Wasteland energy-scapes: A comparative energy flow analysis of India's biofuel and biomass economies

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PRELIMINARY DRAFT – COMMENTS WELCOME

ABSTRACT

Through a comparative energy flow analysis, this paper examines the energy security impacts of growing biofuels on wastelands in a sub-region of South India. India's National Policy on Biofuels claims that wastelands are well suited for biofuel production because they are empty and unused. In contrast, in rural Tamil Nadu, a diverse biomass energy economy based on Prosopis juliflora exists on these lands that services a mix of rural and urban consumers at household and industrial levels. The Prosopis economy provides approximately 3-12 times more energy services than would the Jatropha biodiesel economy that the Government of India envisions for these lands. Using by-products from Jatropha production for energy provision can substitute for some, but not all, of the energy services provided by Prosopis. Thus, contrary to assertions in India's National Policy on Biofuels, growing biofuels on wastelands can weaken, rather than improve, the country's energy security. Further, replacing Prosopis with Jatropha could engender changes in economic and property relations that could further weaken energy security. These findings are not specific to rural Tamil Nadu as Prosopis is widely used as a fuelwood throughout Asia and Africa. Calls to 'develop' degraded lands through biofuel promotion similarly exist in these regions. This study underscores the importance of analyzing wasteland-centered biofuel policies at local levels in order to better understand the changes in human-environmental relationships resulting from this policy push.

1. Introduction

In 2009, after nearly a decade of debate, the Government of India enacted a National Policy on Biofuels (Government of India 2009). The policy restricts biofuel cultivation to ‘wastelands’, an official government term for marginal lands, but provides no guidance as to how wastelands will be identified for biofuel production. Despite a lack of consensus as to what wastelands are (Baka 2013; Baka forthcoming), earlier biofuel policy documents suggested that at least 17.4 million hectares (mha) of wastelands exist – roughly 4% of India’s geographic area -- and are available for establishing Jatropha curcas (hereafter Jatropha) biodiesel plantations (Government of India 2003). This paper examines the impacts, in terms of energy service provision, of locating Jatropha plantations on lands that are ambiguously defined yet seemingly abundant.

India’s biofuel policy is not unique. Calls to locate biofuels on marginal lands have increased over the past decade out of concern over the potential food security and land use change impacts of growing biofuels on arable lands (Fargione, Hill et al. 2008; Searchinger, Heimlich et al. 2008; Tilman, Socolow et al. 2009). Aided by numerous remote sensing analyses estimating the extent of marginal lands ‘available’ globally for biofuel production (Campbell, Lobell et al. 2008; Cai, Zhang et al. 2010; Nijsen, Smeets et al. 2012), this strategy has been incorporated into biofuel sustainability criteria and various government biofuel policies across the global North and South (Bailis and Baka 2011). Recent remote sensing analyses have downgraded initial estimates of the extent of marginal lands after ground truthing (Fritz, See et al. 2012) and in recognition that marginal lands are often used as grazing lands (Gelfand, Sahajpal et al. 2013). However, these adjustments do not address the political relations shaping lands or the politics of land classification processes.

Social scientists have long argued that labels such as wastelands are not neutral, unbiased assessments of landscapes but are social constructions reflecting, and often reinforcing, the (prior) perceptions of dominant stakeholders (c.f. Fairhead and Leach 1996; Robbins 2001; Robbins 2004). As such, land classification processes often simplify complex land use practices on the ground (Scott 1998). Lands classified as wastelands by the state are often common property lands used by the rural poor for fuelwood and fodder gathering (Ostrom 1990). For these reasons, critical scholars of biofuels have challenged calls to locate biofuels on marginal lands arguing that such policies fail to adequately consider the livelihood significance of such lands (Ariza-Montobbio, Lele et al. 2010; Borras, McMichael et al. 2010; Franco, Levidow et al. 2010).

Yet, to date, little evidence has been offered assessing the livelihood significance of marginal lands. Through the lens of socio-ecological metabolism, this paper provides such an assessment in rural India. We find that India's wastelands are dynamic energy landscapes servicing a range of household and industrial consumers in both rural and urban settings. This existing economy, centered on Prosopis juliflora (hereafter Prosopis) biomass, is currently being uprooted to establish a Jatropha biodiesel economy. We compare the changes in energy services this transition would engender through a comparative energy flow analysis (EFA) of the Prosopis and Jatropha economies. Drawing on political ecology theory, we extend socioecological metabolism literature by analyzing how this transition could re-shape human-environment relations in rural India.

In the next section, we review theories of socioecological metabolism and its intersection with political ecology. We introduce the field site and energy flow analysis method in section 3 and present results in section 4. We discuss the implications of our findings in section 5.

2. Theoretical review

Socioecological metabolism is an examination of the physical exchange processes shaping society and how these processes change with societal transitions (Fischer-Kowalski and Haberl 2007). Three main analytic components constitute socioecological metabolism: 1) material flow analysis, the study of material throughputs; 2) energy flow analysis, the study of energy throughputs; and 3) land use change, the examination of how society alters its environment to mobilize its material and energy needs. Analyzing societal metabolism "provides a framework to distinguish cultures, societies or regions according to their characteristic exchange relations with nature" (Fischer-Kowalski and Haberl 1998: 574).

Most socioecological metabolism analyses have been historically grounded characterizing the change in metabolic profiles resulting from societal transitions from hunter-gather, agrarian to industrial modes of production. While most studies have analyzed national or multi-national transitions (e.g. Krausmann, Haberl et al. 2004; Schandl and Krausmann 2007; Singh, Krausmann et al. 2012; West and Schandl 2013), a subsection of studies have analyzed transitions in island or small village settings (Singh, Gruenbuehel et al. 2001; Gruenbuehel, Haberl et al. 2003). Interdisciplinary in nature and influenced by a diversity of fields including cultural anthropology, land-change science and industrial ecology, amongst others (Singh 2013), socioecological metabolism studies help advance human-environment geography.

Socioecological metabolism also examines the integrity of resources as they move through production processes from raw materials to finished goods. This tracking captures both the 'hidden flows' of consumption, materials and energy mobilized in production but not embodied in the end use product (Haberl 2001)[1] and the materials and energy lost in transformation and conversion process. Because many consumptive and production indicators focus on final products (c.f. Haberl 2001; Wiedmann, Schandl et al. 2013), socioecological metabolism provides a more comprehensive perspective on the ecological footprint of society.

In this study, we focus on the energy flows of biofuel production which, in turn, provides insights into land use change impacts. Energy flow analysis distinguishes between three categories of energy (Haberl 2001; Haberl 2002): 1) primary energy, the energy content of feedstocks at the time of extraction (ie. wood); 2) final energy, the energy content of feedstocks after conversion (i.e. charcoal); 3) useful energy, energy that performs work (ie. cooking). Useful energy is also a proxy for energy services, "the immaterial services for which energy is actually used" (Haberl 2002: 74). For this study, EFA offers insights into the possible land use change impacts of biofuels by characterizing and comparing the energy services of India's wastelands

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[1] Mine slag is a common example of a hidden material flow.

under a biomass and biofuel energy system and by profiling how lands would be transformed to establish Jatropha plantations, particularly in terms of fertilizer requirements and lastly. As will be demonstrated, the existing Prosopis economy provides significantly more energy services than would a Jatropha economy. This can increase land use pressures as current Prosopis users seek out energy substitutes.

Energy flow analysis also examines the hidden flows of energy provision, energy mobilized in energy production but not embodied in the energy feedstock (ie. diesel fuel for transporting wood). In this study, hidden flows are the inputs of Jatropha production[2] and the transport energy required to circulate Prosopis and Jatropha. This enables an energy return on investment (EROI) analysis, the ratio of energy delivered (i.e. primary energy) to energy inputs (The Encyclopedia of Earth 2013). An EROI less than 1 indicates that an energy carrier requires more energy for its production than the resulting fuel provides. A high EROI can result from a low-input energy system and/or a high value energy carrier, such as fossil fuels (Hall, Cleveland et al. 1986). In this regard, EROI is both a measure of production efficiency and energy surplus (Cleveland, Kaufmann et al. 2000).

We did not find previous studies using EFA to analyze biofuels although life cycle analyses (LCA), a method with similar intellectual origins, abound. LCA also examines the mobilization of materials and energy but for an individual product rather than a country or region. Further, LCA is forward-looking, examining the environmental impacts of a system over a product's lifecycle (Graedel and Allenby 2010). To date, most LCAs of biofuels have examined the greenhouse gas (GHG)

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[2] Prosopis is not actively managed and thus, transportation energy is the only input to the Prosopis system.

emissions, primarily CO_2, associated with biofuel production (c.f. Farrell, Plevin et al. 2006; van der Voet, Lifset et al. 2010). When compared to a fossil fuel reference system and excluding land use change impacts, most studies have shown a decrease in GHG emissions across a range of biofuel feedstocks relative to fossil fuels (van der Voet, Lifset et al. 2010). Efforts to incorporate the land use change impacts of biofuel production are still under development but involve incorporating economic modeling into LCA to identify regions where biofuel cultivation is likely to take place (direct land use change) and where activities displaced by biofuels may shift (indirect land use change) (Fargione, Hill et al. 2008; Searchinger, Heimlich et al. 2008). While still uncertain, initial research indicates the GHG land use change impacts of biofuel production is sizeable (Plevin, O'Hare et al. 2010).

In this study, we conduct an EFA but apply life cycle thinking to estimate the energy services of India’s wastelands over the lifecycle of a Jatropha plantation (20-years). In contrast to LCA studies of biofuels, we use the Prosopis biomass system as our reference system, which offers a new perspective on the performance of biofuels. This provides a fine-grained examination of the metabolic impacts of transitioning from a biomass to a biofuel energy system. Further, this study not only quantifies the amount of energy services provided by marginal lands, it also interrogates the breadth of services offered as well as the changes in economic and property relations that may result if India were to replace Prosopis with biofuels.

To date, most socioecological metabolism studies have focused on the biophysical dimensions of human-environment interactions. Yet, tracing biophysical flows establishes a foundation for analyzing the associated socio-political factors shaping these relations. These concerns are a key focus of political ecology (Robbins 2004), an interdisciplinary field examining the political, social and environmental factors shaping and shaped by environmental change. Various scholars have used a political ecology framework to analyze biofuels (c.f. Borras, McMichael et al. 2010) and land classification processes associated with biofuels. Specific to Tamil Nadu's Jatropha-centered wasteland biofuels program, Ariza-Montobbio, et al (2010) argues that the concept of 'wasteland' is a politically malleable term applied to lands ranging from fallow lands to agroforestry lands. Extending this analysis, Baka (forthcoming) finds a lack of consensus amongst stakeholders as to what constitutes wastelands. Yet, economic incentives motivate the dominant perception of wastelands appearing in policy documents as 'empty', 'unproductive' spaces. Baka (2013) also finds that this ambiguity has helped to facilitate 'land grabs' of wastelands in Tamil Nadu, which is dispossessing rural farmers.

By integrating socioecological metabolism and political ecology, this study helps to conceptualize the emergent "new geographies of energy" (Zimmerer 2011). These geographies are a sub-field of human-environment geography that analyze the multiple political, economic and biophysical processes shaping and shaped by society's current quest for a low carbon, environmentally benign energy future.

3. Field site and methods

Fieldwork took place between December 2010 and February 2011 in Sattur taluk, Virudhunagar District, Tamil Nadu (Figure 1). This region was selected because of the history of Jatropha promotion in the area as well as the prevalence of Prosopis in the region. While dry land farming is currently the main occupation, primarily corn, cotton and pulse farming, Sattur is in the midst of an industrial transition with an increasing number of fireworks and match factories moving into the area (Virudhunagar District Collector 2009). Average rainfall for the district is approximately 830 millimetres per year and black soil is the predominant soil class (Virudhunagar District Collector 2009).

Data was gathered by surveying 158 users/producers of Prosopis: fuelwood users (n=114), 10 MW biomass power plant (n=1), charcoal makers (n=4), brick makers (n=5), match factories (n=7), restaurants (n=11), paper mills (n=3), oil mills (n=2), wood traders (n=11) and 2 Jatropha companies: plantation (n=1), biodiesel manufacturer (n=1) in 39 randomly sampled villages of Sattur (Figure 2). Calorific analyses of various Prosopis and Jatropha products were conducted to evaluate energy contents (Appendix 1).[3] Energetic contents for all other parameters were obtained from the literature and from Ecoinvent (Appendix 1).

The area of Prosopis in Sattur was estimated through a supervised classification of three seasonal LANDSAT images of Sattur between 2009-2011.[4] We estimate the average Prosopis area in Sattur to be 16,573 ha (36.2% of Sattur's geographic area).

Figure 1: Sattur Taluk

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[3] The products analyzed were: Prosopis charcoal, roots, stems and Jatropha oil and seedcake. Jatropha biodiesel was not available values were obtained from the literature.

[4] Researchers at the Centre for Ecological Sciences, IISc Bangalore assisted with this analysis.

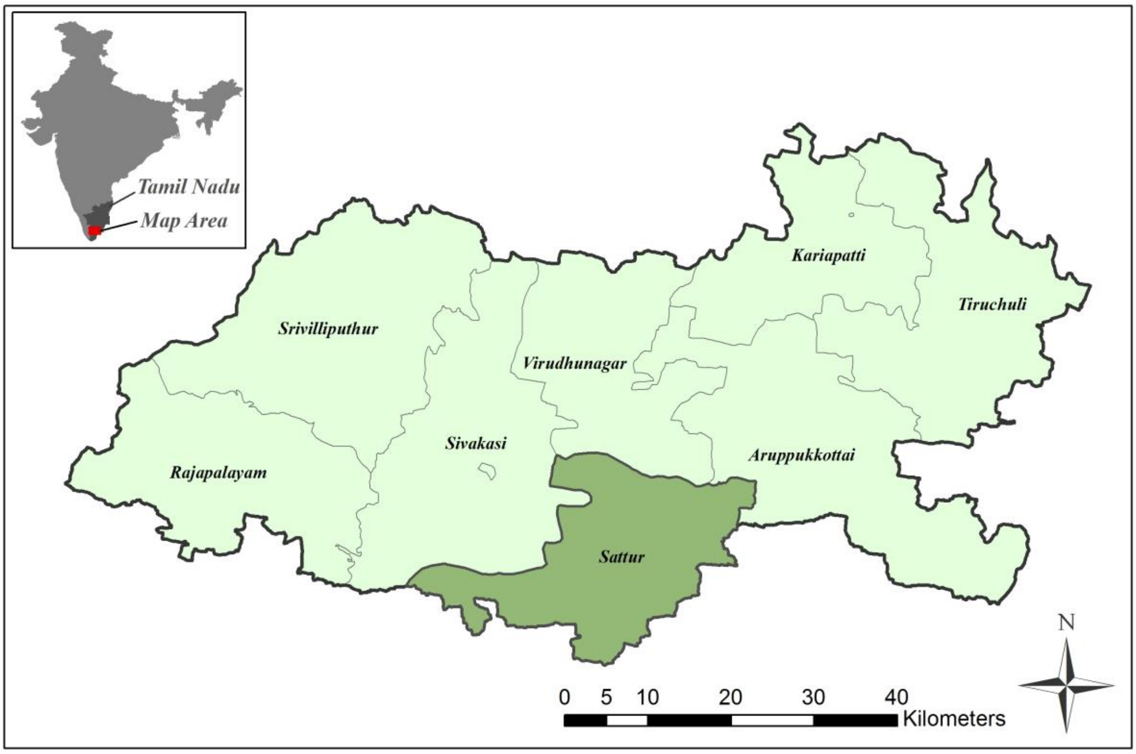
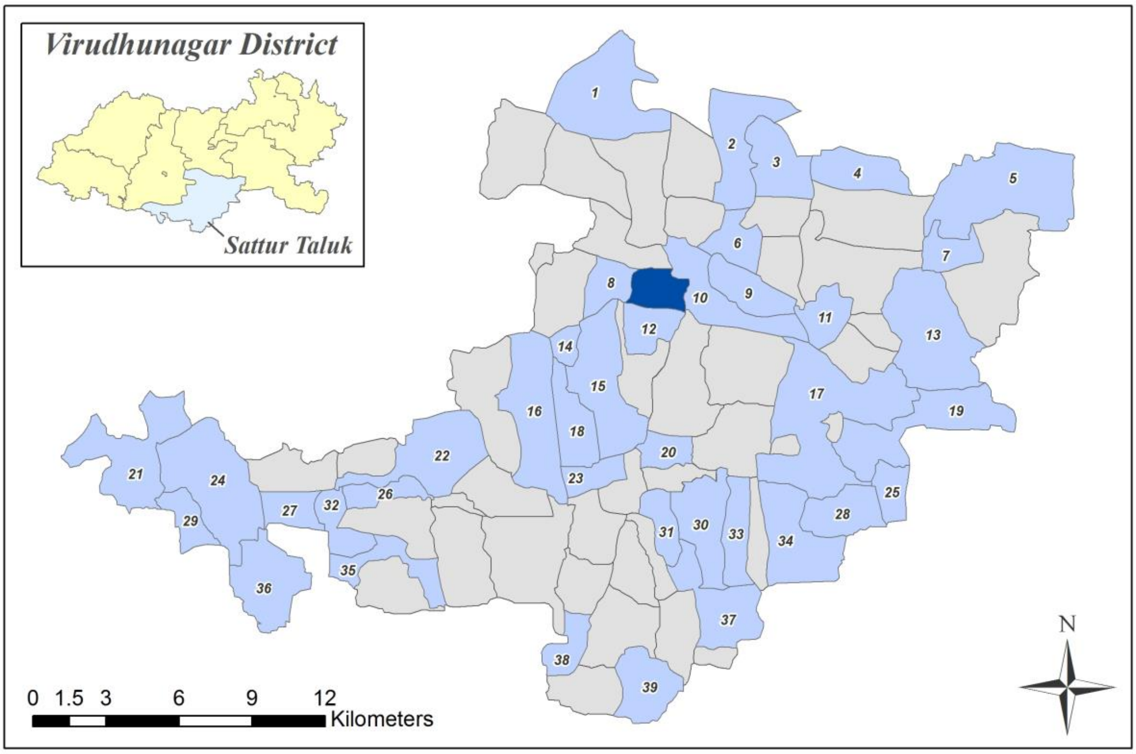


Figure 2: Sattur Field site villages



Village list: (1) Kumaralingapuram, (2) Sandaivur, (3) Golvarpatti, (4) Nallamanayakkanpatti, (5) Pappakudi, (6) Ammapatti, (7) Attipatti, (8) Padantal, (9) Allampatti, (10) Kattalampatti, (11) Melmadai/ Irrukungudi, (12) Chattrapatti, (13) N. Mettupatti, (14) Muthulingapuram, (15) O. Mettupatti, (16) Surankudi (17) Nenmeni (18) Ottaiyal, (19) Mudittalainagalapuram, (20) Chinnodaippatti, (21) Sevalpatti, (22) Kangarakottai/ Keelachalaiahpuram, (23) Chinna Tambiyapuram, (24) Tulukkankurichchi,

(25) Sinduvampatti, (26) Sanankulam/ Sivasankapatti, (27) Sankarapandiyapuram, (28) Ayyampatti, (29) Kukanaparai, (30) Subramaniapuram, (31) Muliseval, (32) Servaikkaranpatti, (33) Ovvanayakkanpatti, (34) Uppathur, (35) Uthupatti, (36) Sippipparai, (37) Nallamuttanpatti, (38) Peranyyanpatti, (39) Kanjampatti, (dark block) Sattur town.

We conducted the EFAs following the methodology developed by Haberl (2001; 2002). Due to the different gestation periods of Jatropha (3 years[5]) and Prosopis (0 years[6]), we modelled the energy services provided over a 20-year lifetime, the standard Jatropha plantation lifespan assumed in the literature (Almeida, Achten et al. 2011). At the time of fieldwork, Jatropha production was stalled in Sattur and across India. To model a Jatropha economy for Sattur, we surveyed a Jatropha company with a plantation in neighboring Ramnad District (Figure 1) and a biodiesel manufacturer in neighboring Aruppukkotai District (Figure 1).[7] Values were triangulated through a literature review of Jatropha lifecycle analyses (LCA).

The spacing, irrigation, fertilizer, pesticide requirements and seed yield of Jatropha are key areas of uncertainty (Whitaker and Heath 2008; Almeida, Achten et al. 2011). We assumed 1,600 trees per hectare (survey data) yielding 4.3 tonnes of seed per hectare per year starting in year 3, the Almeida, et al (2010) reference scenario. We assumed continuous drip irrigation over the 20-year lifespan to deliver the difference between annual rainfall in Sattur and the optimal rainfall target for Jatropha, 1,500 mm per year (Trabucco, Achten et al. 2010). We assumed annual application of NPK

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[5] The gestation period of Jatropha remains uncertain. Due to the breadth of their study, we used the gestation assumption of Almeida, et al, 2011.

[6] According to interviews conducted during fieldwork, Prosopis trees can be harvested within the first year of growth.

[7] The company plans to convert its 121 ha Jatropha plantation to food production (interview with company manager, January 22, 2011). This conversion was not yet completed at the time of fieldwork and we observed a Jatropha harvest during our survey. At the time of our fieldwork, the biodiesel manufacturer was under repair.

chemical fertilizer and pesticide application following Almeida, et al (2011). All products are transported by lorry. Detailed model assumptions are included as Appendix 1.

As van der Voet, et al's (2010) meta analysis of biofuel LCAs demonstrates, the use of by-products is a key driver of the environmental footprint of biofuels. Thus, we estimate the potential energy services of the by-products of the Jatropha system: Jatropha pruning biomass and seed husks, Jatropha seedcake and Prosopis uprooted during Jatropha land clearance. We assume the uprooted Prosopis is used to provide the same energy services as modelled in the Prosopis EFA. Because Jatropha production was stalled at the time of fieldwork, there was no market for Jatropha by-products. We estimate the energy services provided by using Jatropha by-products as substitutes for Prosopis.

Because of the uncertainty of the Jatropha system productivity, following Almeida et al (2010), we conducted a sensitivity analysis of Jatropha seed yield using the seven global yield classification values by Trabucco et al (2010): 0.5, 1, 1.5, 2, 2.5, 3.5 and 5 t/ha.

4. Results

Prosopis

Prosopis is used for three main functions in Sattur: as a fuelwood for cooking in households and restaurants, as a fuelwood for a variety of industries including paper mills, brick making, match making and oil mills and as a feedstock for electricity and charcoal production. Approximately 222 kilo-tonnes (ktonnes) of Prosopis are consumed annually within Sattur (Table 1). The power plant is the largest user, consuming just over 89 ktonnes per year (40.3% of total Prosopis usage), followed by households (30.4%), paper mills (15.2%), brick making (7%), charcoal (5.2%) and restaurants, match factories and oil mills (1.9% combined). Users purchase nearly 73% of their Prosopis needs from wood traders and local villagers. Users self-collect the remaining portion, typically within a few kilometer radius of their home or industry.

Prosopis is also the main energy feedstock for these users accounting for 80-100% of total feedstock demand (Table 1, column 5). Brick makers, charcoal makers and oil mills use Prosopis for 100% of their feedstock needs. The power plant uses Prosopis for 90%, on a mass basis, of its feedstocks and uses wood wastes from match making and plywood manufacturing in the neighboring state of Kerala for its remaining feedstock demand. The paper mills and match factories use Prosopis for approximately 85% and 96%, respectively, of their feedstock needs and use other trees, mainly Neem, Tamrind, and a native Prosopis variety, *Prosopis cineraria*, and other wood and agricultural wastes for the remaining needs. Restaurants use Prosopis for about 81% of their fuelwood needs and use wood wastes, native Prosopis and Indian mulberry (*Morinda citrifolia*)[8] for their remaining needs.

All of the households surveyed were rural households. Prosopis represents 95% of their cooking fuel on a mass basis.[9] Rural households use Indian mulberry, wood wastes, kerosene and LPG for their remaining feedstock needs. Due to time limitations, we did not conduct a cooking energy survey in the town of Sattur, the

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[8] Indian mulberry is colloquially known as *Manjanathi* in Tamil.

[9] On a calorific basis, Prosopis represents 91% of cooking energy feedstocks. Results are presented on a mass basis to be commensurate with Census of India data.

only urban region in Sattur taluk. However, based on Indian census data, we estimate that urban households in Tamil Nadu use fuelwood for approximately 34% of their cooking energy (Government of India 2001). Using these figures and the number of rural and urban households in Sattur, we estimate Prosopis represents 80% of household cooking energy in Sattur.

At these Prosopis usage rates, we estimate that Prosopis produces approximately 84 PJ of total primary energy and delivers roughly 16.3 PJ of energy services to the Sattur region over a 20-year period (Table 2). Nearly 80% of total primary energy is lost in conversion and combustion due to low technological efficiency rates (Appendix 1). We did not find evidence of Prosopis tree farming in Sattur. Prosopis regrows after coppicing and is easily established due to its invasiveness. Thus, the only energy input of the Prosopis energy system is the diesel fuel used to transport Prosopis via lorry and to combust Prosopis at the power plant.

Approximately 20% (3.3 PJ) of the energy services provided by Prosopis will be exported from the Sattur region. Just over 72% of the charcoal manufactured in the region will be exported to other parts of India, primarily to Chennai, Hyderabad and Mumbai and to the t-shirt manufacturing region of Tirupur in northern Tamil Nadu. To be conservative, we considered all electricity sold to the Tamil Nadu grid (90% of generation) as an export as physics will determine what portion, if any, of the electricity generated will stay in Sattur.

Table 1: Prosopis annual usage summary

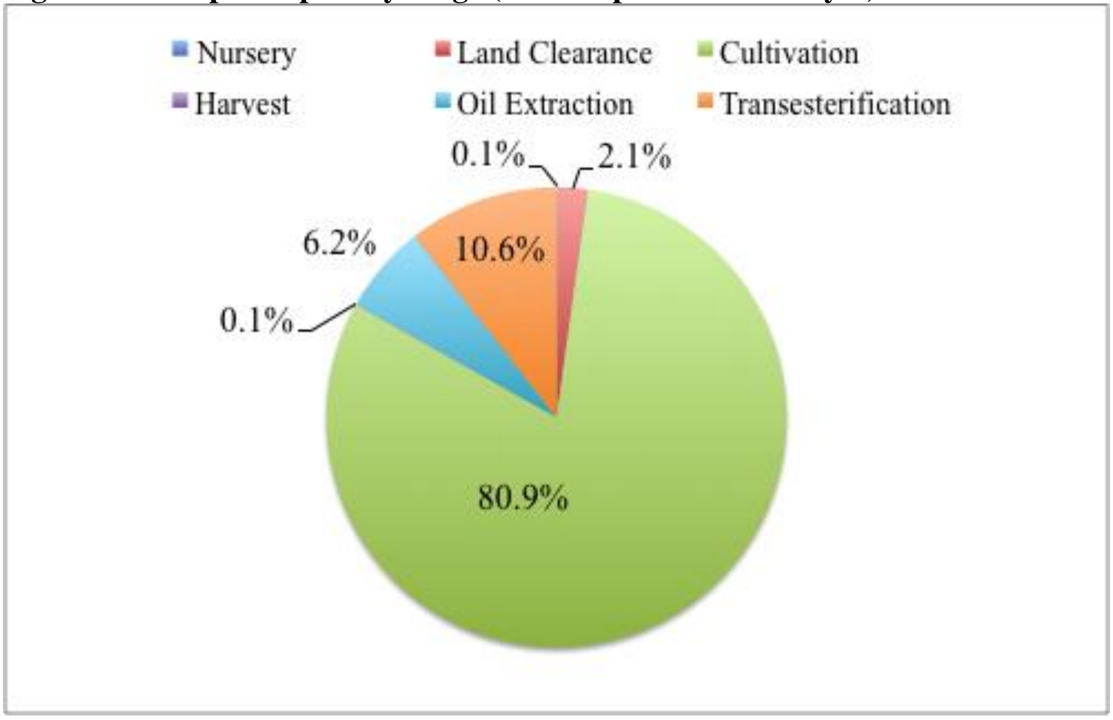
	Usage				***Procurement***		
Industry	**Industries in Sattur**	**Prosopis Use**	**Prosopis Use Percentage**	**Prosopis Percent of Total Energy Supply**	**Self-Procure**	**Purchases from Wood Traders**	**Purchases from Villagers**
	#	ktonnes/yr	%	%	%	%	%
power plant	1	89.3	40.3%	90.0%	0.0%	78.1%	21.9%
households	41,087	67.3	30.4%	80.5%	74.4%	25.6%	0.0%
paper mills	5	33.8	15.2%	84.5%	0.0%	92.6%	7.4%
brick making	125	15.4	7.0%	100.0%	0.0%	100.0%	0.0%
charcoal	121	11.5	5.2%	100.0%	100.0%	0.0%	0.0%
restaurants	76	2.3	1.0%	80.5%	3.3%	96.7%	0.0%
match factories	151	1.3	0.6%	95.9%	3.1%	96.3%	0.6%
oil mills	1	0.8	0.3%	100.0%	0.0%	0.0%	100.0%
TOTAL*	**41,566**	**221.6**	**100.0%**		**27.8%**	**61.9%**	**10.3%**

* Procurement totals are usage percentage weighted averages.

Jatropha

Over a 20-year period, we estimate that the Jatropha biodiesel system will produce approximately 5.0 PJ of total primary energy and deliver 1.4 PJ of energy services (Table 2). Just over 4.5 PJ of energy inputs are required, 81% of which are required in the cultivation stage (Figure 3). If by-products of Jatropha production are used for energy provision, the total energy services can increase to over 5.5 PJ. This represents a 4-fold increase over the energy services provided by Jatropha biodiesel (Table 2). Similar to biofuel LCAs, by-product usage is also a key determinant of EFA results.

Figure 3: Jatropha Inputs by Stage (Total Inputs=4.5 PJ/20-yrs)



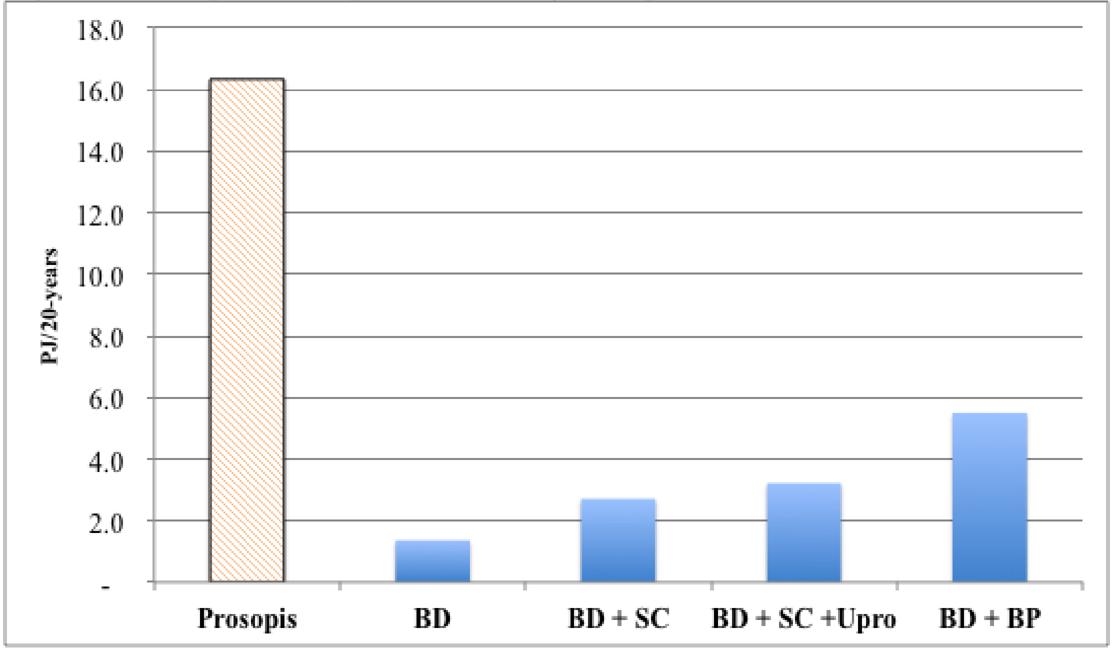
As per the Government of India's Biofuel Purchasing Policy all biodiesel will have to be shipped to the closest oil marketing centre (OMC) for testing and blending (Government of India 2005). The closest OMC to Sattur is located in Karur, Tamil Nadu, 230 km away. Thus, all Jatropha biodiesel produced in Sattur would be exported from the region. Economics will determine what, if any, percentage returns to Sattur. Assuming that uprooted Prosopis is consumed in the same manner as the existing Prosopis system and that 90% of electricity generated will be exported to the grid, a maximum of approximately 0.8 PJ of energy services provided by Jatropha by-products would be consumed within Sattur (Table 2).

Based on these results, the Prosopis system provides approximately 3 to 12 times more useful energy depending on how, if at all, by-products from the Jatropha system are used for energy provision (Table 2, Figure 4).

Table 2: Energy Flow Analysis Comparison

		Primary Energy	**Energy Inputs**	**Conversion & Distribution Losses**	**Total Final Energy**	**Combustion Losses**	**Total Useful Energy**	**Useful Energy Exports**	**Useful Energy %**	**Useful Energy Export %**
		PJ/20-yr	PJ/20-yr	PJ/20-yr	PJ/20-yr	PJ/20-yr	PJ/20-yr	PJ/20-yr	%	%
		[1]	[2]	[3]	[4]=[1]-[3]	[5]	[6]=[4]-[5]	[7]	[8]=[7]/[1]	[9]
	Prosopis	83.82	0.229	31.05	52.77	36.43	16.34	3.28	20%	20%
	Jatropha biodiesel	5.01	4.503	0.15	4.86	3.50	1.36	1.36	27%	100%
by-product	Uprooted Prosopis	5.17	0.001	4.42	0.76	0.24	0.51	0.10	10%	20%
	Jatropha pruning	15.81	0.024	13.50	2.31	0.74	1.57	1.41	10%	90%
	Jatropha husks	7.21	0.003	6.16	1.05	0.34	0.72	0.64	10%	90%
	Jatropha seedcake	13.57	0.004	11.59	1.98	0.63	1.35	1.21	10%	90%

Figure 4: Jatropha-Prosopis useful energy comparison



BD=Jatropha biodiesel; SC=Jatropha seedcake; Upro= Uprooted Prosopis from land clearance; BP=all by-products

Energy Return on Investment

Based on practices observed in Sattur, the Prosopis system has an EROI of 367 (Table 3). If no by-products of the Jatropha system are used for energy provision, Jatropha biodiesel would have an EROI of 1.1. This indicates that Jatropha biodiesel would provide about the same amount of primary energy that is required for its production. If all by-products are used for energy provision, the Jatropha system EROI can increase to 10.3. While these results indicate that Jatropha production is not an energy sink, the returns from Jatropha are significantly lower than the returns from Prosopis.

Table 3: Energy return on investment analysis

Scenario	Inputs	Primary Energy	EROI	Prosopis: Jatropha
	PJ/20-yr	PJ/20-yr	ratio	ratio
	[1]	[2]	[3]=[2]/[1]	[4]=[2]/[1]
Prosopis	0.2	83.8	366.6	
BD	4.5	5.0	1.1	329.7
BD + SC	4.5	18.6	4.1	88.9
BD + SC +Upro	4.5	23.8	5.3	69.6
BD + BP	4.5	46.8	10.3	35.5

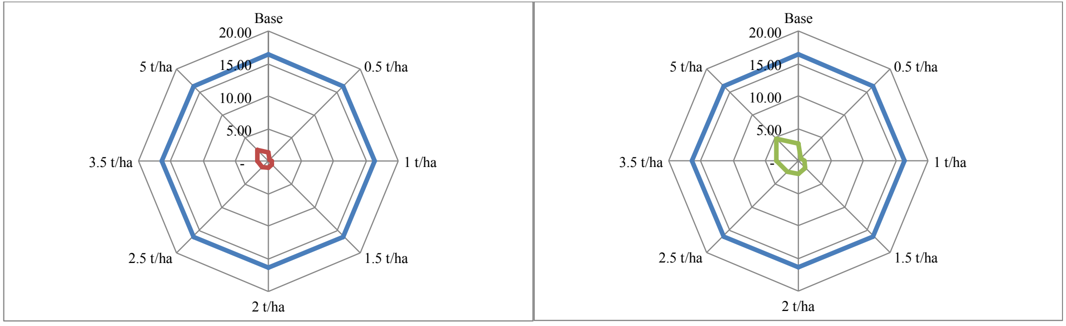
BD=Jatropha biodiesel; SC=Jatropha seedcake; Upro= Uprooted Prosopis from land clearance; BP=all by-products

Sensitivity Analysis

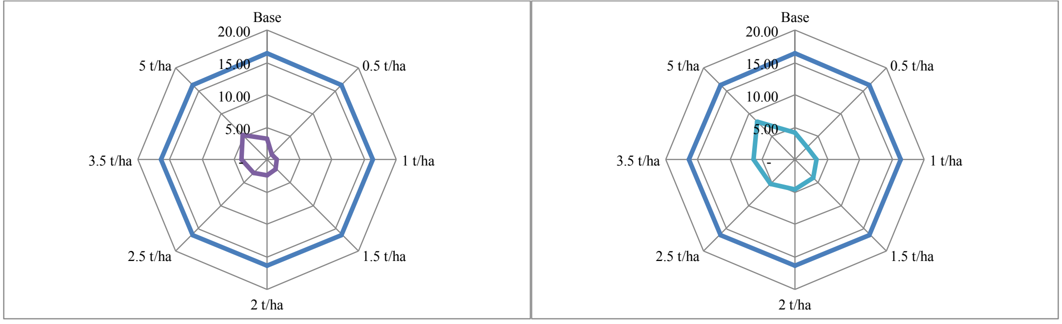
While increasing seed yield improves the energy services of the Jatropha system, the increases do not exceed the energy services of the Prosopis system even under the most aggressive yield assumptions (5 t/ha) (Figure 4). The energy services of the Jatropha system under the most aggressive yield assumptions is 8.3 PJ/20-years, nearly two times less than the Prosopis system energy services (16.3 PJ/20-years). Holding all yield-independent variables constant, a seed yield of 33 t/ha would be required to provide the same quantity of energy services as the Prosopis system (authors' calculations). This yield requirement represents nearly an 8-fold increase over current yields, which far exceeds the doubling in yields anticipated by SG Biofuels, one of the main companies developing hybrid Jatropha seeds (SG Biofuels 2010).

Figure 4: Useful energy sensitivity analysis

a) BD b) BD + SC



c) BD + SC + Upro d) BD + BP



BD=Jatropha biodiesel; SC=Jatropha seedcake; Upro= Uprooted Prosopis from land clearance; BP=all by-products

5. Discussion

The above analysis demonstrates that the Jatropha system provides fewer energy services than the Prosopis system in terms of both quantity and service function. Even under the most ambitious Jatropha production scenario in which all possible by-products are used for energy provision, the Prosopis system provides almost three times more energy services (Table 2). While improvements in Jatropha seed technology can decrease this gap, the sensitivity analysis reveals that the Jatropha system would still provide over two times less energy services than Prosopis even under the most optimistic yield value of 5 t/ha (Figure 4).

Yet differences in the quantity of energy services do not reveal the full magnitude of differences between Jatropha and Prosopis energy services. The systems also differ in terms of the type of energy services offered. At present, Prosopis is used as a fuelwood by households and industries and as a feedstock for charcoal and electricity manufacturing. Jatropha biodiesel is a liquid transportation fuel and thus, cannot substitute for the current energy services provided by Prosopis. By-products from the Jatropha system could be substitutes for some of the energy services of Prosopis, particularly for industries and the power plant.[10] Due to the toxicity of Jatropha, the Jatropha seedcake could not be used for cooking. As result, Jatropha by-products could not be used to replace household and restaurant Prosopis usage. These results indicate that replacing Prosopis with Jatropha could create an energy deficit that could reduce, rather than improve, energy security.

Baka (forthcoming) has previously analyzed how the majority of industries using Prosopis would likely shut down or seek out other biomass substitutes in the case of a Prosopis shortage or price spike. She also reveals how the Prosopis economy currently provides about 7 times more jobs per hectare than Jatropha to a mix of men and women and at higher wages. In addition to these changes, replacing Prospis with Jatropha could also engender further changes in economic and property relations. At present, the Prosopis system has more elements of an informal economy than would a Jatropha system. Household users freely cut Prosopis while cutting crews who work for industries or sell to wood merchants cut Prosopis from common property lands or pay landowners a small sum to cut Prosopis. In some instances, landowners do not charge cutting crews because removing Prosopis frees up their lands for other farming activities.

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[10] Based on our analysis, the calorific value of Jatropha seedcake (20.9 MJ/kg) is higher than Prosopis wood (18.9 MJ/kg) but lower than Prosopis charcoal (31.1 MJ/kg).

In contrast, based on observed practices, Jatropha plantations would be enclosed and would often involve the sale or leasing of land to private companies. Based on our biofuel company interview, companies would enclose land in part to protect Jatropha trees from grazing animals and to reduce the chance of children consuming poisonous Jatropha seeds. Yet, overall, these processes represent a change in access (Ribot and Peluso 2003) because they alter the current land use practices and derived benefits of Prosopis users. Further, because of the government's expressed interest to produce biofuels via public-private partnerships (Government of India 2003), the Jatropha system would be a more formal, market-based economy than Prosopis. As result, market forces would determine what, if any, portion of Jatropha by-products would be used for energy provision within Sattur.

Further, these results are not necessarily specific to Sattur. As has been documented by other social scientists, Prosopis is widely found throughout India (Robbins 2001; Gold 2003; Gidwani 2008) and Africa (Mwangi and Swallow 2008). Based on the government's *Wasteland Atlas of India* (Government of India 2010), scrublands, the categorical classification of Prosopis, is the largest category of wastelands in the country currently representing 18.5 mha or 5.8% of the total geographic area of India. Additional research is required to determine how Prosopis functions as an energy feedstock, if at all, in these regions.

While this study simultaneously considers the biophysical, social and political tradeoffs of replacing Prosopis with Jatropha, it does not consider the environmental and public health impacts of woodfuel usage. Household air pollution associated with using solid fuels is currently the fourth leading risk factor of the global disease burden (Lim, Vos et al. 2012) and accounts for approximately 2% of greenhouse gas emissions. Harvesting fuelwood has also been linked to deforestation, although the magnitude of this relationship is heavily debated (Geist and Lambin 2002). These factors should also be addressed in future research.

6. Conclusion

This study challenges conceptions of India's wastelands as 'empty' and 'unused'. In contrast, in rural Tamil Nadu, a diverse biomass energy economy based on Prosopis juliflora exists on these lands that services a mix of rural and urban consumers at household and industrial levels. The Prosopis economy provides approximately 3-12 times more energy services than would the Jatropha biodiesel economy that the Government of India envisions for these lands. Using by-products from Jatropha production for energy provision can substitute for some, but not all, of the energy services provided by Prosopis. Thus, contrary to assertions in India's National Policy on Biofuels, growing biofuels on wastelands can weaken, rather than improve, the country's energy security. Further, replacing Prosopis with Jatropha could engender changes in economic and property relations that could further weaken energy security. These findings are not specific to rural Tamil Nadu as Prosopis is widely used as a fuelwood throughout Asia and Africa. Calls to 'develop' degraded lands through biofuel promotion similarly exist in these regions. This study underscores the importance of analyzing wasteland-centered biofuel policies at local levels in order to better understand the changes in human-environmental relationships resulting from this policy push.

Appendix 1: EFA modeling assumptions

System	Parameter	Value	Unit	Source
Jatropha	nursery saplings	2,000.00	saplings/ha	calculated based on tree spacing requirements
Jatropha	nursery sapling survival rate	0.80	%	Whitaker, Heath, 2008
Jatropha	nursery area	447.32	ha	calculated from sapling requirements
Jatropha	seedling gestation	3.00	months	Emami survey
Jatropha	nursery irrigation system	0.55	KWh/ha	Emami survey
Jatropha	Prosopis area	16,573.10	ha	remote sensing analysis
Jatropha	tree spacing	4x1.5	m^2	Emami survey
Jatropha	irrigation system electric capacity	7.50	kW for 2/5 hrs/wk for 10 acres	Emami survey
Jatropha	Irrigation duration	52.00	weeks/yr for 20 years	Emami survey, Almeida, et al (2010)
Jatropha	Water Requirements	15*10^6	L/ha	Trabucco, et al, 2010
Jatropha	Weeding duration	2.00	times per year for first 5 years	Whitaker, Heath, 2008
Jatropha	Pruning duration	annually		Whitaker, Heath, 2008
Jatropha	pruning biomass, yr 1	2.5	kg/tree	Whitaker, Heath, 2009
Jatropha	pruning biomass, yr 2	4.5	kg/tree	Whitaker, Heath, 2010
Jatropha	pruning biomass, mature	8.5	kg/tree	Whitaker, Heath, 2011
Jatropha	Stem %	67%	%	Whitaker, Heath, 2012
Jatropha	Leaves %	33%	%	Whitaker, Heath, 2013
Jatropha	Stem energy	3.62	MJ/kg	Whitaker, Heath, 2014
Jatropha	Leaf energy	3.93	MJ/kg	Whitaker, Heath, 2015

System	Parameter	Value	Unit	Source
Jatropha	Seed yield	1.72	kg/tree	Almeida, et al, 2010 (reference case)
Jatropha	gestation period	3.00	years	Almeida, et al, 2010
Jatropha	Jatropha husk biomass	38%	% capsule weight	(Vyas and Singh 2007)
Jatropha	Jatropha seed biomass	63%	% capsule weight	(Vyas and Singh 2007)
Jatropha	Jatropha husk calorific value	15.50	MJ/kg	Reinhardt, 2008
Jatropha	Jatropha seed oil content	35.0%	%	Whitaker, Heath, 2008
Jatropha	Oil extraction efficiency	16.3%	%	Almeida, et al, 2010
Jatropha	Seed crusher capacity	500.00	kg/hr	ACS survey, Almeida, et al (2010)
Jatropha	Seed crusher electricity usage	76.00	kW	ACS survey, Almeida, et al (2010)
Jatropha	Seedcake calorific value	20.92	MJ/kg	calorific analysis
Jatropha	Transesterification efficiency	0.97	%	Whitaker, Heath, 2008
Jatropha	Jatropha biodiesel calorific value	39.65	MJ/kg	Achten, et al, 2008
Jatropha	diesel fuel efficiency 3.5-7.5 tonne truck	*	g/vkm	EcoInvent
Jatropha	diesel fuel efficiency 7.5-16 tonne truck	*	g/vkm	EcoInvent
Jatropha	diesel fuel efficiency 16-32 tonne truck	*	g/vkm	EcoInvent
Jatropha	Diesel fuel calorific value	44.83	MJ/kg	NIST Chemistry weBBook
Prosopis	Prosopis wood calorific value	18.91	MJ/kg	calorific analysis
Prosopis	Prosopis charcoal calorific value	31.14	MJ/kg	calorific analysis

System	**Parameter**	**Value**	**Unit**	**Source**
Energy conversion	Biodiesel conversion efficiency	97%	%	Almeida, et al, 2010
Charcoal conversion	Charcoal conversion	49%	%	Charcoal surveys
Combustion	Biodiesel combustion efficiency	28%	%	(Agarwal and Agarwal 2007)
Combustion	Biomass power plant efficiency	15%	%	Power plant survey
Combustion	Cookstove efficiency	12%	%	average of: (Pohekar and Ramachandran 2004), (Rajvanshi 2004), (Ravindranath, Manuvie et al. 2009).
Combustion	Industrial boiler efficiency	62%	%	Average of Prosopis industrial user surveys

* Withheld due to EcoInvent publication restrictions.

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