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Hydrological consequences of cultivating Jatropha crop in degradable waste lands of India and ecosystem trade-offs at watershed scale

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Abstract

Biofuel production from feedstocks grown on wastelands is considered as a means to address concerns about climate change and improve energy security while at the same time provide an additional source of income for improving livelihood. The establishment of biomass plantations on wastelands is likely to affect local livelihoods and surrounding ecosystems by influencing hydrologic flows and processes such as erosion. We analyzed the technical feasibility for cultivating Jatropha on degraded waste lands in India using a water balance approach. More specifically, an assessment was made for a wasteland located in the Velchal watershed, Andhra Pradesh, India, which recently was converted to a biofuel plantation with Jatropha. The previous land-use, in this case grazing, could continue in the Jatropha plantations. Several desirable effects occurred as a result of the land-use conversion: non-productive soil evaporation was reduced as a larger share of the precipitation was channeled to productive plant transpiration and groundwater recharge, and at the same time a more stable (less erosive) runoff resulted in reduced soil erosion and improved downstream water conditions. A win-win situation between improved land productivity and soil carbon content was observed for the Jatropha plantations. Results did not show a negative impact on the blue water generation after introducing Jatropha on waste lands. Using parameterized and validated hydrological model “Soil and Water Assessment Tool” we assumed the impact of Jatropha cultivation on 13.4 million ha of wastelands (15% of the total wasteland area) in seven states of India. The analysis shows that 22 million tons of Jatropha seed could be produced from Jatropha cultivable waste lands in India. In addition, Jatropha plantations on waste lands would not create negative impact on downstream water availability and ecosystem services.

1. Introduction

1.1 Biofuels in India

In India, rapid urbanization, coupled with industrialization and economic growth, drives the increasing energy demand and the substantial import of crude petroleum (TERI, 2002). Since the beginning of the 1990s, India’s oil import has increased more than five-folds and has considerable influence on the country’s foreign exchange expenditures. The Indian economy is expected to continue to grow, with resulting further increase in energy demand and rising oil imports, projected to reach 166 and 622 million tons by 2019 and 2047, respectively (TERI, 2002). A large increase compared to the 111 million tons of crude oil that was imported in 2006-2007 (GOI, 2006).

As in many other countries, in India biofuels are considered an option for addressing the energy security concerns (GOI, 2009; Achten et al., 2010b). Moreover, they respond to the challenges of climate change mitigation (Phalan, 2009). A Petrol blending program mandated a 5% ethanol blending of petrol, initially for selected states and union territories. In 2006, the program was extended to the whole country (Ministry of Petroleum and Natural Gas 2009). Programs for stimulating complementary use of biodiesel to displace petroleum-based diesel primarily focused on biodiesel production based on non-edible oil seeds from marginal or degraded lands. In 2009, the Government of India approved the National Policy on Biofuels targeting a 20% blend of biofuels with gasoline and diesel by 2017 (Achten et al, 2010a).

1.2. Wastelands in India

Wastelands are characterized by sparse vegetation cover, exposing soils to both rainfall and solar radiation. Large soil losses occur during instances of intensive rainfall, and the non-productive soil evaporation can be very large due to the lack of vegetative cover. The results show that under favorable soil management and with a good water supply, the water uptake of Jatropha is similar to that of many water demanding cereal crops. However, on wastelands where crop management is quite difficult, Jatropha plantations might be a better option for enhancing productive water flows and at the same time protect these areas from further degradation (Achten et al, 2010a). Based on National Bureau of Soil Science and Land Use Planning (NBSS&LUP), Nagpur, India classification, nearly 120 Million ha of land in India is defined as degraded land, with nearly 13 million ha of land suitable to grow biodiesel crops like Jatropha (GOI, 2003, 2006, 2010). There are several criteria available to classify a soil into wasteland, such as excessive erosion, pH, salinity, alkalinity, water logging and land slope. Rajasthan, Madhya Pradesh, Utter Pradesh and Andhra Pradesh cover the largest land area with degraded or waste land, together 48% of entire waste land in India (GOI, 2003, 2010). Soil degradation processes have severely reduced the soil productivity. It has been estimated that, on average, wastelands have a biomass productivity less than 20% of the original potential (Ramachandra and Kumar 2003).

A substantial wasteland area consists of degraded lands that are deteriorating due to the lack of appropriate soil and water management, or due to natural causes. These soils can be brought into more productive use. The establishment of biofuel plantations is considered an option for rehabilitating wastelands, enhancing energy security, and providing employment opportunities and better livelihoods in rural areas (Wani and Sreedevi, 2005; Wani et al., 2006; Sreedevi et al., 2009; Wani et al., 2009; Phalan, 2009; Achten, 2010b). Considering that about 35% of India's inhabitants live below the poverty line and more than 70% of the poor are small or marginal farmers or landless labourers (Srivastava, 2005), it is essential that wasteland development provides socioeconomic benefits for poor people.

1.3. Jatropha

Jatropha (*Jatropha curcas L.*), commonly known as "purging nut" or "physic nut", is a tropical, perennial deciduous, C_3 plant belonging to the family Euphorbiaceae (Tatikonda et al., 2009; Divakara et al., 2010). It adapted to perform best under conditions of warm temperatures and, as with many members of the family Euphorbiaceae, contains compounds that are highly toxic. Jatropha has its native distributional range in Mexico, Central America and part of South America, but has today a pan tropical distribution (Trabucco et al., 2010). The productivity of Jatropha depends on precipitation rates, soil moisture availability, soil characteristics including fertility (Francis et al., 2005; Kumar and Sharma, 2008; Da Schio, 2010; Jingura et al., 2011), genetics (Kaushik et al., 2007; Sunil et al., 2008; Divakara et al., 2010), plant age (Carels, 2009) and various management factors, like pruning, fertilization and disease control (Kaushik et al. 2007; Achten et al., 2008; Behera et al., 2010; Ghosh et al., 2011; Jingura, 2011). Annual yield levels at 2-3 tons dry seeds are proposed as achievable in semi-arid areas and on wastelands, while 5 tons ha^{-1} can be obtained with good management on good soils receiving 900-1200 mm average annual rainfall (Foidl et al. 1996; Francis, et al. 2005; Carels, 2009).

Jatropha is considered to be drought tolerant and possible to cultivate on degraded, sandy and saline soils with low nutrient contents (Da Schio, 2010). Nitrogen and phosphorous inputs may be required for high yields (Daey Ouwens et al., 2007; Jongschaap et al., 2007; Henning, 2009), but nutrient recirculates through the leaf fall reduces the need for fertilizer input (Wani et al., 2009). It is estimated that three-year old Jatropha plants return about 21 kg N ha^{-1} back to the soil, although the quantity and nutrient content of the fallen leaves from the Jatropha plant vary with the plant age and the fertilizer application (Wani et al., 2009, 2012). Jatropha is found to be accumulated and added to soil significant amounts of C (305 kg ha^{-1} $year^{-1}$) from the year one itself. Three to five year old plantation added per year around 4000 kg plant biomass equivalent to 1450 kg C ha^{-1} (Wani et al., 2012). Jatropha can be grown in a broad spectrum of rainfall regimes, from 300 to 3000 mm, either in the fields as a commercial crop or as hedges along the field boundaries to protect other plants from grazing animals and to prevent erosion (Achten et al., 2008; Kumar and Sharma, 2009).

Policy support and demand for biodiesel are however building up; there is limited data and knowledge available on water requirements of Jatropha. Gerbens-Leenes et al., 2009a estimated water footprint of bioenergy generated from agricultural crops and also from Jatropha crop. For producing bio-diesel from Jatropha, water footprint was estimated relatively high (600 m^3/GJ) compared to rapeseed and Soybean (400 m^3/GJ). In contrary, recent studies on plant–water relations of Jatropha suggests relatively low water footprint (Maes et al., 2009). According to Maes et al., 2009 Jatropha strongly controls its stomatal conductance resulting in high transpiration efficiency and high water productivity. Data on Jatropha crop is limited available for different ecological regions resulted in to large uncertainty in estimating water foot prints (Hoekstra et al., 2009; Maes et al., 2009; Gerbens-Leenes et al., 2009a, b). There is an urgent need to carry out research efforts to address such issues (Raju, 2006). In the present study, the technical feasibility of cultivating Jatropha on degradable waste land is analyzed. The specific objectives of the current study are: i) to analyse the impacts of two different land-use scenarios (wasteland state vs. biofuel cropping with Jatropha) on a watershed scale hydrology and ecosystem trade-offs; ii) to analyze field water balances of Jatropha in different ecological regions of India and iii) to analyze crop yield potentials of degradable and waste lands in India.

2. Methodology and study area

In 2005, the National Oilseeds and Vegetable Oils Development (NOVOD), together with the ICRISAT consortium, planted Jatropha on 160 ha common property land belonging to the

Velchal village, classified as wasteland. Jatropha seedlings, approximately 60 cm high, were planted at 2 m x 2 m spacing at the Velchal watershed. The plants were grown under rainfed conditions and without irrigation. Soil and water conservation practices (e.g., bunding and trenches) were implemented to harvest more rainfall. Fertilization (30 kg N ha^{-1} and 12 kg P_2O_5 ha^{-1}) was applied during the Jatropha planting. Further fertilization (50 kg N ha^{-1} and 57 kg P_2O_5 ha^{-1}) was applied in 2007. The growth parameters and seed yields of Jatropha were recorded. The plantations were mainly located in the hillock area, although some plantations are also found in the valley. Soil, hydrology and crop yield data collected from the Velchal watershed is used to parameterize the hydrological model SWAT (Soil and Water Assessment Tool). A detailed description of the SWAT modeling and parameterization processes is given by Garg et al., 2011.

Figure 1 shows a conceptual representation of the hydrological cycle at the watershed scale. Rainfall is partitioned into various hydrological components as defined by a mass balance equation: Rainfall = Out flow from the watershed boundary (Surface runoff + base flow) + Groundwater recharge + Evapotranspiration (Evaporation + Transpiration) + Change in soil moisture storages. Where fraction of rainfall stored into Vadoze zone is known as green water; and water available into groundwater aquifer and amount of water reached at river stream is known as blue water (Falkenmark, 1995).

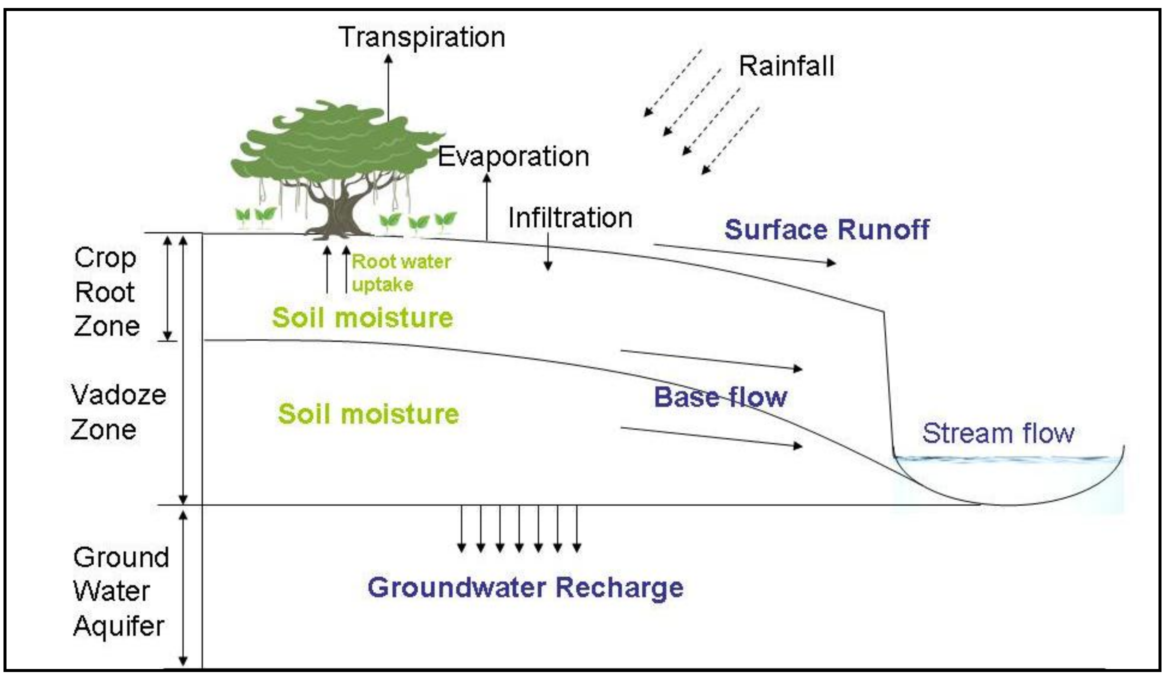

Figure 1: Conceptual representation of the hydrological cycle and different hydrological components at a field and watershed scale.

The results are analyzed for dry, normal and wet years, according to the following classification (Indian Meteorological Department, Pune):
- Rainfall less than 20% of the long term average (< 725 mm*) = dry;
- Rainfall between -20% to +20% of the long term average (> 725 mm and <1100 mm)= normal;
- Rainfall greater than 20% of long term average (>1100 mm) = wet.

(*Note: Values in parenthesis describes rainfall of Velchal watershed, Andhra Pradesh, India)

From 2001 to 2010, the annual average rainfall in the study area was 910 mm. We included two land use scenarios:
- The "Wasteland" scenario, representing the situation where the soil is in a degraded stage. Soils are highly eroded and poor in organic matter and have poor water holding capacity. Bushes and seasonal grasses dominate the land, which is used for grazing.
- The "Jatropha land" scenario, representing the situation where Jatropha is cultivated and some soil and water conservation measures (*in-situ* interventions) are implemented. Leaf fall, stem and other bush and tree biomass is added to the soil, mainly at dormancy period. The local community harvests the Jatropha seeds.

In addition, we collected data on crop characteristics to estimate crop water uptake at the ICRISAT experimental site, a micro-watershed located at the ICRISAT campus in Hyderabad (17.53^{o}N latitude and 78.27^{o}E longitude) where in 2004 Jatropha seedlings (3m x 2m spacing) were planted on 4 ha of land. Since then, the Jatropha has been cultivated under good management practices, including fertilization (90 kg N and 40 kg P_2O_5 ha^{-1} $year^{-1}$) and various agronomic measurements. Seed yield and oil content has been monitored. Soil moisture of different layers were monitored and used to estimate crop coefficients using a water balance approach.

The Jatropha crop coefficient estimated from the ICRISAT data base, a modeling study, is conducted to assess the technical feasibility to grow Jatropha on waste land in India. Nine states (Andhra Pradesh, Chhattisgarh, Gujarat, Karnataka, Madhya Pradesh, Orissa, Rajasthan and Utter Pradesh) that cover nearly 75% of the total waste lands of India are selected. We collected soil properties of different locations in these states from the NBSS&LUP database (Mandal et al., 1999). The water retention properties of the wasteland vary between 110 to 150 mm per m. The model was run for a 10 year period (2001-2010) with the two land use conditions as mentioned above.

3. Results

3.1 Impact of Jatropha plantation on the water balance in Velchal

Figure 2 shows that the water balance differs substantially for the two conditions and depends on the land use and the amount of annual rainfall. In general, there is a larger share of the total rainfall that forms runoff during wetter years when compared to drier years. For the Wasteland scenario, the runoff constituted 40-60% of the total rainfall, while for the Jatropha scenario, the corresponding fraction is 20-40%. Between 4 and 17% of the total rainfall was going to groundwater recharge, while the remainder was transferred to the atmosphere through evaporation or evapotranspiration.
A comparison of the different land management scenarios shows that more than 50% of the non-productive soil evaporation in the Wasteland scenario is shifted into productive transpiration in the Jatropha plantation scenarios (Figure 2), while the total amount of evapotranspiration (ET) is relatively similar in all both scenarios, except during dry seasons when ET is higher in the Jatropha scenarios, and even higher under improved soil conditions. Groundwater recharges doubles in the Jatropha scenario, compared with the Wasteland scenario (Figure 2). As a result of higher ET and groundwater formation, runoff formation decreases in the Jatropha scenarios, in

particular during dry years. In the Wasteland scenario, runoff constitutes around 40% of the total rainfall during dry years while the corresponding figure for the Jatropha scenario is around 30%.

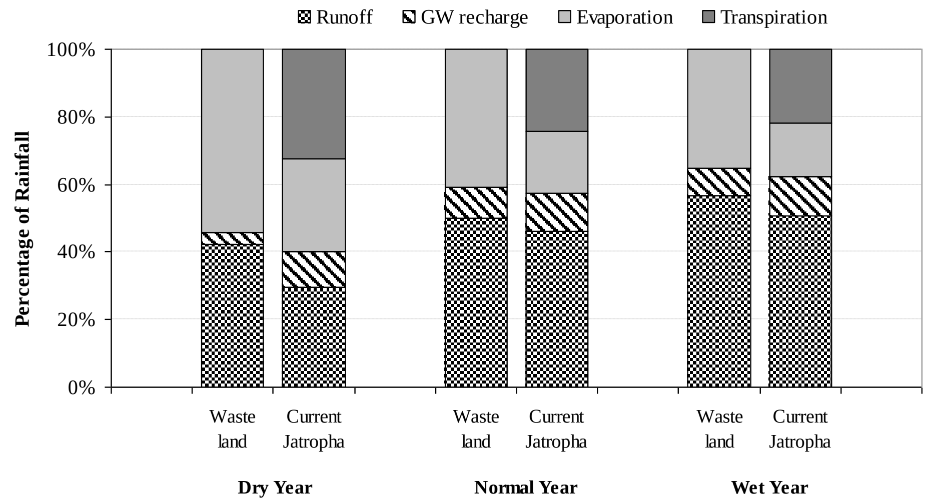

Figure 2: Water balance components of different land management scenarios during dry, normal and wet years (data from 2001 to 2010).

Figure 3 shows that the distribution of the water balance components over the year also varies with land use (Figure 3). While the total ET is lower for the two Jatropha plantation scenarios during the dry season (December-March), it becomes higher during the wetter parts of the year. This means that the annual fluctuations in runoff and groundwater generation are smaller in the Jatropha plantation scenarios compared with the wasteland scenario.

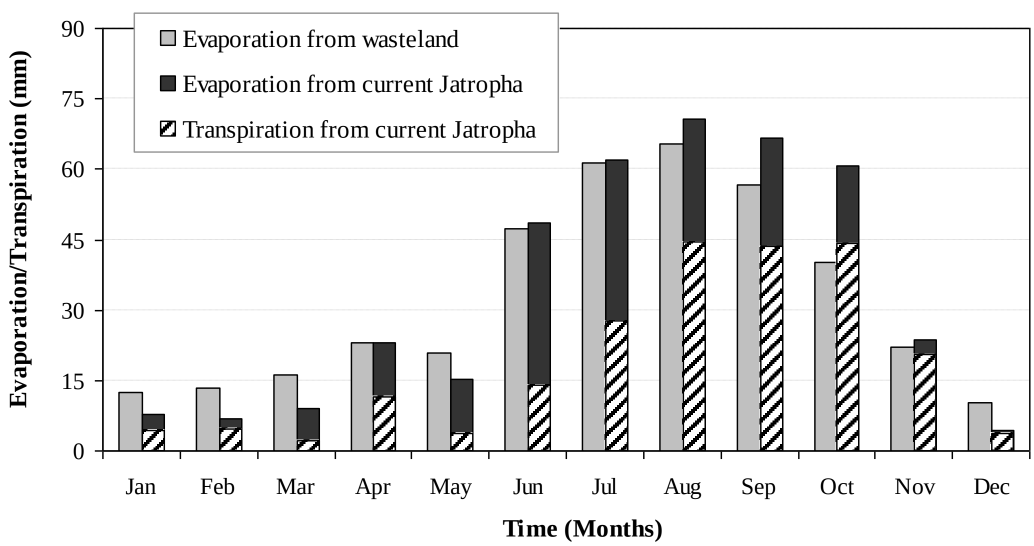

Figure 3: Monthly soil evaporation and transpiration for three different land management scenarios in Velchal watershed.

Runoff generated from the watershed consists of two components: i) surface runoff and ii) base flow generation. Figure 4 shows that even though the total runoff was slightly lower with Jatropha plantations compared with the waste-land condition, the base flow was in fact higher with Jatropha plantations. On average, the total amount of base flow generation in the Wasteland scenario was only 70% of the base flow in the Jatropha scenarios.

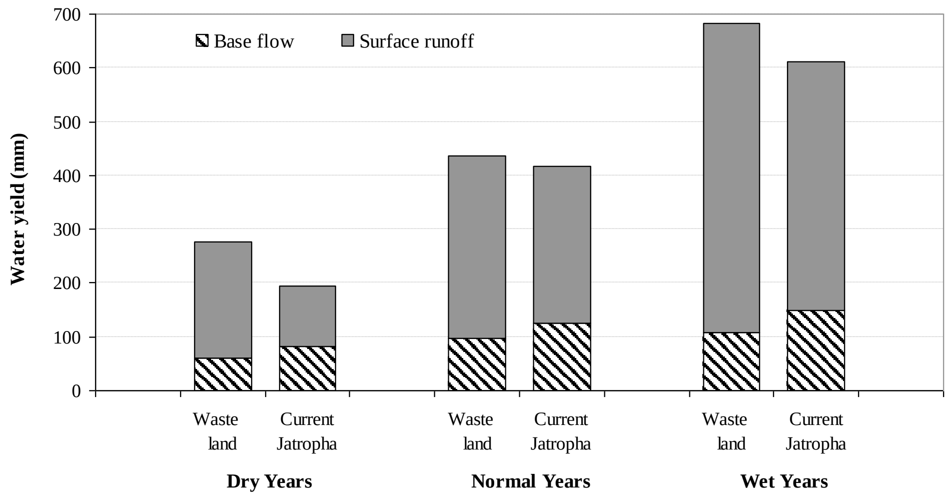

Figure 4: Total runoff generation from the watershed, divided up into base flow and surface runoff, for three different land management scenarios during dry, normal and wet years (data from 2001 to 2010).

Land management also affects the runoff intensity. In general, higher runoff intensities were predicted for the wasteland state, compared with the Jatropha plantations (Figure 5). The results show that the average daily run-off intensity decreased by 12 % for the Jatropha plantation, compared with the wasteland condition.

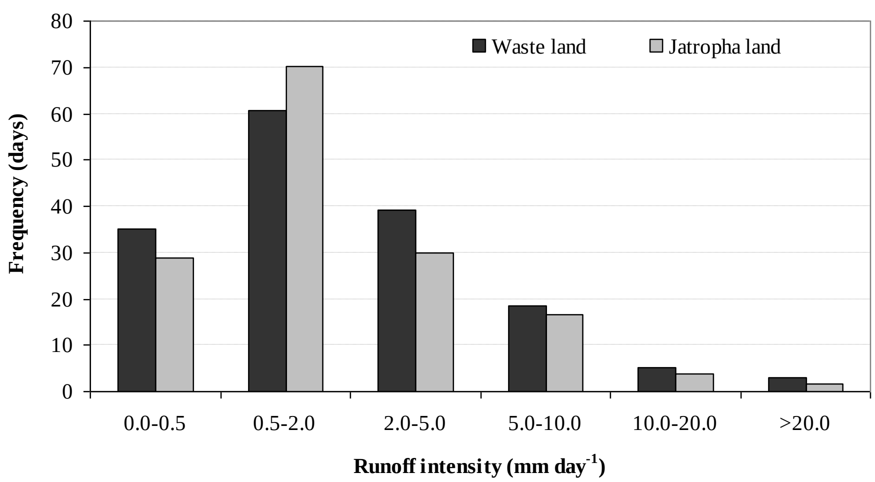

Figure 5: Frequency of daily runoff intensity, for three different land management scenarios (data from 2001 to 2010).

3.2 Crop coefficients of Jatropha crop

The crop coefficient of Jatropha estimated from the ICRISAT experimental site lies between 0.05-0.90 (Garg et al, forthcoming). Figure 6 shows the variation of the crop coefficient on a monthly scale. The Figure shows the largest K_c in July and August and the smallest between January and March. New leaf flushes and biomass growth start by the beginning of April; flowering is initiated by May/June; and pod formation and harvesting stage start between September and December (Rao et al., 2012). These differences have consequences for water requirements.

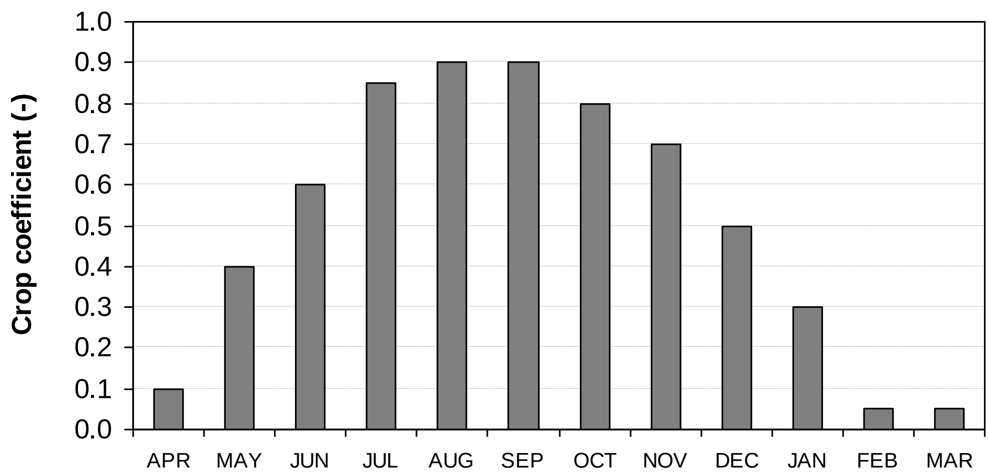

Figure 6: Monthly crop coefficients of Jatropha estimated at ICRISAT experimental site.

3.3 Water requirement of Jatropha crop

Table 1 shows that based on the ET_0-K_c approach, the annual water requirement of Jatropha lies between 720 to 975 mm (Rao et al., 2012; Garg et al., forthcoming). The water requirement of Jatropha is largest for Rajasthan and smallest for Orissa. Jatropha is a perennial crop and requires significant amounts of water, especially from May to August. Especially May and June are critical for Jatropha, because the water requirements during this period are large, but moisture availability is relatively poor due to the depleted soil moisture status.

3.4 Yield potential of Jatropha in waste lands

Table 1 summarizes the water balance components for all the nine meteorological stations. The data show that rainfall in different states vary from 400 mm to 1500 mm. Out of that, 35-80 % of the rain is partitioned into ET and 30-60 % is exported as surface runoff and percolated down into groundwater recharge and develop base flow.

The level of water stress caused lower crop yields during dry years than in normal and wet years. At a location where rainfall was less than 500 mm, the crop experienced water stress half of the crop growth period. Jatropha cultivated in medium and high rainfall regions also experienced water stress during 20-40% of the crop growth period. Several studies in India and elsewhere showed that production potential of Jatropha is 3-5 ton/ha under non limiting input conditions. Water stress estimated for Jatropha is transformed into seed yields. We considered 3 ton/ha seed yield from five to six year old tree under the optimal conditions, and then computed the actual yield under stresses inferred by water deficiency. Potential average crop yields for different states are found in range between 0.8 to 2.6 ton/ha (Table 1).

15% of the waste lands (14 Million ha) is considered for cultivating Jatropha crop out of 88 Million ha of waste lands in nine states. Our analysis suggested that 14 Million ha of degraded waste lands have the potential to produce nearly 22 Million ton of Jatropha seed every year on an average (Table 1).

3.5 Soil and water related impacts

The results from this study confirm the hypothesis that Jatropha plantations on waste lands can have several positive effects in relation to soil and water:

- Reduced soil losses are expected as because soils are better protected by vegetation and roots. Besides the on-site benefits this also has the benefit that sedimentation loads on rivers and other water bodies are reduced;
- Increased soil carbon content (Wani et al., 2012), which changes the soil physical characteristics so that both water infiltrability and soil water holding capacity increase. The soil carbon increases also enhances the climate change mitigation benefit by withdrawing CO_2 from the atmosphere;
- Redirection of non-productive soil evaporation into productive transpiration, which improves the field level water productivity;
- Increased groundwater recharge.

In this study, the total runoff amount was 5-10% larger for the wasteland condition, but despite of this, base flows were higher when Jatropha was grown and runoff intensities were at the same time lower, which is generally positive, since it reduces the risks of flooding of cultivated areas. Higher deep percolation and base flow result 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 the key processes and functions. Jatropha plantations on waste lands in India is an attractive option. A larger share of the precipitation was channeled to productive transpiration and groundwater recharge, and a more stable (less erosive) runoff improved the downstream water conditions. The study clearly indicates that Jatropha plantation on waste lands would not create negative impact on downstream water availability and ecosystem services.

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Abbreviations

SWAT: Soil and Water Assessment Tool
TERI: The Energy and Resources Institute
GOI: Government of India
NBSS&LUP: National Bureau of Soil Science and Land Use Planning
NOVOD: National Oilseeds and Vegetable Oils Development
ICRISAT: International Crops Research Institute for the Semi-Arid Tropics
ET: Evapotranspiration
Kc: Crop coefficient

Table 1: Degraded waste land area, water balance components of Jatropha crop and yield potential in different nine Indian States

State	Metrological data used	AWC (mm)	Total waste land area (Mha)	Proposed waste land for Jatropha cultivation (Mha)	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		ET	Change in SMC				
						Runoff	Deep percolation						
Andhra Pradesh	ICRISAT	100	9.19	1.38	957	164 (17)*	191 (20)	577 (60)	23 (2)	867	0.33	2.0	2.76
Chhattisgarh	Raipur	80	4.78	0.72	1211	185 (15)	474 (39)	534 (44)	18 (1)	831	0.36	1.9	1.36
Gujarat	Anand	125	3.13	0.47	764	149 (20)	210 (27)	415 (54)	-10 (1)	753	0.45	1.7	0.80
Karnataka	Bengalore	80	8.09	1.21	905	156 (17)	116 (13)	639 (71)	-7 (1)	865	0.26	2.2	2.67
Madhya Pradesh	Jabalpur	70	14.10	2.12	1324	194 (15)	642 (48)	443 (33)	44 (3)	693	0.36	1.9	4.02
Maharashtra	Sholapur	80	9.73	1.46	814	139 (17)	145 (18)	539 (66)	-9 (1)	779	0.31	2.1	3.06
Orissa	Bhubneshwer	75	3.72	0.56	1514	241 (16)	613 (40)	637 (42)	23 (2)	720	0.12	2.6	1.45
Rajasthan	Jodhpur	80	20.42	3.06	342	64 (19)	32 (9)	277 (81)	-31 (9)	975	0.72	0.8	2.45
Uttar Pradesh	Jhansi	90	14.41	2.16	820	91 (11)	280 (34)	465 (57)	-16 (2)	869	0.46	1.6	3.46

Note: * Values given in parenthesis shows percentage of rainfall received

Table 2: Water balance components of current land use (waste land) in different nine Indian states

State	Data Meteorological Station used current analysis	Available water capacity (mm)	Total waste land area (Million ha)	Water balance components (mm)				
				Rain fall	Blue water		ET	Change SMC
					Runoff	Deep percolation		
Andhra Pradesh	ICRISAT	100	9.19	957	213 (22)*	145 (15)	589 (62)	10 (1)
Chhattisgarh	Raipur	80	4.78	1211	229 (19)	414 (34)	571 (47)	-2 (0)
Gujarat	Anand	125	3.13	764	182 (24)	157 (21)	428 (56)	-3 (0)
Karnataka	Bengalore	80	8.09	905	210 (23)	77 (9)	631 (70)	-13 (1)
Madhya Pradesh	Jabalpur	70	14.10	1324	244 (18)	574 (43)	495 (37)	11 (1)
Maharashtra	Sholapur	80	9.73	814	178 (22)	106 (13)	537 (66)	-7 (1)
Orissa	Bhubneshwer	75	3.72	1514	300 (20)	527 (35)	697 (46)	-10 (1)
Rajasthan	Jodhpur	80	20.42	342	83 (24)	25 (7)	264 (77)	-30 (9)
Uttar Pradesh	Jhansi	90	14.41	820	123 (15)	239 (29)	480 (59)	-22 (3)

Note: * Values given in parenthesis shows percentage of rainfall