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Jennifer Baka and Robert Bailis

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

Jennifer Baka*
Assistant Professor
Geography and Environment, London School of Economics and Political Science
Houghton Street
London UK WC2A 2AE
Telephone: +44 (0)207 955 6573
Email: j.baka@lse.ac.uk

Robert Bailis
Associate Professor
Yale School of Forestry and Environmental Studies
195 Prospect Street
New Haven, CT USA 06511
Telephone: +1 203 432 5412
Email: robert.bailis@yale.edu

*Corresponding author

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, 2014), 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) 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 et al., 2008; Searchinger et al., 2008; Tilman et al., 2009). Aided by numerous remote sensing analyses estimating the extent of marginal lands ‘available’ globally for biofuel production (Cai et al., 2010; Campbell et al., 2008; Nijsen 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 et al., 2012) and in recognition that marginal lands are often used as grazing lands (Gelfand 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, 2001a; Robbins, 2004). As such, land classification processes often simplify complex land use practices on the ground (Scott, 1998). Other scholars have questioned estimates of ‘spare’ lands arguing that such figures often overestimate the availability of cultivable lands by failing to adequately consider the full range of services lands provide (Young, 1999). 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 et al., 2010; Borras et al., 2010; Franco et al., 2010).

Yet, to date, little empirical evidence has been offered assessing the livelihood significance of marginal lands in the context of biofuel development. Through the lens of social metabolism, this paper provides such an assessment in a subregion of 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), is currently being uprooted to establish a Jatropha biodiesel economy. We compare the changes in useful energy this transition would engender through a comparative energy flow analysis (EFA) of the Prosopis and Jatropha economies. Drawing on political ecology theory, we extend social metabolism literature by analyzing how this transition could re-shape human-environment relations in rural India.

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

2. Theoretical review

Grounded in ecological metaphors, social metabolism, or its synonym, socioeconomic metabolism, analyzes the biophysical exchange processes mediating human-environment relations (Fischer-Kowalski, 1997). This involves studying the material and energy throughputs and associated land use changes required to sustain socioeconomic systems. Interdisciplinary in nature and influenced by a diversity of fields including cultural anthropology, land-change science and industrial ecology, amongst others (Singh et al., 2013), this approach "provides a framework to distinguish cultures, societies or regions according to their characteristic exchange relations with nature" (Fischer-Kowalski and Haberl, 1998: 574).

Many social metabolism studies analyze socioecological transitions, the changes in metabolic profiles accompanying broad economic transformations, such as transformations from agrarian to industrial societies (Fischer-Kowalski and Haberl, 2007). While most such studies have analyzed national or multi-national transitions (e.g. Krausmann et al., 2004; Schandl and Krausmann, 2007; Singh et al., 2012; West and Schandl, 2013), a subsection of studies have analyzed transitions in island or small village settings (Gruenbuehel et al., 2003; Singh et al., 2001).

To date, most of these studies have focused on the biophysical dimensions of socioecological transitions with limited research on the associated socio-political factors shaping and shaped by these transitions. An emerging strand of literature has combined ecological economics and political ecology to analyze how a changing global social metabolism can lead to conflicts (Martinez-Alier et al., 2010; Muradian et al., 2012). This literature posits that a fundamental transformation in the extraction and provision of natural resources is underway, engendered, in part, by rising food and energy prices and continued population growth. Conflicts can and have been occurring along commodity frontiers as actors seek out new territories for resource provision.

The new bioeconomy (ETC, 2010), the emerging industrial economy centered on bio-based materials and premised on replacing fossil fuels with biomass, represents a fundamental transformation in social metabolism. Many recent studies of the new bioeconomy have focused on the political-economic dynamics of the transformation.

Smolker (2008) argues that substituting biomass for fossil fuels is facilitating a fundamental restructuring of the global agricultural system as it interlocks agriculture, energy, land use, climate change, transportation, trade and human rights policies. McMichael (2012) asserts that the global 'land grab' (c.f. Borras et al., 2011; Fairhead et al., 2012; White et al., 2012; Wolford et al., 2013) marks the beginning stages of this restructuring as it "anticipates the rising value of living biomass" (687). The land conflicts that have resulted, documented extensively by the Environmental Justice Organizations, Liabilities and Trade project (EJOLT, 2011), presage what may result as the new bioeconomy advances. Overall, Birch, et al (2010) argue that the new bioeconomy continues the neoliberalization of nature and knowledge as new innovations and requisite markets and property rights are developed to unlock (and adequately value) the potential of biomass in today's society.

Biofuel production, a component of the bioeconomy, has been a key focus of the social metabolism and political ecology literatures. However, similar to the above, the core of this research has focused on the political dimensions (c.f. Borras et al., 2010) and associated conflicts (c.f. Martinez-Alier et al., 2010; Muradian et al., 2012) of biofuel promotion. Fundamentally, the low energy density and spatial requirements of biofuel feedstocks compared to fossil fuels creates new land use pressures as land is now needed to service society's food, fiber and fuel needs (Scheidel and Sorman, 2012). While this literature is too vast to review in this paper, we review the section of this literature relevant to Jatropha promotion in Tamil Nadu, India.

In an analysis of 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 (2014) finds a lack of consensus amongst biofuel stakeholders as to what constitutes wastelands in India. Yet, economic incentives motivate the dominant perception of wastelands appearing in biofuel policy documents as 'empty', 'unproductive' spaces. Baka (2013) also finds that this ambiguity has helped to facilitate biofuel-related land grabs of wastelands in Tamil Nadu, which are dispossessing rural farmers. For these reasons, in addition to lower than anticipated seed yields and higher than anticipated water requirements, Ariza-Montobbio and Lele (2010) characterize Jatropha promotion in northern Tamil Nadu as a latent conflict between farmers and the state.

Overall, the social metabolism literature on biofuels has primarily focused on the political-economic drivers and potential for ecological conflicts stemming from biofuel promotion. Limited empirical research has examined the biophysical dynamics underlying this energy transition. This study fills this research gap. We analyze the metabolic transition underway in southern Tamil Nadu by characterizing the changes in the quantity and quality of energy resulting from replacing biomass with biofuels. We also examine the resultant socio-political transformations stemming from this transition.

Collectively, this study contributes to the emergent "new geographies of energy" literature (Zimmerer, 2011), which seeks to 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 rainfed cultivation of corn, cotton and pulses farming are currently the main forms of production in the Taluk, 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), a 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 (Appendices A-C).[1] Energetic contents for all other parameters were obtained from the literature and from Ecoinvent, a common lifecycle analysis (LCA) database (Appendices A-C).

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

The area of Prosopis in Sattur was estimated through a supervised classification of three seasonal LANDSAT images of Sattur between 2009-2011.[2] We estimate the average Prosopis area in Sattur to be 16,573 ha (36.2% of Sattur's geographic area).

[Figure 1]

[Figure 2]

We conducted the EFAs following the methodology developed by Haberl (2001, 2002). EFA distinguishes between three categories of energy (Haberl, 2001, 2002): 1) primary energy, the energy content of feedstocks at the time of extraction (i.e. wood); 2) final energy, the energy content of feedstocks after conversion (i.e. charcoal); 3) useful energy, energy that performs work (i.e. cooking). For this study, EFA offers insights into the possible land use change impacts of biofuels by characterizing and comparing the useful energy of Sattur's wastelands under a biomass and biofuel energy system. Further, EFA provides insights into how lands would be transformed to establish Jatropha plantations, particularly in terms of fertilizer and irrigation requirements. As will be demonstrated, the existing Prosopis economy provides significantly more useful energy than would a Jatropha economy.

EFA 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[3] 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

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

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

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 et al., 1986). In this regard, EROI is both a measure of production efficiency and energy surplus (Cleveland et al., 2000).

Due to the different gestation periods of Jatropha (3 years[4]) and Prosopis (1 year[5]) and the uncertainty about Prosopis system performance over an extended lifespan, we modeled the current useful energy provided by Prosopis and the annual useful energy provided when Jatropha trees reach maturity. Thus, in contrast to previous EFA studies, our study is a one-year comparative study. 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).[6] Values were triangulated through a literature review of Jatropha life cycle analyses (LCAs), described below.

In addition to the uncertain gestation period of Jatropha, the spacing, irrigation, fertilizer, pesticide requirements and seed yield of Jatropha are also variable (Almeida

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[4] The gestation period of Jatropha remains uncertain. Due to the breadth of their study, we used the gestation assumption of Almeida and colleagues (2011).

[5] According to interviews conducted during fieldwork, Prosopis trees can be harvested within the first year of growth. Additionally, trees are typically coppiced on a 3-4 year rotation.

[6] 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.

et al., 2011; Whitaker and Heath, 2008). We assumed 1,600 trees per hectare (survey data) yielding 4.3 tonnes of seed per hectare per year starting in year 3, which is the reference scenario suggested by Almeida, et al (2010). We assumed continuous drip irrigation to deliver the difference between annual rainfall in Sattur and the optimal rainfall target for Jatropha, 1,500 mm per year (Trabucco et al., 2010). We assumed annual application of NPK chemical fertilizer and pesticide application following Almeida, et al (2011). All products are transported by lorry. Detailed model assumptions are included in Appendix A.

As van der Voet, et al’s (2010) meta analysis of biofuel LCAs demonstrates, the use of by-products is a key component of the environmental footprint of biofuels. Thus, we estimate the potential useful energy of the by-products of the Jatropha system, which include the pruning biomass and seed husks resulting from Jatropha cultivation and harvesting and the seedcake residue resulting from Jatropha oil extraction. Because Jatropha production was stalled at the time of fieldwork, there was no market for Jatropha by-products. We estimate the useful energy provided by using Jatropha by-products as substitutes for Prosopis. Additionally, the Prosopis uprooted to establish Jatropha plantations can be considered a by-product to the Jatropha system. We included the annual useful energy from the uprooted Prosopis, assuming it is used in the same manner as the existing Prosopis system, amortized over a 20-year lifespan of a Jatropha plantation (Almeida et al., 2011).

We conducted a scenario analysis to estimate the range of useful energy provided by Jatropha biodiesel plus various combinations of Jatropha by-products (Table 1). Because of the uncertainty of the Jatropha system productivity, following Almeida et al (2010), we also 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/yr after maturity.

[Table 1]

4. Results

4.1 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 2). 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).

Prosopis users either self-collect or purchase Prosopis from wood traders or local villagers. Charcoal manufacturers self-collect all of their Prosopis supplies, households self-collect approximately 74% of their Prosopis supplies and restaurants and match factories self-collect about 3% of their Prosopis needs (Table 2). These users self-collect Prosopis typically within a few kilometer radius of their home or industry. Yet, the overall amount of self-collection accounts for only 28% of the Prosopis circulating in Sattur. The majority of Prosopis circulating in Sattur is purchased (Table 2).

Prosopis is also the main energy feedstock across user groups accounting for 80-100% of total feedstock demand (Table 2, 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 feedstock 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% of their feedstock needs respectively, and use other trees, mainly Neem, Tamarind, 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)[7] for their remaining needs.

All of the households surveyed were rural households. Prosopis represents 95% of their cooking fuel on a mass basis.[8] 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 only urban region in Sattur taluk. However, based on Government of India 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.

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

[8] 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.

At these Prosopis usage rates, we estimate that Prosopis currently provides approximately 4,191 TJ/yr of total primary energy and delivers roughly 825.1 TJ/yr of useful energy to the Sattur region (Table 3). Nearly 80% of total primary energy is lost in conversion and combustion due to low technological efficiency rates (Appendix C). Prosopis is invasive and has spread throughout the Taluk with little active intervention. As a result, it requires no active management. It is harvested on a three-year cycle and regenerates through coppicing with no additional inputs. Thus, the only energy input of the Prosopis energy system is the diesel fuel used to transport Prosopis via lorry and to aid in the combustion of Prosopis at the power plant.

Approximately 20% (164.2 PJ/yr) of the useful energy provided by Prosopis are exported from the Sattur region in the form of charcoal and electricity (Figure 3). Just over 72% of the charcoal manufactured in the region is exported to other parts of India, including urban centers like Chennai, Hyderabad and Mumbai as well as the t-shirt manufacturing region of Tirupur in northern Tamil Nadu. In addition, because the 10 MW power plant accounts for only a small portion of Tamil Nadu's 20.7 GW of installed capacity (Government of India, 2013), we assume that electricity produced by the power plant and sold to the Tamil Nadu grid (90% of generation) is exported outside Sattur Taluk.

[Table 2]

4.2 Jatropha

At maturity, we estimate that the Jatropha biodiesel system, consisting of 16,573 ha, the same area of the current Prosopis economy, will produce approximately 294.5

TJ/yr of total primary energy and deliver 80 TJ/yr of useful energy (Figure 3). Just over 242 TJ/yr of energy inputs are required annually (Figure 3).[9] If by-products of Jatropha production and the uprooted Prosopis are used for energy provision, the total useful energy would increase to over 335 TJ/yr. This represents a 4-fold increase over the useful energy provided by Jatropha biodiesel alone (Figure 3). Thus, similar to biofuel LCAs, by-product usage is also a key determinant of EFA results.

According to 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 90% of electricity generated from Jatropha system by-products is also exported to the grid, that the 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 61.3 TJ/yr of useful energy provided by Jatropha by-products and uprooted Prosopis would be consumed within Sattur (Figure 3).

Based on these results, the Prosopis system provides approximately 2.5 to 10.3 times more useful energy depending on how, if at all, by-products from the Jatropha system are used for energy provision (Figure 4).

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[9] Inputs include annual inputs for cultivation, harvest, oil extraction and transesterification stages of Jatropha production. We also amortized the nursery and land preparation inputs over an assumed 20-year Jatropha plantation lifespan, the typical lifespan assumed in the literature (Almeida, et al, 2010).

[Figure 3]

[Figure 4]

4.3 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 1.2. 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 10.7. While these results indicate that Jatropha production yields positive energy returns, the returns from Jatropha are significantly lower than the returns from Prosopis.

[Table 3]

4.4 Sensitivity Analysis

While increasing seed yield improves the useful energy of the Jatropha system, the increases do not exceed the useful energy of the Prosopis system even under the most aggressive yield assumptions (5 t/ha/yr) (Figure 5). The useful energy of the Jatropha system under the most aggressive yield assumptions and full by-product use are 500.2 TJ/yr, which is approximately 40% of the useful energy delivered by the Prosopis system (825.1 TJ/yr). Holding all yield-independent variables constant, a seed yield of 17.7 t/ha/yr would be required to provide the same quantity of useful energy as the Prosopis system (authors' calculations), which is far beyond any conceivable yield. Indeed, the most optimistic projections for Jatropha are a doubling of yields anticipated by SG Biofuels, one of the main companies developing hybrid Jatropha seeds (SG Biofuels, 2010).

[Figure 5]

5. Discussion

The above analysis demonstrates that the Jatropha system provides less useful energy than the Prosopis system in terms of both quantity and service function. Further, the sensitivity analysis reveals that Jatropha seed yield improvements cannot significantly reduce this gap.

Yet differences in the quantity of useful energy do not reveal the full magnitude of differences between Jatropha and Prosopis useful energy. The systems also differ in terms of the type of useful energy 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 useful energy provided by Prosopis. By-products from the Jatropha system could be substitutes for some of the useful energy of Prosopis, particularly for industries and the power plant.[10] Due to the toxicity of Jatropha, the Jatropha seedcake should not be used for cooking. As result, Jatropha by-products should not be used to replace household and restaurant Prosopis usage (Matsumura, 2012). These results indicate that replacing Prosopis with Jatropha could create an energy deficit that could reduce, rather than improve, energy security.

Baka (2014) 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

[10] Based on our analysis, the air dry basis 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).

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 Prosopis 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.

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 researchers, Prosopis is widely found throughout India (Gidwani, 2008;

Gold, 2003; Robbins, 2001b) 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.

However, the Prosopis system also faces limitations – beyond its invasiveness -- that detract from its viability as an energy source. To be a self-sustaining system, annual usage rates should not exceed annual regeneration rates. Assuming 16,573 ha of Prosopis in Sattur with an average biomass of 16.5 tonnes/ha (Bailis and McCarthy, 2011) and a three-year regeneration cycle, a self-sustaining harvest rate for Sattur is 91.2 ktonnes/year. The current Prosopis usage rate in Sattur (221.6 ktonnes/yr) is 2.4-times the self-sustaining harvest rate.[11] Thus, at current usage rates, there is a high likelihood of a Prosopis shortage in coming years, which can further increase land use pressures and weaken energy security. However, absent the biomass power plant, annual usage rates (132.3 ktonnes/yr) would be 1.5 times the self-sustaining harvest rate, a marked (but not self-sustaining) improvement over current usage rates. Coupled with the Jatropha EFA analysis, these findings point to the unsustainable land use and energy security pressures resulting from the introduction of 'modern' energy technologies.

Secondly, while this study simultaneously considers the biophysical, social and political tradeoffs of replacing Prosopis with Jatropha, it does not consider the

[11] Based on interviews with wood traders in Sattur, most of the wood circulating in Sattur is collected from within the talluk or within close proximity to the talluk borders. Hence, this finding is not explained away by wood trading in Sattur.

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, 2012). Moreover, emissions from woodfuel consumption contribute approximately 2% of greenhouse gas emissions (Bailis et al., in review). Harvesting woodfuel has also been linked to forest degradation and deforestation, although the magnitude of this relationship is unclear (Geist and Lambin, 2002; Hosonuma et al., 2012). These factors are beyond the scope of this analysis, but should be addressed in future research analyzing tradeoffs between tradition and modern bioenergy systems.

Despite these limitations, the main finding of this paper still holds: the current framing of wastelands in India's biofuel policy masks an existing biomass energy economy that provides significantly more useful energy in terms of quantity and diversity than would the country's proposed Jatropha biodiesel system.

6. Conclusion

Through a comparative energy flow analysis, this study challenges conceptions of India's wastelands as 'empty' and 'unused'. In rural Tamil Nadu, a diverse biomass energy economy based on Prosopis exists on these lands that services a mix of rural and urban consumers spread across residential, commercial, and industrial sectors. The Prosopis economy provides 2.5-10.3 times more useful energy than 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 useful energy 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.

The energy security impacts of replacing Prosopis with Jatropha will depend on user responses. As Baka (2014) reveals, most users would either shut down their businesses or seek out other fossil fuel or biomass substitutes. If users accelerate their transition to LPG, a strategy favored by the government, India’s fossil fuel imports could increase. Seeking out other biomass substitutes would likely increase land use pressures, which can potentially lead to land degradation. Thus, replacing Prosopis with Jatropha will likely impact energy security in perverse ways that are not currently being considered by policy makers.

Finally, 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.

Theoretically, this study advances both the social metabolism and new geographies of energy literature through a combined analysis of the biophysical and political-economic impacts of biofuel promotion. Empirically, 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.

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Appendix A
Table A.1: Jatropha Modeling Assumptions

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

*Withheld due to EcoInvent publication restrictions.

Appendix B

Table B.1: Prosopis Modeling Assumptions

Parameter	Value	Unit	Source
Prosopis wood calorific value	18.91	MJ/kg	Authors’ calorific analysis
Prosopis charcoal calorific value	31.14	MJ/kg	Authors’ calorific analysis
Prosopis wood moisture content	2.2%	Air dry basis	Authors’ calorific analysis

Appendix C

Table C.1: Conversion and Combustion Efficiencies

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

REFERENCES

Almeida, J., Achten, W.M.J., Duarte, M.P., Mendes, B., Muys, B., 2011. Benchmarking the Environmental Performance of the Jatropha Biodiesel System through a Generic Life Cycle Assessment. Environmental Science & Technology 45, 5447-5453.

Ariza-Montobbio, P., Lele, S., 2010. Jatropha plantations for biodiesel in Tamil Nadu, India: Viability, livelihood trade-offs, and latent conflict. Ecological Economics 70, 189-195.

Ariza-Montobbio, P., Lele, S., Kallis, G., Martinez-Alier, J., 2010. The Political Ecology of Jatropha Plantations for Biodiesel in Tamil Nadu, India. Journal of Peasant Studies 37, 875-897.

Bailis, R., Baka, J., 2011. Constructing Sustainable Biofuels: Governance of the Emerging Biofuel Economy. Annals of the Association of American Geographers 101, 827-838.

Bailis, R., Drigo, R., Ghilardi, A., Masera, O., in review. The Global Footprint of Traditional Woodfuels.

Bailis, R., McCarthy, H., 2011. Carbon impacts of direct land use change in semiarid woodlands converted to biofuel plantations in India and Brazil. GCB Bioenergy 3, 449-460.

Baka, J., 2013. The Political Construction of Wasteland: Governmentality, Land Acquisition and Social Inequality in South India. Development and Change 44, 409-428.

Baka, J., 2014. What wastelands? A critique of biofuel policy discourse in South India. Geoforum 54, 315-323.

Birch, K., Levidow, L., Papaioannou, T., 2010. Sustainable capital? The neoliberalization of nature and knowledge in the European knowledge-based bio-economy. Sustainability 2, 2898–2918.

Borras, S.M., Hall, R., Scoones, I., White, B., Wolford, W., 2011. Towards a better understanding of global land grabbing: an editorial introduction. Journal of Peasant Studies 38, 209-216.

Borras, S.M., McMichael, P., Scoones, I., 2010. The politics of biofuels, land and agrarian change: editors' introduction. The Journal of Peasant Studies 37, 575-592.

Cai, X., Zhang, X., Wang, D., 2010. Land Availability for Biofuel Production. Environmental Science & Technology 45, 334-339.

Campbell, J.E., Lobell, D.B., Genova, R.C., Field, C.B., 2008. The Global Potential of Bioenergy on Abandoned Agriculture Lands. Environmental Science & Technology 42, 5791-5794.

Cleveland, C.J., Kaufmann, R.K., Stern, D.I., 2000. Aggregation and the role of energy in the economy. Ecological Economics 32, 301-317.

EJOLT, 2011. Mapping Environmental Justice.

ETC, 2010. The new biomasters. Synthetic biology and the next assault on biodiversity and livelihoods.

Fairhead, J., Leach, M., 1996. Misreading the African landscape: Society and Ecology in a Forest-Savanna Mosaic. Cambridge University Press, Cambridge.

Fairhead, J., Leach, M., Scoones, I., 2012. Green Grabbing: a new appropriation of nature? The Journal of Peasant Studies 39, 237-261.

Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land Clearing and the Biofuel Carbon Debt. Science 319, 1235-1238.

Fischer-Kowalski, M., 1997. Society's metabolism: On the childhood and adolescence of a rising conceptual star, in: Redclift, M., Woodgate, G.R. (Eds.), The international handbook of environmental sociology. Edward Elgar, Cheltenham, Northhampton.

Fischer-Kowalski, M., Haberl, H., 1998. Sustainable development: socio-economic metabolism and colonization of nature. International Social Science Journal 50, 573-587.

Fischer-Kowalski, M., Haberl, H., 2007. Conceptualizing, Observing and Comparing Socioecological Transitions, in: Fischer-Kowalski, M., Haberl, H. (Eds.), Socioecological Transitions and Global Change: Trajectories of Social Metabolism and Land Use. Edward Elgar, Cheltenham, UK.

Franco, J., Levidow, L., Fig, D., Goldfarb, L., Hoenicke, M., Luisa Mendonca, M., 2010. Assumptions in the European Union biofuels policy: frictions with experiences in Germany, Brazil and Mozambique. The Journal of Peasant Studies 37, 661-698.

Fritz, S., See, L., van der Velde, M., Nalepa, R.A., Perger, C., Schill, C., McCallum, I., Schepaschenko, D., Kraxner, F., Cai, X., Zhang, X., Ortner, S., Hazarika, R., Cipriani, A., Di Bella, C., Rabia, A.H., Garcia, A., Vakolyuk, M.Ä., Singha, K., Beget, M.E., Erasmi, S., Albrecht, F., Shaw, B., Obersteiner, M., 2012. Downgrading Recent Estimates of Land Available for Biofuel Production. Environmental Science & Technology 47, 1688-1694.

Geist, H.J., Lambin, E.F., 2002. Proximate Causes and Underlying Driving Forces of Tropical Deforestation. BioScience 52, 143-150.

Gelfand, I., Sahajpal, R., Zhang, X., Izaurralde, R.C., Gross, K.L., Robertson, G.P., 2013. Sustainable bioenergy production from marginal lands in the US Midwest. Nature 493, 514-517.

Gidwani, V., 2008. Capital, Interrupted: Agrarian Development and the Politics of Work in India. University of Minnesota Press, Minneapolis, MN.

Gold, A.G., 2003. Foreign Trees: Lives and Landscapes in Rajasthan, in: Greenough, P., Tsing, A.L. (Eds.), Nature in the Global South: Environmental Projects in South and Southeast Asia. Duke University Press, Durham, NC.

Government of India, 2001. Census of India. Office of the Registrar General, India.

Government of India, 2003. Report of the Committee on the Development of Biofuel, in: Planning Commission (Ed.). Government of India, New Delhi.

Government of India, 2005. Bio-Diesel Purchase Policy, in: Ministry of Petroleum and Natural Gas (Ed.), New Delhi.

Government of India, 2009. National Policy on Biofuels.

Government of India, 2010. Wastelands Atlas of India: 2010, in: Centre, N.R.S. (Ed.), Delhi.

Government of India, 2013. All India Regionwise Generating Installed Capacity of Power in: Central Electricity Authority, Ministry of Power (Eds.).

Gruenbuehel, C.M., Haberl, H., Schandl, H., Winiwarter, V., 2003. Socioeconomic Metabolism and Colonization of Natural Processes in Sangsaeng Village: Material and Energy Flows, Land Use, and Cultural Change in Northeast Thailand. Human Ecology 31, 53-86.

Haberl, H., 2001. The Energetic Metabolism of Societies Part I: Accounting Concepts. Journal of Industrial Ecology 5, 11-33.

Haberl, H., 2002. The Energetic Metabolism of Societies: Part II: Empirical Examples. Journal of Industrial Ecology 5, 71-88.

Hall, C.A.S., Cleveland, C.J., Kaufmann, R., 1986. Energy and Resource Quality: The ecology of the economic process, 2nd ed. University Press of Colorado, NY.

Hosonuma, N., Herold, M., De Sy, V., De Fries, R.S., Brockhaus, M., Verchot, L., Angelsen, A., Romijn, E., 2012. An assessment of deforestation and forest degradation drivers in developing countries. Environmental Research Letters 7.

Krausmann, F., Haberl, H., Erb, K.H.K.-H., Wackernagel, M., 2004. Resource flows and land use in Austria 1950-2000: using the MEFA framework to monitor society-nature interaction for sustainability. Land Use Policy 21, 215-230.

Lim, S.S., et al, 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010. The Lancet 380, 2224-2260.

Martinez-Alier, J., Kallis, G., Veuthey, S., Walter, M., Temper, L., 2010. Social Metabolism, Ecological Distribution Conflicts, and Valuation Languages. Ecological Economics 70, 153-158.

Matsumura, K., 2012. Jatropha Emissions Toxicity Testing – Feasibility Study Results. Mortenson Center for Engineering in Developing Countries, University of Colorado Boulder, Boulder, CO.

McMichael, P., 2012. The land grab and corporate food regime restructuring. Journal of Peasant Studies 39, 681-701.

Muradian, R., Walter, M., Martinez-Alier, J., 2012. Hegemonic transitions and global shifts in social metabolism: Implications for resource-rich countries. Introduction to the special section. Global Environmental Change 22, 559-567.

Mwangi, E., Swallow, B., 2008. Invasion of Prosopis Juliflora and Local Livelihoods: Case study from the Lake Baringo Area of Kenya. Conservation and Society 6, 130-140.

Nijsen, M., Smeets, E., Stehfest, E., van Vuuren, D.P., 2012. An evaluation of the global potential of bioenergy production on degraded lands. GCB Bioenergy 4, 130-147.

Ostrom, E., 1990. Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press, Cambridge.

Pohekar, S.D., Ramachandran, M., 2004. Multi-criteria evaluation of cooking energy alternatives for promoting parabolic solar cooker in India. Renewable Energy 29, 1449-1460.

Rajvanshi, A., 2004. R&D strategy for lighting and cooking energy for rural households. Current Science 85.

Ravindranath, N.H., Manuvie, R., Fargione, J., Canadell, J.G., Berndes, G., Woods, J., Watson, H., Sathaye, J., 2009. Greenhouse Gas Implications of Land Use and Land Conversion to Biofuel Crops, in: Bringezu, R.W.H.a.S. (Ed.), Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) Cornell University, Ithaca, NY.

Ribot, J.C., Peluso, N.L., 2003. A Theory of Access. Rural Sociology 68, 153-181.

Robbins, P., 2001a. Fixed categories in a portable landscape: the causes and consequences of land-cover categorization. Environment and Planning A 33, 161-179.

Robbins, P., 2001b. Tracking Invasive Land Covers in India, or Why Our Landscapes Have Never Been Modern. Annals of the Association of American Geographers 91, 637-659.

Robbins, P., 2004. Political Ecology. Blackwell Publishers, Malden, MA.

Schandl, H., Krausmann, F., 2007. The great transformation: a socio-metabolic reading of the industrialization of the United Kingdom, in: Fischer-Kowalski, M., Haberl, H. (Eds.), Socioecological Transitions and Global Change. Edward Elgar, Cheltenham, UK.

Scheidel, A., Sorman, A.H., 2012. Energy transitions and the global land rush: Ultimate drivers and persistent consequences. Global Environmental Change 22, 588-595.

Scott, J., 1998. Seeing Like a State: How Certain Schemes to Improve the Human Condition Have Failed. Yale University Press, New Haven, CT.

Searchinger, T., Heimlich, R., Houghton, R., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T., 2008. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. Science 319, 1238-1240.

SG Biofuels, 2010. SG Biofuels Develops Jatropha Hybrid Seed Technology.

Singh, S.J., Gruenbuehel, C.M., Schandl, H., Schulz, N., 2001. Social Metabolism and Labour in a Local Context: Changing Environmental Relations on Trinket Island. Population and Environment 23, 71-104.

Singh, S.J., Haberl, H., Chertow, M., Mirtl, M., Schmid, M., 2013. Introduction, in: Singh, S.J.H., H.; Chertow, M.; Mirtl, M.; Schmid, M. (Ed.), Long Term Socio-ecological Research: Studies in Society: Nature Interactions Across Spatial and Temporal Scales. Springer, Heidelberg, Germany.

Singh, S.J., Krausmann, F., Gingrich, S., Haberl, H., Erb, K.-H., Lanz, P., Martinez-Alier, J., Temper, L., 2012. India's biophysical economy, 1961-2008. Sustainability in a national and global context. Ecological Economics 76, 60-69.

Smolker, R., 2008. The New Bioeconomy and the Future of Agriculture. Development 51, 519-526.

The Encyclopedia of Earth, 2013. Energy return on investment (EROI).

Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., Williams, R., 2009. Beneficial Biofuels--The Food, Energy, and Environment Trilemma. Science 325, 270-271.

Trabucco, A., Achten, W.M.J., Bowe, C., Aerts, R.A.F., Orshoven, J.V., Norgrove, L., Muys, B., 2010. Global mapping of Jatropha curcas yield based on response of fitness to present and future climate. GCB Bioenergy 2, 139-151.

van der Voet, E., Lifset, R.J., Luo, L., 2010. Life-cycle assessment of biofuels, convergence and divergence. Biofuels 1, 435-449.

Virudhunagar District Collector, 2009. District Statistical Handbook of Virudhunagar District 2008-2009, in: Collector, V.D. (Ed.), Virudhunagar.

Vyas, D.K., Singh, R.N., 2007. Feasibility study of Jatropha seed husk as an open core gasifier feedstock. Renewable Energy 32, 512-517.

West, J., Schandl, H., 2013. Material use and material efficiency in Latin America and the Caribbean. Ecological Economics 94, 19-27.

Whitaker, M., Heath, G., 2008. Life Cycle Assessment of the Use of Jatropha Biodiesel in Indian Locomotives, in: NREL (Ed.). NREL, Golden, CO, p. 100.

White, B., Borras Jr, S.M., Hall, R., Scoones, I., Wolford, W., 2012. The new enclosures: critical perspectives on corporate land deals. The Journal of Peasant Studies 39, 619-647.

Wolford, W., Borras, S.M., Hall, R., Scoones, I., White, B., 2013. Governing Global Land Deals: The Role of the State in the Rush for Land. Development and Change 44, 189-210.

Young, A., 1999. Is there Really Spare Land? A Critique of Estimates of Available Cultivable Land in Developing Countries. Environment, Development and Sustainability 1, 3-18.

Zimmerer, K.S., 2011. New Geographies of Energy: Introduction to the Special Issue. Annals of the Association of American Geographers 101, 705-711.

Figure Captions

Figure 1: Sattur Taluk

Figure 2: Sattur Field site villages: (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.

Figure 3: Jatropha-Prosopis energy flow comparison

Figure 4: Jatropha-Prosopis useful energy comparison

Figure 5: Useful energy sensitivity analysis

Table Captions

Table 1: Jatropha Scenarios

Table 2: Prosopis annual usage summary

Table 3: Energy return on investment analysis