha

Description of simulation model

Water balance is an essential and primary step to quantify resource availability and various demands at a given landscape. A one-dimensional water balance model - the Water Impact Calculator[30] - is assumed to capture field-scale hydrology in the current analysis. Rainfall, the source of the water, is partitioned into different hydrological components as defined by mass balance equation such as:

$$\begin{aligned}\text{Rainfall} = {} & \text{Surface run-off} \\ & + \text{Groundwater recharge} + \text{Evapotranspiration} \\ & (\text{Evaporation} + \text{Transpiration}) \\ & + \text{Change in soil moisture storages}\end{aligned} \quad (1)$$

In Eqn (1), a fraction of rainfall stored in the vadoze zone is known as green water; and rainfall stored/partitioned in a groundwater aquifer and surface run-off is known as blue water.[31] A description of the system parameters and hydrological processes used in WIC is give below.

Run-off estimation

Surface run-off is the water flow that occurs when top soil is saturated during or after the rain event and excess rainwater flows over the landscape. Run-off is an important hydrological process which is controlled by soil biophysical, climatic, topographical, and land management factors (soil type, land slope, land use, and land management practices). The empirical Soil Conservation Service (SCS) run-off equation[32] was used to estimate surface runoff in WIC:

$$Q = \frac{(P-I)^2}{P - I + S} \quad (2)$$

where Q is surface run-off, P is precipitation, I is initial abstractions, and S is retention parameters which depend on soil physical properties, topography, and land use-land management factors.

Retention parameter and Initial abstraction is defined as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \quad (3)$$

$$I = 0.2S \quad (4)$$

where, CN is the curve number of a day under average soil moisture condition (CN_2). WIC calculates the daily curves number value based on antecedent moisture content of top soil layer (assumed for 15 cm depth in the current analysis). The curve number for three types of moisture situation is defined in WIC: dry, medium, and wet soil. Dry represents when soil moisture status reaches closer to permanent wilting stage, and wet represents when soil moisture level is at field capacity. The curve number for dry (CN_1) and wet (CN_3) situation are defined as:[33]

$$CN_1 = CN_2 - \frac{20(100 - CN_2)}{(100 - CN_2 + \exp[2.533 - 0.0636(100 - CN_2)])} \quad (5)$$

$$CN_3 = CN_2 \cdot \exp[0.00673 \cdot (100 - CN_2)] \quad (6)$$

WIC initially assigns CN based on average land slope as defined by Hawkins.[34] After initialing CN for day^{-1}, CN for subsequent days is estimated based on available moisture in top 0–15 cm layer (Eqns (5) and (6)).

Soil water balance

Soil water balance is most crucial to evaluate as it largely controls hydrological processes. It is assumed that moisture in soil profile varies between field capacity and permanent wilting point. After separating run-off from rainfall, effective rainfall is allowed to infiltrate into soil. After filling soil pores up to field capacity, surplus water is allowed to move down in subsequent layers. Moisture in each centimeter soil layer is defined by mass balance approach such as:

$$\text{Soil moisture at day}_i = \text{Rainfall} + \text{Soil moisture at day}_{i-1} - \text{run-off} - \text{Evaporation} - \text{Transpiration} - \text{Deep percolation} \quad (7)$$

Deep percolation

Excess infiltrated water after satisfying soil storage capacity is allowed to drain out from bottom boundary of the profile. This water either joins the groundwater aquifer or partially contributes to the base flow at downstream location (not partitioned into base flow in current version).

Evapotranspiration (ET) estimation

The term evapotranspiration comprises two basic hydrological components: evaporation and plant transpiration. Evaporation is the vapor movement from earth surface, soil (green water), and water bodies (blue water) to atmosphere; whereas vapor movement through plant stomata is known as transpiration. Evaporation and transpiration, however, are two process/components of the hydrological cycle but their separation and quantification is challenging due to its complexity and inter-dependability.

Reference crop evapotranspiration (ET_0)

ET_0 is ET under a situation when a large area is covered uniformly with growing vegetation (usually alfalfa) and the water availability for the plants is non-limiting.[35,36] WIC calculates ET_0 from meteorological parameters (max and min temp, relative humidity, wind speed, and solar radiation) using the Penman-Monteith method;[37] or alternatively it also could be directly taken from other sources and used as input into the model. ET_0 is the parameter describing daily evaporative demand of a given location and is the primary basis for calculating actual evaporation and transpiration on a given boundary conditions.

Actual evapotranspiration

After obtaining or estimating ET_0, WIC calculates actual evaporation and transpiration based on imposed surface boundary conditions and moisture availability in top soil layer and root zone. We considered that available soil moisture in the top 10 cm layer will contribute to satisfying evaporation demand, whereas moisture up to root zone will be available for crop use (for transpiration). Moreover, it is assumed that evaporation from the landscape is inversely proportional to vegetative growth. After achieving full vegetative crop growth ($K_c >= 1.0$), evaporation will be negligible.

Mathematically crop water requirement (CWR) and evaporation demand (ED) are described as:

$$CWR = K_C \times ET_0 \quad (8)$$

$$ED = (1 - K_C) \times ET_0 \quad (9)$$

$$\text{if}: \sum_{j=1}^{rootzone} AWC > CWR \text{ then } T = CWR$$

$$\text{otherwise } T = \sum_{j=1}^{rootzone} AWC \quad (10)$$

$$\text{if}: \sum_{j=1}^{10\,cm} AWC > ED \text{ then } E = ED$$

$$\text{otherwise } E = \sum_{j=1}^{10\,cm} AWC \quad (11)$$

where *AWC* is the available water content (Field Capacity – Permanent Wilting Point). WIC makes the water balance for each cm soil layer up to a defined soil depth (one-dimensional) as shown by the symbol (j) in Eqns (10) and (11).

Data collected from field experiments was used to analyze field-scale hydrology using WIC. WIC requires soil (water retention and soil depth), weather (ET_0 and rainfall), crop growth [biomass (k_c), root growth function, and topography (land slope, land form conditions) details as inputs to the model. WIC was well calibrated and validated with different soil types, land use, and cropping systems using different water balance components (surface run-off and soil moisture) measured at ICRISAT and during on-farm trials[31] before applying to the present data set.

Crop coefficients and estimating water requirement of Jatropha

The water requirement of a plant could be estimated by multiplying crop coefficients (K_c) with atmospheric water demand (ET_0). In this method, the effects of crop transpiration and evaporation are integrated by a single coefficient, which is known as crop coefficient.[37] The K_c-ET_0 approach provides a simple, convenient, and reproducible way to estimate the water requirement of crops in different climatic conditions.[32] Crop coefficients of Jatropha estimated by Garg *et al.*[38] were used directly to assess the water requirement of experimental fields at ICRISAT and also at other targeted states in India. Crop coefficient of Jatropha varies between 0.01 and 0.90 (Table 2)[38] used in the current study. New leaf flushes and biomass growth starts by the beginning of April; flowering is initiated by May/June; and pod formation and harvesting stage enters between September and December[38,39] and consequently water requirements differ. The largest K_c of Jatropha is reported in July and August and the minimum between January and March under the Indian semi-arid tropical climatic condition (Table 2).

Production function of Jatropha

Water stress developed in Jatropha is estimated based on consumptive water used (ET_a) and water required under non-stress conditions (ET_c). FAO (Paper No. 33, Irrigation and Drainage) describes the linear relationship between crop yield and water use where relative yield reduction is related to the corresponding relative reduction in evapotranspiration or developed crop water stress[40–42] as shown in Eqns (12) and (13):

Table 2. Crop coefficient for Jatropha on a monthly time scale.[38]

Month	Kc for Jatropha
January	0.2
February	0.4
March	0.6
April	0.85
May	0.90
June	0.95
July	0.80
August	0.70
September	0.50
October	0.30
November	0.10
December	0.10

$$\left(1 - \frac{Y_a}{Y_x}\right) = K_y\left(1 - \frac{ET_a}{ET_c}\right) \quad (12)$$

$$CropWaterStress = 1 - \frac{ET_a}{ET_c} \quad (13)$$

where Y_x and Y_a are maximum and actual yields, respectively; ET_c and ET_a are maximum (non-stress) and actual evapotranspiration, respectively; and Ky is the correlation or proportionality factor between the related productivity loss and the related evapotranspiration reduction.[36]

Water balance components at watershed scale

Jatropha cultivation in community watershed, Velchal

The effects of wasteland conversion to biofuel plantations on water flows and sedimentation losses are assessed for a formerly degraded wasteland belonging to the Velchal village (17.28°N latitude, 77.52°E longitude, 645 meters AMSL), approximately 50 km outside of the city of Hyderabad, Telangana. This wasteland consists of hillock, which is relatively flat (2–3% slope) and with a sparse vegetation cover of some trees and grass, and a valley (10–25% slope) covered with various types of bushes and perennial trees. Soils have been classified as intergrade Vertisols with a very shallow soil depth between 10 and 50 cm as an effect of over grazing. The water holding capacity is medium to low, and the soil organic carbon content is between 0.60 and 1.2%.[21]

In the year 2005, ICRISAT together with local community, planted Jatropha on 160 ha common property belonging to the Velchal village and classified as wasteland. These plantations are mainly located in the hillock area, although some plantations are also found in lower flat areas. The purpose of the Jatropha cultivation in the community wasteland was to develop a model to improve the livelihoods of the poor, through promotion of plantations managed by user groups on common pool land resources. Water balance components of Jatropha cultivated landscape are analyzed and compared with control watershed (barren land). Jatropha plantation in village and details on model calibration and parameterization are described by Garg *et al.*[21]

Water requirement and yield potential of Jatropha in different rainfall and ecological regions of India

The further technical suitability of Jatropha plantation was analyzed for ten Indian states (Andhra Pradesh, Telangana, Chhattisgarh, Gujarat, Karnataka, Madhya Pradesh, Orissa, Rajasthan, and Utter Pradesh) which cover nearly 75% of total wasteland in India. Soil physical properties of different locations in these states were collected from the NBSS&LUP database. The water retention properties of wasteland are the range of 50 to 80 mm/m. The water-holding capacity of the deeper soil layer (50–100 cm) is found to be half as much as the top soil layer (0–50 cm) due to a large portion of rock and gravel fraction.

Meteorological data (daily rainfall, wind speed, max and min temperature, solar radiation, and relative humidity) were collected from the Indian Meteorological Department, Pune, India. Weather parameters were used to estimate reference evapotranspiration (ET_0). Model (WIC) was run for two land use conditions: (i) current stage of wasteland which considers grasses over the landscape and (ii) a fully grown Jatropha condition. To capture these scenarios, land management and agronomic parameters were modified as shown in Table 3. Initial curve number values of both land uses were assigned with a difference of number five; Root uptake depth for bare wasteland and Jatropha land were considered as 50 cm and 100 cm, respectively; Crop coefficients (K_c) of bare wasteland was considered 0.1–0.5 and for Jatropha landscape was taken at 0.1–0.9.

The model was run for a 10-year period. Water balance results were analyzed for dry, normal, and wet years according to the following classification (Indian Meteorological Department, Pune, India): Rainfall less than 20% of the long-term average = dry; Rainfall between –20% and +20% of the long-term average = normal; Rainfall greater than 20% of long-term average = wet.

Results and discussion

Field experimental results

Genotype yield response and crop water requirement

Jatropha yields measured from the ICRISAT experiment between 2009 and 2013 are summarized in Fig. 1. Huge variability is found in seed yield from different accessions and also from year to year. Seed yields in 2009 were relatively low as it was merely the second or third year of Jatropha plantation. Yield levels increased from the fourth year onwards. Average seed yield was between 350 and 560 Kg/ha from 2010 to 2012 (Table 4). The performance of various genotypes is grouped into four categories based on seed yield which is summarized in Table 5. Out of 124 genotypes, seed yields measured from 19 accessions were only higher than 1000 Kg/ha and most of them were below 500

Table 3. Parameters to simulate two different land use in current study (i) wasteland, (ii) Jatropha land on wasteland.

Parameters	Wasteland covered by wild grass	Wasteland covered by Jatropha crop
Root depth (cm)	50	100
Land management	Rain-fed without land management	Rain-fed with in situ interventions
Runoff estimation	SCS curve number (CN)	CN – 5
Land slope (%)	5–10%	5–10%
Soil Available water (mm/m)	50–80	50–80
Crop coefficients	0.1–0.5	0.1–0.9

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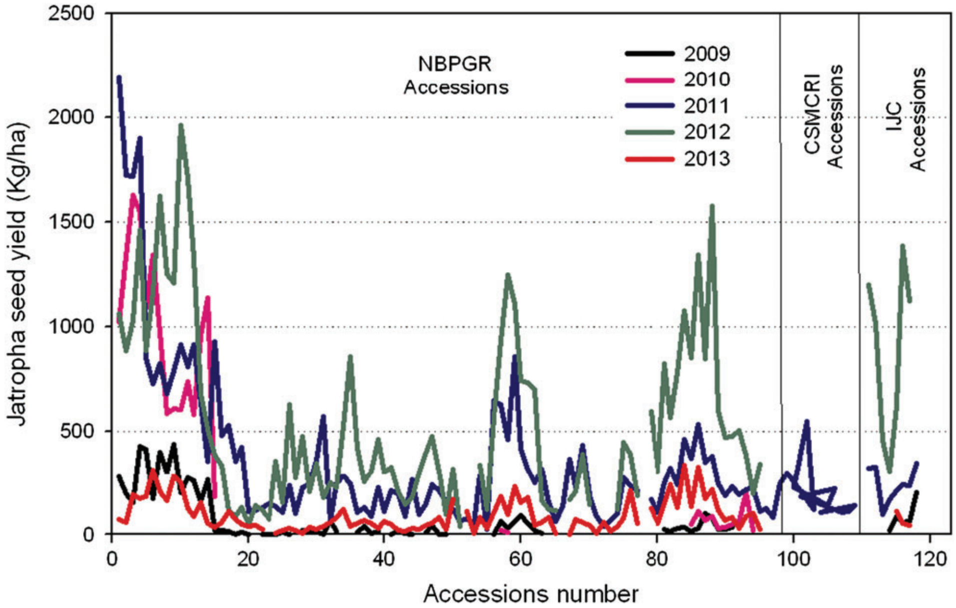

Figure 1. Jatropha seed yield measured from 124 accessions between 2009 and 2013 at ICRISAT.

Table 4. Field water balance components of ICRISAT research station.

Year	2009-10	2010-11	2011-12	2012-13	2013-14
Rainfall (mm)	1034	1165	535	776	1076
Water surplus (mm)	575	573	138	275	475
Actual Evapotranspiration, ET_a (mm)	459	592	396	501	601
Crop water need, ET_c (mm)	810	763	794	808	812
Crop water stress (%)	43	22	50	38	26
Av. measured Seed Yield (Kg/ha)	78 (σ = 113)*	558 (σ = 543)	341 (σ = 362)	554 (σ = 440)	92** (σ =77)

*Values in Parenthesis show standard deviation from mean.
**Crops were heavily pruned in 2013–14.

Table 5. Genotype grouping based on yield response from ICRISAT field experiments.

Year	No of Accessions monitored	<500 Kg/ha	500–1000 Kg/ha	1000–2000 Kg/ha	2000–3000 Kg/ha
2009–10	75	75	0	0	0
2010–11	27	13	7	7	0
2011–12	118	97	17	3	1
2012–13	99	59	21	19	0
2013–14	95	95	0	0	0

Kg/ha. Maximum yield during experiment were recorded as 1800–2200 Kg/ha.

Seed yield was dependent on rainfall amount and its distribution. Years 2010, 2011, and 2012 were experienced as wet, dry, and normal years as annual rainfall received at ICRISAT was 1165, 535, and 776 mm, respectively (Table 4). Water balance analysis showed that crops suffered with 22%, 50%, and 38% of the water deficit of the required amount in respective years (Table 4). Crop water requirement of Jatropha was estimated to be 750–810 mm annually; whereas water use by Jatropha was estimated at 400 to 600 mm during the field experiment. In response, average seed yields were 560 Kg/ha (wet year), 340 Kg/ha (dry year), and 555 Kg/ha (normal year). Yield measured in 2013 was poor because of heavy pruning done in the beginning of the crop season and also a higher rainfall during monsoon might have developed a waterlogged situation which negatively affected seed yield.

Agronomic parameters such as plant height, stem diameter, number of branches, and crown area measured from different accessions are summarized in Fig. 2. Average height of Jatropha was recorded as 200–230 cm, ranging from 70 cm to 320 cm by the end of third and fourth years. Average stem diameter was recorded at 12 cm by the end of third and fourth years which increased with 1–2 cm/year rate up to the sixth year, whereas maximum stem diameter size was recorded as 20–22 cm. The number of branches per plant varied with plant age and also with rainfall variability (due to induced crop water stress). Branch number per plant on average was recorded highest (120/plant) during 2010/2011 as this year was one of the good years in terms of rainfall and soil moisture availability. Maximum number of branches/plant was recorded as high as 305 during the experiment. Crown area of plant varied from year to year and also for different accessions with an average value of 4–5 m^2 (Fig. 2).

Soil moisture dynamics

Average variation of soil moisture from month to month is shown in Fig. 3. Figure 3 is divided into four panels and each one shows the moisture profile of three subsequent months. In the Jatropha field, new leaf flushes and biomass growth started at the beginning of April; flowering initiated by May/June; and pod formation and harvesting stage occurred between September and December. Previous stored soil moisture into subsurface layers was used by the Jatropha plants to fulfill water requirements during leaf sprouting. Thus, moisture level depleted significantly between April and June. Large variations in moisture profile are observed between July and September, as this period coincided with peak vegetative growth and the occurrence of monsoonal rainfall. Soil moisture availability was highest during September. Moisture in the soil profile depleted slightly during pod formation and the harvesting stage during November/December. A variation in profile moisture was minimal between January and March because the crop entered the dormancy phase and leaves started falling. Soil moisture fluctuation was

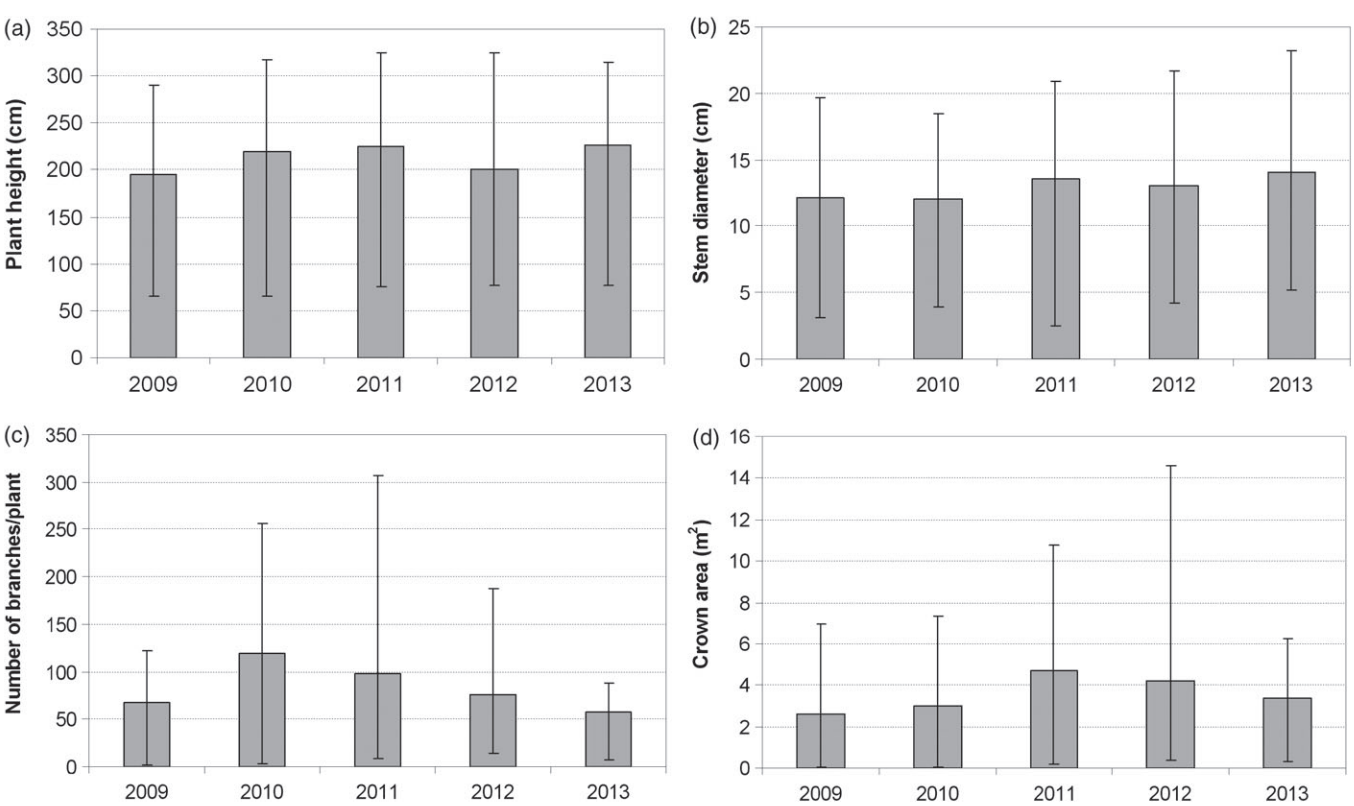

Figure 2. Agronomic parameters (plant height, stem diameter, number of branches per plant and crown area) measured from ICRISAT field experiments between 2009 and 2013; column shows average values of 124 accessions and bar defines maximum to minimum range.

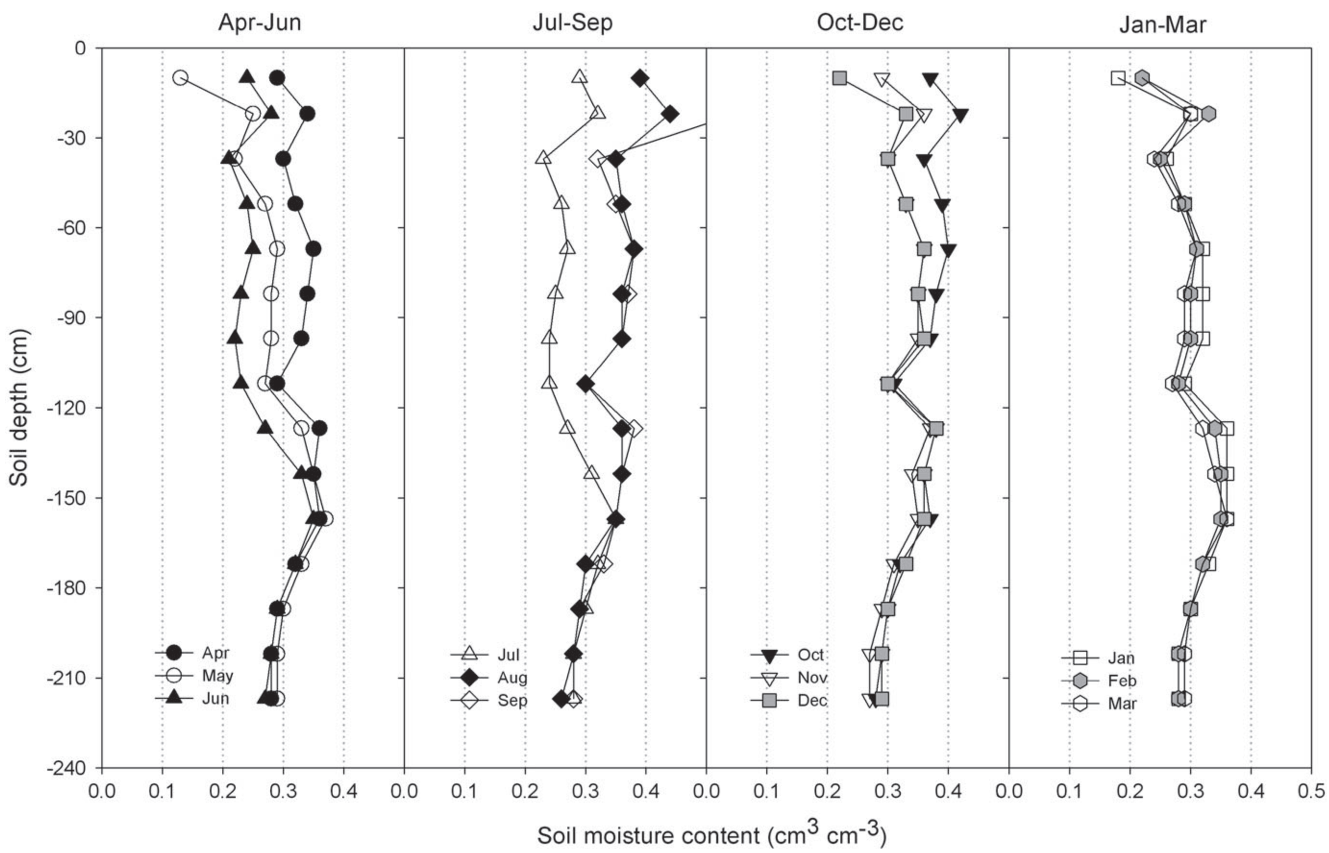

Figure 3. Depth wise soil moisture content during 12 months in Jatropha experimental field.

generally up to 150 cm indicating the maximum effective rooting depth for Jatropha crop.[31]

Water balance components and upstream-downstream trade-offs of Velchal watershed

Water balance of fallow wasteland and Jatropha cultivated land is drawn and presented in Table 6. Water balance partitioned rainfall amount into three important hydrological components: evaporation (*E*) or evapotranspiration (ET_a), run-off (outflow), and groundwater recharge. Table 6 shows that 43% of rainfall was being partitioned as surface run-off from the watershed boundary, 5% was recharged to ground aquifer, and 52% of total rainfall was captured by soil and subsequently lost to the atmosphere by an evaporation process from fallow wasteland. Whereas after plantation of the Jatropha, outflow reduced from 43 to 31%; water (vapor) movement toward the atmosphere shifted in the form of E to ET and increased from 52 to 64% of the total rainfall amount. Groundwater recharge was almost unchanged compared to unmanaged land. The study shows that cultivating Jatropha in wasteland has large potential to utilize green water effectively.

Table 6. Annual water budget of Velchal village under two different land uses.

	Fallow-wasteland	*Jatropha* cultivated land with land management practices
Rainfall (mm)	896	896
Outflow from the watershed (mm)	393 (43%)	274 (31%)
E or ET (mm)	460 (52%) (Non-productive)	580 (64%) (Productive use)
Groundwater recharge (mm)	43 (5%)	42 (5%)

E or ET components for both fallow wasteland and Jatropha cultivated land is described more clearly in Fig. 4. Figure 4 presents evaporation losses from fallow land, and evaporation and transpiration losses from *Jatropha* cultivated land on a monthly time scale. A large fraction of rainfall entrapped by soil (in the form of soil moisture) was being lost through evaporation in monsoon and

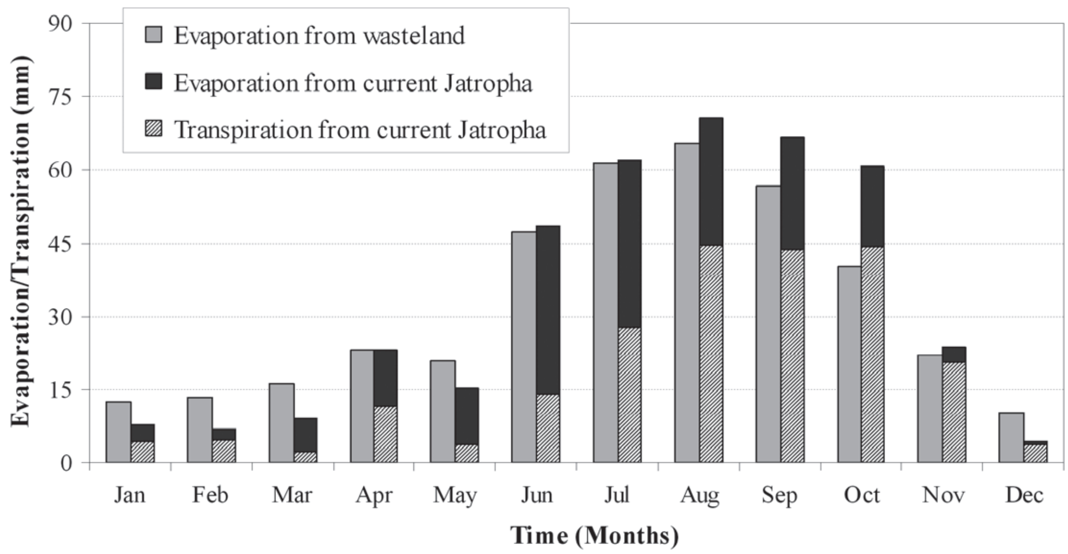

Figure 4. Comparing evaporation/transpiration from fallow wasteland and Jatropha cultivated wasteland in selected normal year at Velchal village.

non-monsoon periods in fallow wasteland. A shift of vapor flow from evaporation to transpiration was found to be significant when Jatropha was in fields.

Analysis shows that *in situ* watershed development and Jatropha cultivation together reduced run-off volume from 43% to 31% in the Velchal project site. This amount of water was harvested in the form of soil moisture and made available for plant growth. This has benefited the landscape both by storing more moisture in soil and by protecting the land from soil erosion and nutrient losses. Seed yield in Velchal is recorded in the range from 200 to 600 kg ha^{-1} from year to year as per water availability. Details of water balance and other ecosystem trade-offs for the Velchal watershed is further described by Garg *et al.*[21] in detail.

Technical feasibility of Jatropha cultivation in India

Water balance components and yield potential of Jatropha

The annual water requirement of the Jatropha crop was in the range between 720 and 975 mm at different location/states (Table 7). The water requirement of Jatropha was at maximum for Rajasthan and minimum for Orissa due to climatic variability (Table 7). Jatropha is a perennial crop and requires significant amount of water especially during May to August. The months of May and June are critical for Jatropha because water requirements during this period are significant but moisture availability is relatively poor due to depleted soil moisture status.

Table 7 summarizes the water balance components for all nine meteorological stations. Data show that rainfall received in different states varied from 400 mm to 1500 mm. Out of that, 35–80% of rain was partitioned into ET and 30–60% was exported as surface run-off and percolated down into groundwater recharge and developed base flow.

Annual variation of water balance among different states is further described in Table 7. For example, Anand in Gujarat (low rainfall zone) received an average of 760 mm rainfall between 1995 and 2005. Out of that, 55% of rainfall was partitioned into ET and 45% was generated as blue water under Jatropha cultivated wasteland. Hyderabad in Telangana, which belongs to a medium rainfall zone, received 900 mm rainfall. Water balance showed that 60% of total rainfall partitioned into ET and 40% into blue water. Jabalpur in M.P. (a moderate to high rainfall zone) received on average 1300 mm rainfall annually. Nearly 35% of total rainfall was utilized by consumptive water use (ET) and 65% converted into blue water from Jatropha land. Irrespective of rainfall, ET from Jatropha cultivated lands range between 400 and 650 mm (except in Jodhpur). Due to shallow soil depth and the poor water-holding capacity of wastelands, a large fraction of rainfall received in medium and large rainfall is exported out from landscape (in terms of surface runoff) and a small portion of rainfall is only been utilized by crops.

Table 7. Degraded wasteland area, water balance components of Jatropha crop and yield potential in nine different Indian states.

State	Data of Meteorological Station used in current analysis	Available water capacity (mm)	Total waste-land area (Million ha)	Proposed wasteland for Jatropha cultivation (Million ha)	Water balance components (mm)				Crop water requirement under no stress condition	Water Stress (–)	Yield potential (ton/ha)	Total Seed production (Million tons)
					Rain fall	Blue water (runoff + deep percolation)	ET	Change in SMC				
Andhra Pradesh + Talangana	ICRISAT	100	9.19	2.76	957	356	577	23	867	0.33	1.3	3.7
Chhattisgarh	Raipur	80	4.78	1.44	1211	659	534	18	831	0.36	1.3	1.8
Gujarat	Anand	125	3.13	0.94	764	358	415	-10	753	0.45	1.1	1.0
Karnataka	Bengalore	80	8.09	2.43	905	273	639	-7	865	0.26	1.5	3.6
Madhya Pradesh	Jabalpur	70	14.10	4.23	1324	836	443	44	693	0.36	1.3	5.4
Maharashtra	Sholapur	80	9.73	2.92	814	284	539	-9	779	0.31	1.4	4.0
Orissa	Bhubneshwer	75	3.72	1.12	1514	854	637	23	720	0.12	1.7	2.0
Rajasthan	Jodhpur	80	20.42	6.13	342	96	277	-31	975	0.72	0.5	3.4
Uttar Pradesh	Jhansi	90	14.41	4.32	820	371	465	-16	869	0.46	1.1	4.7

The soil database collected from NBSS&LUP suggested that available water capacity (FC-PWP) of wastelands located in different states is narrow in range (50–80 mm/m). Thus the water balance response for different locations was not very sensitive due to soil properties but was largely responsive to rainfall and weather-generated parameters. Figure 5 summarizes the hydrological response (blue water, ET, and change in soil moisture) of different states due to rainfall variability [based on ten locations and three rainfall scenarios (dry, normal, and wet years)]. Generated blue water from a given year strongly correlated with total rainfall. ET however increased with increasing rainfall but this rise after 1000–1200 mm was insignificant. Soil moisture status at the end of the crop period was estimated as negative in low and medium rainfall regions indicating a net loss of soil moisture from Jatropha land; and positive for high rainfall zones indicating a net moisture gain.

The water stress situation declined with increasing rainfall amount (Fig. 6). The level of stress was evidenced by low crop yields during dry years than normal and wet years. A location where rainfall received was <500 mm, the crop experienced a water stress situation during 50% of the crop growth period. Jatropha cultivated in medium and high rainfall regions also experienced water stress situation during 20–40% of the crop growth period. Several studies in India and elsewhere indicated that the production potential of Jatropha crop was 3–5 ton/ha under non-limiting input conditions.[16] Moreover the Jatropha maximum seed yield obtained from the ICRISAT field experiment was in the range range between 2000 and 2200 Kg/ha. Based on literature data and our own experiments, maximum seed yield under optimum condition was considered 2.0 ton/ha under rain-fed conditions and used to compute the actual yield under stress inferred by water deficiency using a linear productive function. Potential average crop yields for different states are in a range between 0.5 and 1.7 ton/ha (Table 7). Thirty per cent of the wastelands (26 million ha) is considered for cultivating Jatropha crop out of 88 million ha of wastelands in ten states. Our analysis suggested that 26 million ha of degraded wastelands have the potential to produce nearly 30 million ton of Jatropha seed every year on average (Table 7).

Impact of land-use change on water resources availability and eco-system trade-offs

Simulations are made to analyze water balance of the current land use (i.e., wild grass) and compared with the

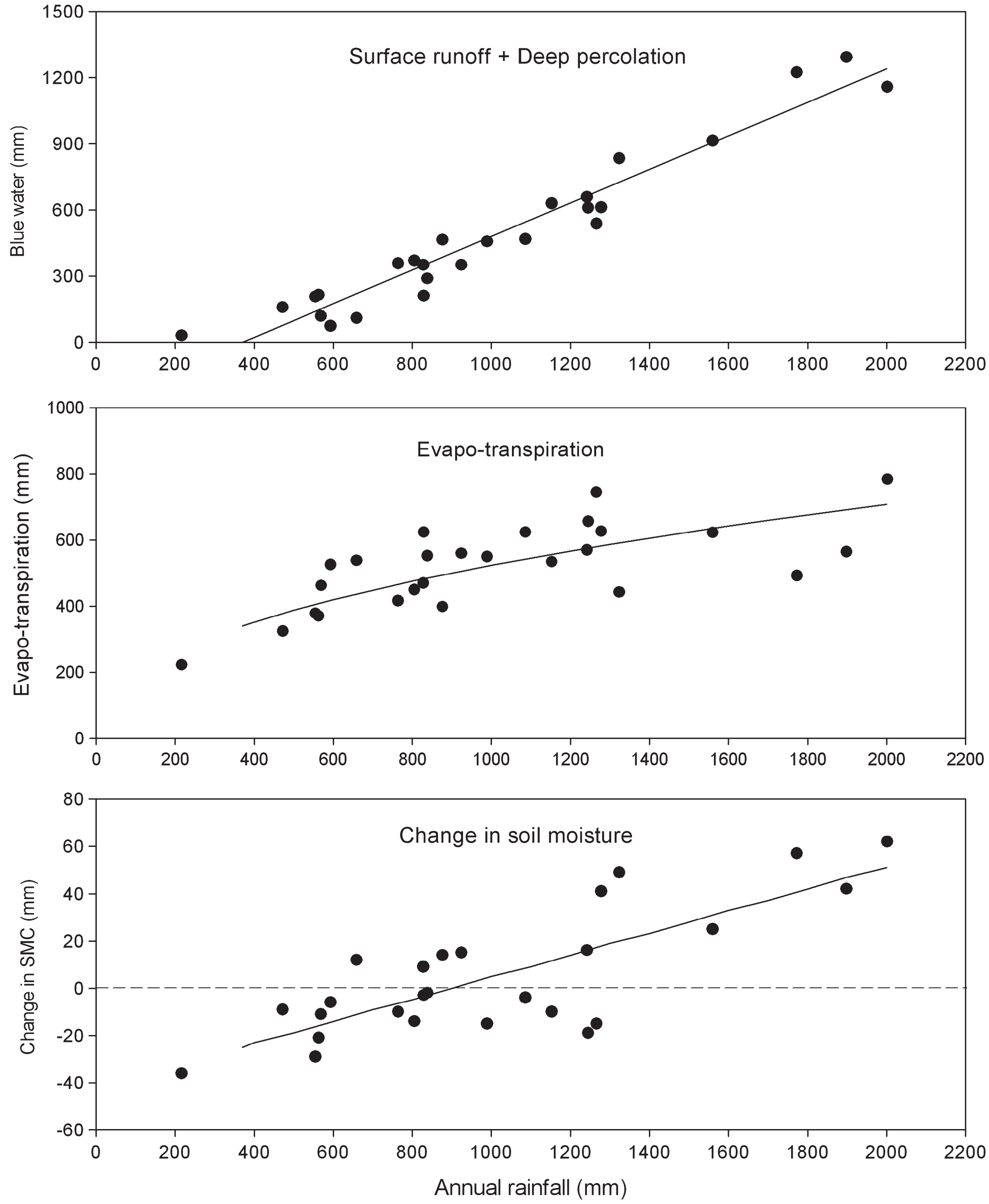

Figure 5. Hydrological response of wastelands with increasing rainfall.

Jatropha scenario. Twenty-six million ha of proposed land situated in ten states receives 226 km^3 of rainfall annually. Fifty-five per cent of total rainfall is converted as ET (125 km^3), 26% is converted into deep percolation (58 km^3), and 20% exported as surface run-off (45 km^3) from wastelands in the current stage. ET, deep percolation, and groundwater recharge from the Jatropha land are 54% (122 km^3), 31% (69 km^3), 16% (35 km^3), respectively. Results clearly show that generated blue water from both scenarios are almost similar but generated run-off from Jatropha land is decreased by 22% and deep percolation enhanced by 19% compared to current land use. Moreover there is not much variation observed in ET from both the land uses.

An additional amount of deep percolation from Jatropha lands would generate more base flow and groundwater recharge and would be helpful in maintaining and improving ecosystem services. Lower run-off intensities would reduce the risks of flooding of cultivated areas downstream.

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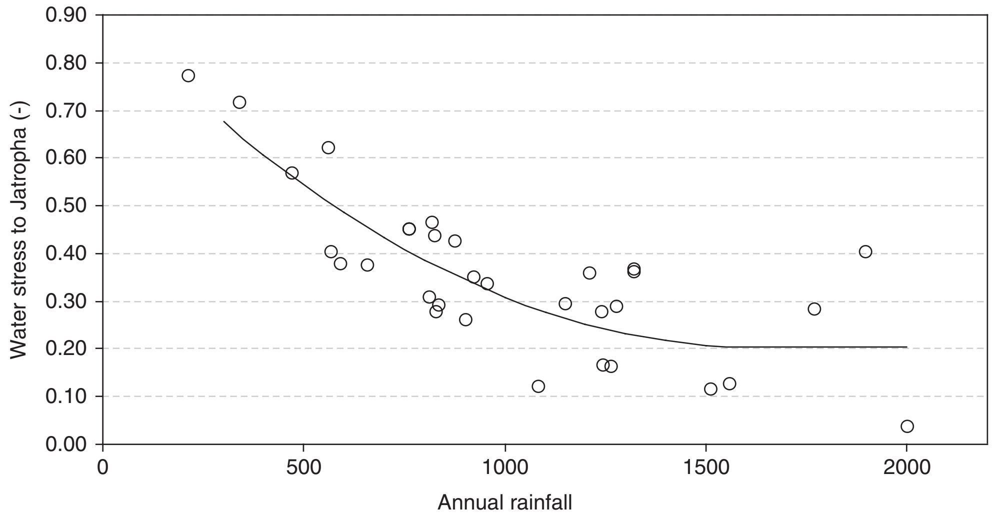

Figure 6. Impact of rainfall on crop water stress.

Higher base flow results in lower differences between high and low flows in rivers, which again is beneficial from a flood-risk perspective. Most likely this is also positive for the riverine ecosystems, since rivers in this region are perennial and thus require a certain amount of base flow to sustain regulating and supporting ecosystem services.

Yield potential of present genotype is insufficient

Results from ICRISAT field experiments along with this modeling study shows that the yield potential of Jatropha with its present genotype is poor. Harvesting less than one ton per ha seed yield after five years of crop planting may not be remunerative as cost of cultivation and land prices are increasing consistently. Most of the accessions cultivated at ICRISAT yielded less than 500 Kg/ha despite application of fertilizers and weed management. The present genotype is sensitive to water, nutrients, and also to pest and disease infestation. A serious research effort is needed to improve cultivars of *Jatropha curcas* with synchronized flowering to enable mechanical harvesting, along with improved land and water management needed for harnessing the potential of Jatropha as a commercially viable biofuel crop.

Model assumptions and uncertainties

Modeling natural systems is a challenging task. Natural systems are highly complex, heterogeneous, and nonlinear in nature. Ecohydrological modeling includes various assumptions, errors in input and measured data, and limitation to capture the complete physical process of a system which turns up uncertainty in simulation outputs. We have listed some of the assumptions made in the present study and model limitations. We assumed one kind of land use practice throughout the simulation period in the entire wasteland area to simplify the process. Moreover one meteorological station from each state is taken despite every state in India holding large diversity in rainfall both in terms of amount and distribution. However, we selected a representative station for the state such that the average rainfall of the state should be closer to the average normal rainfall of the selected station. The study uses long-term data from a 10-year period which captures large variability in terms of rainfall amount and its distribution.

Conclusions

The technical suitability of Jatropha as a biodiesel plant is studied based on field experiments and simulation modeling at three different scales. A large number of Jatropha accessions tested at the ICRISAT research station showed that yield varies with rainfall and soil moisture availability. Crop utilized nearly 400–600 mm water compared to 750–1000 mm requirement resulted in 20–50% water deficit. Average seed yield from different years is in the range between 350 and 560 Kg/ha. Out of 124 accessions, seed yield from 19 accessions were higher than 1000 Kg/ha and the rest performed below 500 Kg/ha showing the poor production ability of current genotypes. Based on field-based experiments, water balance and yield potential were estimated at watershed and regional scale using simulation modeling. Thirty per cent of the wasteland (26 million ha) is considered for cultivating Jatropha crop out of 88 million ha of wasteland in ten states. Potential average crop yields for different states are in the range between 0.5 and 1.7 ton/ha. Our analysis suggested that 26 million ha of degraded wasteland have the potential to produce nearly 30 million ton of Jatropha seed every year on an average. The study concluded that Jatropha is a drought-tolerant crop but not a less-water-requiring crop for achieving targeted economic production. Jatropha however has demonstrated good potential to rehabilitate degraded wasteland by utilizing green water effectively and increasing carbon sequestration.

References

1. Government of India, Petroleum Planning and Analysis Cell, Government of India, New Delhi, India (2014).
2. European Commission, Communication from the European Commission on An EU Strategy for Biofuels, COM (2006) 34 final. European Commission, Brussels (2006).
3. EEA, *Climate change and a European low-carbon energy system*. EEA Report, No. 1/2005, Copenhagen K, Denmark (2005).
4. Government of India, *National Policy on Biofuels*. Ministry of New & Renewable Energy, New Delhi (2009).
5. Achten WMJ, Maes WH, Aerts R, Verchot L, Trabucco A, Mathijs E, Singh VP and Muys B, Jatropha: From global hype to local opportunity. *J Arid Environ* **74**:164–165 (2010).
6. Phalan B, The social and environmental impacts of biofuels in Asia: An overview. *Appl Energ* **86**:S21–S29 (2009).
7. Wani SP, Sreedevi TK, Marimuthu S, Kesava Rao AVR and Vineela C, Harnessing the potential of Jatropha and Pongamia plantations for improving livelihoods and rehabilitating degraded lands. *6th International Biofuels Conference*, March 4–5, New Delhi, India (2009).
8. Food and Agriculture Organization, The State of Food and Agriculture. Biofuels: prospects, risks, and opportunities. Food and Agriculture Organization of the United Nations, Rome (2008).
9. Ramachandra TV and Kumar R, Wastelands: rehabilitation and management approaches. *Low External Input Sustainable Agriculture* **5**(4):10–12 (2003).
10. Wani SP and Sreedevi TK, *Pongamia's Journey from forest to Microenterprise for improving livelihood, International Crop Research Institute for the Semi-Arid Tropics*. Research Report, Global Theme of Agroecosystems, Patancheru, India (2005).
11. Sreedevi TK, Wani SP, Srinivasa Rao CH, Chaliganti R and Reddy RL, Jatropha and Pongamia rain-fed plantations on wastelands in India for improved livelihoods and protecting environment. *6th International Biofuels Conference*, March 4–5 New Delhi, India (2009).
12. Garg KK, Karlberg L, Wani SP and Berndes G, Jatropha production on wastelands in India: opportunities and trade-offs for soil and water management at the watershed scale. *Biofuels Bioprod Bioref* **5**:410–430 (2012).
13. Tatikonda L, Wani SP, Kannan S, Beerelli N, Sreedevi TK, Hoisington DA, Devi P and Varshney RK, AFLP-based molecular characterization of an elite germplasm collection of *Jatropha curcas L.,* a biofuel plant, *Plant Sci* **176**(4):505–513 (2009).
14. Divakara BN, Upadhyaya HD, Wani SP and Laxmipathi G, Biology and genetic improvement of *Jatropha curcas* L.: A review. *Applied Energy* **87**:732–742 (2010).
15. Zhang YG, Nearing MA, Zhang XC, Xie Y and Wei H, Projected rainfall erosivity changes under climate change from multimodel and multiscenario projections in Northeast China, *Journal of Hydrology* **384**(1–2):97–106 (2010).
16. Achten WMJ, Verchot L, Franken YJ, Mathijs E, Singh VP and Aerts R, Review: *Jatropha* bio-diesel production and use. *Biomass Bioenerg* **32**:1063–1084 (2008).
17. Ragwit, M, Schleich J, Huber C, Resch G, Faber T, Voogt, M *et al., FORRES 2020: Analysis of the renewable energy sources' evolution up to 2020*. Final report. Karlsruhe (2005).
18. Kumar A and Sharma S, An evaluation of multipurpose oil seed crop for industrial uses (*Jatropha curcas L.*): A review. *Indus Crops Prod* **28**:1–10 (2008).
19. Jingura RM, Matengaifa R, Musademba D and Musiyiwa K, Characterisation of land types and agro-ecological conditions for production of Jatropha as a feedstock for biofuels in Zimbabwe. *Biomass Bioenerg* **35**:2080–2086 (2011).
20. Wani SP, Osman M, D'Silva E and Sreedevi TK, Improved livelihoods and environmental protection through biodiesel plantations in Asia. *Asian Biotechnology and Development Review* **8**(2):11–29 (2006).
21. Garg KK, Karlberg L, SP Wani and Berndes G, Jatropha production on wastelands in India: opportunities and trade-offs for soil and water management at the watershed scale. *Biofuels Bioprod Bioref* **5**(4):410–430 (2011).
22. Francis G, Edinger R and Becker K, A concept for simultaneous wasteland reclamation, fuel production, and socio-economic development in degraded areas in India: need, potential and perspectives of *Jatropha plantations*. *Natural Resources Forum* **29**:12–24 (2005).
23. Schio B, *Jatropha curcas* L., a potential bioenergy crop, On field research in Belize. M.Sc. dissertation, Padua University, Italy and Wageningen University and Research Centre, Plant Research International, the Netherlands (2010).
24. Carels N, Chapter 2 *Jatropha Curcas*: A review. *Advances in Botanical Research* **50**:39–86 (2009).
25. Kaushik N, Kumar K, Kumar S, Kaushik N and Roy S, Genetic variability and divergence studies in seed traits and oil content of Jatropha (*Jatropha curcas L.*) accessions. *Biomass Bioenerg* **31**:497–502 (2007).
26. Sunil N, Varaprasad KS, Sivaraj N, Kumar TS, Abraham B and Prasad RBN, Assessing *Jatropha curcas* L. germplasm in situ – A case study. *Biomass Bioenerg* **32**:198–202 (2008).
27. Behera SK, Srivastava P, Tripathi R, Singh JP and Singh N, Evaluation of plant performance of *Jatropha curcas* L. under different agro-practices for optimizing biomass- A case study. *Biomass Bioenerg* **34**:30–41 (2010).
28. Ghosh A, Chikara J and Chaudhary DR, Diminution of economic yield as affected by pruning and chemical manipulation of *Jatropha curcas* L. *Biomass Bioenerg* **35**:1021–1029 (2011).
29. Foidl N, Foidl G, Sanchez M, Mittelbach M and Hackel S, *Jatropha curcas* L. as a source for the production of biofuel in Nicaragua. *Bioresource Technol* **58**:77–82 (1996).

30. Garg KK, Wani SP and Patil MD, Simple and farmer-friendly decision support system for enhancing water use efficiency in agriculture: tool development, testing and validation. *Accepted in "Current Science"* (2015).
31. Falkenmark M, Land-water linkages - A synopsis, Land and Water Integration and River Basin Management. *FAO Land and Water Bulletin*, No.1, 15–16, FAO, Rome, Italy (1995).
32. USDA SCS, *National Engineering Handbook Section 4. Hydrology*. USDA-SCS, Washington, DC, USA (1972).
33. Neitsch SL, Arnold JG, Kiniry JR, Williams JR and King KW, Soil and water assessment tool. Theoretical Documentation, Version 2005, Grassland, Soil and Water Research Laboratory and Blackland Research Centre, Texas Agricultural Experiment Station, Temple, Texas, 76502 USA.
34. Hawkins R, Asymptotic determination of runoff curve numbers from data. *J Irrig Drain Eng* **119**(2):334–325 (1993).
35. Thornthwaite CW, An approach toward a rational classification of climate. *Geogr Rev* **38**:55–94 (1948).
36. Penman HL, Evaporation: An introductory survey. *Netherlands J Agric Sci* **1**:9–29, 87–97,151–153 (1956).
37. Allen RG, Pereira LS, Raes D and Smith M, Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage. Paper No. 56. United Nations FAO, Rome, Italy (1998).
38. Garg KK, Wani SP and Rao AVR, Crop coefficients of Jatropha (*Jatropha curcas*) and Pongamia (Pongamia pinnata) using water balance approach. *Wiley Interdisciplinary Reviews: Energy and Environment* **3**(3):301–309 (2014).
39. Rao AVRK, Wani SP, Singh P, Srinivas K and Srinivasa Rao Ch, Water requirement and use by *Jatropha curcas* in a semi-arid tropical location. *Biomass Bioenerg* **39**:175–181 (2012).
40. Stewart JI, Cuenca RH, Pruitt WO, Hagan RM and Tosso J, Determination and utilization of water production functions for principal California crops W-67 CA Contributing Project Report. University of California, Davis, USA (1977).
41. Doorenbos J and Kassam AH, Yield response to water. FAO Irrigation and Drainage Paper No. 33. United Nations FAO, Rome, Italy, pp. 1–40 (1979).
42. Lovelli S, Perniola M, Ferrara A and Tommaso TD, Yield response factor to water (Ky) and water use efficiency of Carthamus tinctorius L. and Solanum melongena L. *Agric Water Manage* **92**:73–80 (2007).

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