Integrated Assessment of Regional Biofuel Scenarios – a Case Study from India

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Summary

Land use and land cover changes are a result of human modification and transformation processes applied to ecosystems and landscapes. Terrestrial change is considered as the largest human induced change on earth. Changes in land use and land cover pattern are particularly important for countries like India, where existing levels of high pressure on land systems are exacerbated by an increasing number of driving factors. To exemplify, the reduction in consumption of limited fossil fuels has increased the production of bioenergy, which partly uses the finite resource 'land', thus making bioenergy production a driver of land use change. Land intensive bioenergy production (from energy crops) has given rise to concerns regarding its implications in the form of land conversion, degradation, intensification, food shortages and altered levels of greenhouse gas emissions. It is therefore important to estimate the capacity of available land and potential future changes in extend and patterns of land use and their consequences. For this reason, simulation tools are needed to analyse current and potential future land use dynamics and investigate options and limitations as well as potential impacts on environment and society.

The research presented in this dissertation was conducted for the state of Karnataka in South India. It aimed at building a comprehensive understanding of the various aspects related to bioenergy in India, ranging from policy and the socio-economics of biofuels to productivity, availability and allocation of land resources. Findings from literature and contemporary political directives concluded that the Indian biofuel programme has centered around the use of sugarcane as bioethanol feedstock and *Jatropha curcas L.* as biodiesel feedstock (which is expected to be planted only on wastelands). Jatropha cultivation is characterised by a large degree of uncertainty with respect to productivity on wastelands and management practices. A target of 20% blending until 2017 for both biodiesel and bioethanol has been recommended by the Indian government. Based upon these preconditions, an integrated modelling framework was developed to investigate if biofuel production in the region would meet political targets, study potential future impacts of energy production on current land use and land cover and analyse implications regarding food security.

The modelling framework –SITE (SImulation of Terrestrial Environments) was applied within the paradigm of integrated assessment studies covering biophysical, social and economic components. Biofuel production was estimated by the application of a process based model simulating Jatropha and sugarcane while food production was estimated by modelling the other six major food crops in the region. Using the policy target of 20% blending of biofuels, two scenarios based on trajectories of economic growth were constructed- 'Industrial Economy" (IE) and 'Agricultural Economy' (AE).

Simulations run until 2025 indicated that against the 20% target of biofuel blending by 2017, bioethanol production is almost met under both scenario conditions (88% in IE and 93% in AE) while biodiesel targets cannot be met if production is limited only to wastelands as planned in the biofuel policy. Biodiesel targets can be successfully met only with a combination of biodiesel production on agricultural land (74% in IE and 71% in AE) together with wastelands (26% in IE and 29% in AE) under both scenarios. Food production under both scenarios is not impacted directly until 2025 but this occurs at the expense of utilisation of long and short-term fallows, however reducing the intended function of fallows to provide opportunities for soil fertility restoration.

In conclusion, food-fuel balance seems achievable in the state of Karnataka (and in India), however land use intensification emerges as a major trade-off, manifested by sharp decline in fallow area. For biofuels to be a sustainable component of the renewable energy matrix there is scope to improve some of the critical factors associated with biofuel production systems. These factors include reducing dependence on single crops (currently Jatropha and sugarcane), improving oil extraction technologies for Jatropha, implementing alternative higher-yielding routes for ethanol production (bagasse-ethanol), reducing the dependence on wastelands by using dual purpose food-fuel crops and conserving available resources, especially water to improve productivity of energy crops. If land management, production practices and economic incentives are improved, first generation biofuels can certainly contribute to the renewable energy matrix in India.

Zusammenfassung

Landnutzungs- und Landbedeckungsänderungen werden als ein Ergebnis menschlicher Eingriffe und Transformationsprozesse in Ökosysteme und Landschaften gesehen. Sie zählen damit global zu den größten von Menschen verursachten Eingriffen. Bedingt durch eine Vielzahl zunehmender Antriebsfaktoren wächst in Ländern wie Indien der Druck auf terrestrische Systeme. Die angestrebte Verminderung in der Nutzung fossiler Energieträger und der damit verbundene Anstieg der Bioenergieproduktion, ist als einer dieser Treiber anzusehen. Der Anbau von landintensiven Bioenergiepflanzen wirft daher vermehrt Fragen auf, insbesondere was die Auswirkungen im Hinblick auf Landkonversion, Bodendegradation, Intensivierung, Verknappung von Nahrungsmitteln sowie den Ausstoß von Treibhausgasen betrifft. Daher ist es besonders wichtig eine Abschätzung der vorhandenen Kapazitäten sowie zukünftiger potentieller Veränderungen bezüglich der Ausdehnung von Landnutzung und ihrer räumlichen Anordnung durchzuführen. Zu diesem Zweck werden Simulationswerkzeuge benötigt, die einerseits in der Lage sind aktuelle und zukünftige Landnutzungsdynamiken zu analysieren, andererseits potentielle Optionen und Einschränkungen sowie mögliche Einflüsse auf Umwelt und Gesellschaft abzuschätzen.

Als Fallbeispiel wurde in dieser Dissertation der Bundesstaat Karnataka in Südindien analysiert. Ziel war es, ein umfassendes Verständnis wichtiger Aspekte des Bioenergieanbaus zu erlangen, angefangen bei den politischen Zielen und Richtlinien, den sozioökonomischen Bedingungen, bis zur Produktivität von Bioenergiepflanzen und der Verfügbarkeit bzw. Allokation von Landressourcen. Erkenntnisse aus der Literatur sowie die aktuelle politische Ausrichtung zeigten, dass das indische Bioenergieprogramm sich im Wesentlichen auf den Anbau von Zuckerrohr (*Saccharum officinarum*) und Jatropha (*Jatropha curcas L.*) konzentriert. Zuckerrohr wird dabei als Rohstoff für die Bioethanol Herstellung herangezogen und Jatropha als Ausgangsmaterial für die Erzeugung von Biodiesel. Jatropha soll ausschließlich auf Ödland angebaut werden, wobei der Anbau von einer Vielzahl von Unsicherheitsfaktoren begleitet ist. Diese beziehen sich zum einen auf die Pflanzenproduktivität, zum anderen auf die Bewirtschaftungsmaßnahmen. Ziel der indischen Regierung ist bis 2017 eine Biodiesel-, bzw. Bioethanolbeimischung von 20 % bei Kraftstoffen zu erreichen. Aufbauend auf der Entwicklung eines integrierten Modells, untersucht diese Arbeit, ob die geplanten politischen Vorgaben für die Biokraftstoffproduktion erreicht werden können und welchen Einfluss die Bioenergieproduktion auf die Landnutzung- und Landbedeckung haben wird, beziehungsweise welche Implikationen in Bezug auf die Nahrungsmittelsicherheit auftreten können.

Die Modellierungsplatform SITE (SImulation of Terrestrial Environments) wurde für diese Studie weiterentwickelt, um ein „Integriertes Assessment“ anhand von biophysikalischen, sozialen und ökonomischen Faktoren durchzuführen. Die Herstellung von Biokraftstoff, insbesondere der Anbau von Jatropha und Zuckerrohr wurde dabei durch die Anwendung eines prozessbasierten Pflanzenwachstumsmodells abgeschätzt. Die Simulation der Nahrungsmittelproduktion in der Region wurde durch die Modellierung der sechs wichtigsten Anbauprodukte abgedeckt. Auf Basis der politischen Vorgabe einer 20%igen Beimischung von Biokraftstoff wurden zwei Zukunftsszenarien entwickelt, welche auf unterschiedlichen ökonomischen Entwicklungsrichtungen beruhen: „Industrial Economy” (IE) und „Agricultural Economy“ (AE). Simulationsläufe bis zum Jahr 2025 zeigten, dass die politischen Vorgaben bei der Herstellung von Bioethanol in beiden Szenarien erreicht werden können, wohingegen die angestrebte Produktion von Biodiesel nur zum Teil erreicht wird, wenn der Anbau auf Ödland beschränkt bleibt. Unter der Annahme, dass für die Herstellung von Biodiesel auch Agrarflächen hinzugezogen werden, können die fehlenden 74% in Szenario IE und 71% in Szenario AE erzeugt werden. Direkte Auswirkungen auf die Nahrungsmittelproduktion sind bis 2025 nicht zu erwarten. Die in den Szenarien aufgetretene starke Zunahme der Nutzung von Brachland könnte sich jedoch mittel- bzw. langfristig negativ auf die Bodenfruchtbarkeit auswirken.

Insgesamt scheint es möglich eine Balance zwischen Nahrungsmittelproduktion und der Herstellung von Biokraftstoffen in Karnataka bzw. unter Umständen auch in ganz Indien zu erreichen. Die damit verbundene Intensivierung der Landwirtschaft hat jedoch einen starken Rückgang von Brachland mit möglicherweise negativen Auswirkungen zur Folge. Um das Ziel zu erreichen, Biokraftstoffe als nachhaltige Komponenten im Bereich „erneuerbare Energien“ einzusetzen, müssen wichtige Faktoren im Prozess der Biokraftstoffproduktion neu überdacht werden. Einer dieser Faktoren ist die momentane Abhängigkeit von nur wenigen Energiepflanzen wie Zuckerrohr und Jatropha. Zudem besteht Verbesserungsbedarf bei den Extraktionsmethoden des Öls, insbesondere bei Jatropha, die bis zu 40% Effizienzgewinne ermöglichen. Des Weiteren sollte über unterschiedliche ertragssteigernde Entwicklungspfade nachgedacht werden, beispielsweise bei der Ethanolproduktion (Bagasse-Ethanol) oder über die Einschränkung des Anbaus auf Ödland. Ein möglicher Weg wäre die Einführung von weiteren multifunktionalen Nahrungs- und Bioenergiepflanzen (vergleichbar mit Zuckerrohr). Ein weiterer wesentlicher Faktor ist der Schutz vorhandener Ressourcen, insbesondere des Frischwassers welches für eine verbesserte Produktion eingesetzt werden könnte.

Indiens Bioenergiesektor hat das Potenzial, bei koordinierter Verbesserung von Landbewirtschaftung, Prozessierung und ökonomischer Anreize, dass Biokraftstoffe der ersten Generation in Zukunft einen wichtigen Beitrag zu einer nachhaltigeren Energieerzeugung leisten.

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List of Abbreviations

ACRP	Agro-Climatic Regional Planning
AD	Application Domain
AE	Agricultural Economy
APMC	Agricultural Produce Marketing Committees
CA	Cellular Automata
CDM	Clean Development Mechanism
CFT	Crop Functional Types
COC	Cost of Cultivation
CPR	Common Property Resources
DOLR	Department of Land Resources
dLUC	Direct land use change
EBP	Ethanol Blended Petrol
FAO	Food and Agricultural Organization
FDI	Foreign Direct Investment
FHP	Farm Harvest Prices
GDP	Gross Domestic Product
GHG	Greenhouse Gas Emissions
GIS	Geographic Information Systems
GUI	Graphical User Interface
HSD	High Speed Diesel
IE	Industrial Economy
iLUC	Indirect land use change
KSAMB	Karnataka State Agricultural Marketing Board
LCA	Life Cycle Analysis
LUCC	Land-use and land-cover change
MIS	Marketing Information System
MPP	Minimum Purchase Price
MSP	Minimum Support Price
NGO	Non Governmental Organisation
NOVODB	National Oilseeds and Vegetable Oil Development Board
NRSA	National Remote Sensing Agency
OMC	Oil Marketing Companies
PFT	Plant Fuctional Types
ROC	Relative Operating Characteristic
SD	System Domain
SITE	Simulation of Terrestrial Environments
SMP	Statutory Minimum Price
SVO	Straight Vegetable Oils
TFR	Total Fertility Rate

1 Introduction

1.1 Background and motivation

Land use change is a complex and dynamic process that links natural and human systems with impacts on soil, water and atmosphere, all of them issues of potential environmental significance (Meyer and Turner 1994). Land use change models are tools for understanding and explaining the causes and consequences of land use dynamics and explore future land use changes under different boundary conditions or scenarios (Alcamo *et al.* 2006; Veldkamp and Verburg 2004). The processes, drivers and consequences are also intimately linked with each other (Briassoulis H 2000) thereby signifying the need for multidisciplinary analyses (Clayton and Radcliffe 1996).

Drivers of land use change in the tropics range from natural variability of climate and soils, or landscape attributes, over agricultural expansion and intensification, to demographic and economic changes, technological advancement, or institutional or cultural factors (Lambin *et al.* 2003). In recent years, bioenergy crops have emerged as important new drivers of land use change, and concerns regarding the spatial demands and socio-economic consequences have been put forth by several scientists (Beringer *et al*. 2011).

Bioenergy includes all forms of energy derived from plant matter (trees, shrubs and crops) and animal dung. In developing countries all across the world, and particularly in India, various forms of bioenergy have been used for several millennia for cooking and domestic heating. Biomass based energy is used in both urban and rural areas in India across the domestic and industrial sector. In rural areas traditional forms of energy sources are fuelwood, cattle dung and crop residues used for cooking and heating water for bathing. In urban areas a gradual shift from biomass based energy to liquid and gaseous fuels has been observed in India, although there are large regional variations. Moreover, low income groups in urban areas use traditional forms of bioenergy for cooking. Industrial uses of biomass include manufacture of bricks, tiles, lime and agro-processing units such as those involved in jaggery production. Urban users of bioenergy also include establishments such as hotels, bakeries and marriage halls where fuelwood is used for cooking (Ravindranath and Hall, 1995). The limited availability of petroleum and increasing prices of fossil fuel fostered research towards modern forms of bioenergy (liquid or gaseous fuels for the transport sector -biofuels) that are predominantly derived from seeds of plants, eg., *Jatropha curcas*, *Pongamia pinnata*(biodiesel) or ethanol from sugarcane, sweet sorghum, cassava (bioethanol).

However, bioenergy remains one of the most complex and strongly debated forms of renewable energy considering multiple inter-linkages it shares with other natural resources (Schubert *et al*. 2009). While on one hand, forest based sources of energy such as fuelwood have been linked to increased levels of deforestation in Africa (Struhsaker 1987; Sankhayan and Hofstad 2001) and biodiversity loss, it has been argued that fuelwood collection does not contribute to direct felling/clear cutting of forests in India (Nagothu 2001, Ravindranath and Hall 1995). Loss of biodiversity due to bioenergy has also been heavily debated (Sullivan 1999). Similarly, for modern forms of bioenergy, while increased use of biofuels is said to reduce dependence on fossil fuels and help in making a transition to low-carbon economies through reduction of greenhouse gas emissions (GHGs) (Beringer *et al.* 2011; Liaquat *et al.* 2010) several scientists have reported that biofuel use is not always sustainable in the long-term as net GHG emissions due to land use change may override the effects of short-term mitigation potential of biofuels (Fargione *et al.* 2008; Brindaban *et al.* 2009, Romijn 2010). Direct and indirect land use change (dLUC and iLUC) due to biofuels production have captured widespread interest amongst scientists and related studies have been carried out presenting a wide range of results (Hellmann and Verburg 2010; Overmars *et al.* 2011; Havlik *et al.* 2010; Rathmann *et al.* 2010). The increasing demand of land to grow biofuels has given rise to the concern that large tracts of arable land for biofuel production may be diverted to grow biofuels, thus causing food insecurity. Food insecurity issues, in turn have been linked to increased food prices globally thus identifying biofuels as one of the causes (OECD 2008; Gerber *et al.* 2009; Eide 2008). This aspect has also been argued against by authors who report that biofuels has had only a modest contribution to increased food prices (Ajanovic, 2010; Mueller *et al.* 2011). Advantages of using biofuels include employment generation in rural economies and benefits derived from co-products of biofuel feedstock, or producing biofuels as co-products e.g. from processing sugarcane or jatropha (FAO 2008; Openshaw 2000; Ewing and Msangi 2009). However, the income-generation capacity of biofuels for the poorer sections of the society remains unclear (Brittaine and Lutaladio 2010; Ariza-Montobbio and Lele 2010; Romijn and Caniels 2011).Therefore almost all aspects of biofuels remain debatable; however, it is evident that the implications of the multi-dimensional nature of biofuel development are largely dependent on the region, scale, associated management practices and policies at the state and other administrative levels.

Land use changes due to biofuels and impacts thereof are especially significant for developing countries and raise urgent scientific questions that need to be answered (Thrän *et al* 2010; Ewing and Msangi 2009). With increasing economic development, a shift from biomass energy to fossil fuels and electricity has been observed historically in developed countries. Notably this has not been the case in India, where 20 years of statistical data proves that dependence on biomass based energy sources has risen constantly

(Ravindranath and Hall 1995). India as an emerging economy is faced with the challenge of simultaneously meeting rising demands (food, feed and fuel) as well as ensuring environmental compliance of sustainable practices to meet these demands. Compounding the challenge is India's population size (~1 billion) and economically heterogeneous society across which these demands have to be fulfilled (Ravindranath and Balachandra 2009). The increasing importance of the discourse surrounding food-fuel issues is reflected in India's legislative steps towards legalising both energy and food rights through policy mechanisms (Ministry of New and Renewable Energy 2009; Ministry of Agriculture 2010). However as Dale 2009, contends in an editorial article- "Good science must precede good policy". Future pathways of ensuring food and energy security in India require to be substantiated by robust scientific evidence of the possible range of positive and negative impacts of biofuel production (Ravindranath *et al*. 2010). Rising economy, rapid urbanization and food-fuel demands have been recognized as key forces of land use change in India (DeFries and Pandey 2010). Since land use change in the context of biofuel expansion is a complex process driven by several interdependent drivers, a landscape approach that accounts for changes in land use and management for bioenergy feedstocks is critical. Further, this approach helps clarify trade-offs involved in making choices for food or energy production, protection of biodiversity or fulfilling societal needs (Dale *et al.* 2010).

The research carried out in this dissertation was motivated by the strong emergence of biofuels in India starting in 2003-2004 and the limited number of studies evaluating the potential contribution and environmental consequences of biofuel production. Using the southern Indian state of Karnataka as an example this study has adopted an integrated modelling approach to analyze the role of biofuels in the energy matrix, implications on land use, trade-offs with food production and contribution of biofuels to income generation. The modeling framework used is SITE (**SI**mulation of **T**errestrial **E**nvironments) (Mimler and Priess 2008; Schweitzer *et al*. 2011) which has been successfully employed for regional scale studies in Mongolia and Indonesia (Priess *et al*. 2011; Priess *et al.* 2007). The study addresses regionally significant biophysical and socio-economic drivers of land use change and explores future pathways of land use dynamics through scenario analysis up to 2025. The results of this study contribute to the subject of biofuels and land use in India.

1.2 Aims of the study

The specific aims of this research were-

(i) Assessment of current land use patterns, key drivers of land-use change in the region, existing biofuel options in India and research gaps

(ii) Analysis of the institutional context of current policy frameworks for biofuels in India and identification of potential governance options

(iii) Parameterization of the biofuel crop *Jatropha curcas* and assessment of the production chain of biodiesel from Jatropha

(iv) Scenario analysis of future land use dynamics in Karnataka integrating food and biofuel demands

1.3 Structure of the dissertation

This dissertation consists of seven chapters. Chapter 2, 3, 5, 6 and part of Chapter 4 (section 4.2) correspond to separate journal articles and retain the structure of the original manuscripts including supplementary material and reference sections. References for all other sections of the dissertation can be found at the end of the thesis.

Chapter 2 introduces the biofuel options being pursued in India and the corresponding policy mechanisms that have been developed or are under development. Next, the chapter provides an overview of land use systems and the status of contentious land such as forest and common property lands. Perspectives on land availability and scope of land conversion have also been covered. The chapter produces short representations of four modelling case studies for biofuel assessments at the national and sub-national scale in India and observes the need for conducting more integrated land use change studies in India especially in the context of food-fuel issues.

Chapter 3 traces the changing status of the Indian policies with respect to biofuels over the course of time that this study was conducted. The chapter outlines the different aspects of the biofuel policies in India and the lack of consistency displayed over a zigzag pattern for several years in the finalization of a national level policy. Thereafter the chapter focuses on investigating the role of scientific assessments of Jatropha biofuel production in policy formulation. Along with Chapter 1, this chapter identifies the important areas of research and contributes to the research design and priorities of the next chapters of the thesis.

Chapter 4 of the thesis starts with the description of the study area, the state of Karnataka in south India and provides key information on climate and topography. Relevant details of the land use structure, demography, agriculture and forest use are also explained. The main methods used in the thesis are then elaborated, viz. an overview of the SITE framework, details of the application of the SITE framework to Karnataka (SITE-Karnataka) and important additions and new aspects introduced therein.

Chapter 5 focuses on features of the Jatropha based biodiesel system in Karnataka. The chapter gives the details of the parameterization of the energy crop and validates it against available field based data from Karnataka and other parts of India that are either share spatially proximity or climatic conditions with the state. The paper then identifies the most significant factors in Jatropha biodiesel production chain that impact energy outputs. Findings presented in this chapter include simulated Jatropha yield estimation on wastelands and preliminary range of land use change expected due to biofuel expansion.

Chapter 6 describes the application of the model SITE Karnataka and investigates the extent of potential land use change due to biofuel expansion using boundary conditions of two scenarios. The results focus on whether adequate biofuel production would be possible in Karnataka to reach recommended policy mandates and the implications on food production and land use due to energy plantations. Further, the economic aspects of the production of biofuels, in terms of net income generation from Jatropha and sugarcane have been shown.

Chapter 7, the last chapter of the dissertation summarizes the main findings and presents major conclusions and recommendations emerging from the study

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2 Biofuel options for India- Perspectives on land availability, land management and land-use change[1]

Abstract

India's energy dependence on oil imports has led to energy security becoming a prime concern for policy makers and has thus warranted an exploration of alternative energy sources. Globally rising oil prices have led to greater interest in the development of bioenergy from plant based systems. This paper examines various policy options and mechanisms with respect to biofuel oilseed crops like *Jatropha curcas* and *Pongamia pinnata*, the potential of the expansion of sugarcane as a source of bioethanol and the emergence of the increased inclination towards afforestation of wastelands and associated implications and challenges. Historical land use data indicates that the agricultural area in India has stabilized over the last decades and has little opportunities of expansion. Considering India's still fast growing population, it is expected that land use conversions due to new bioenergy cropping systems are likely to intensify the already existing competition between residential/industrial land, and land required for food and energy generation. The paper reviews national and sub-national scale case studies, which are addressing a number of different topics related to bioenergy production, such as intensity of land use, crop yields, potential land demands or scenarios blending petrol with bioethanol.

1. Introduction

India is the sixth largest energy consumer in the world although the per capita use of energy is one of the lowest in the world, with 439 kgoe, as compared against the world average of 1688 kgoe[1]. Oil import dependency is expected to increase from currently 73% to 91% by 2030[2]. In order to reduce the dependency on (imported) fossil fuels and to develop alternative sustainable strategies, the Ministry of New and Renewable Energy (MNRE), functions as the institutional and policy making department for renewable energy in the country. In view of the limited amount of conventional domestic sources of energy, to deliver a sustained growth rate of 8% through 2031-32 and to meet the energy needs of all citizens, India needs, at the very least, to increase its primary energy supply by 3 to 4 times and, its electricity generation capacity/supply by 5 to 6 times of their 2003-04 levels[3].In this context, biodiesel generation is one of the emerging technologies being explored. While biodiesel

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[1] Das S, Priess JA, Schweitzer C (2010) Biofuel options for India- perspectives on land availability, land management and land-use change, *Journal of Biobased Materials and Bioenergy* **4,** 243-255

from non-edible oils such as *Jatropha curcas, Pongamia pinnata, Azadirachta indica* etc., has recently attracted much attention, its economic feasibility depends largely on the yields achievable from wastelands and marginal lands and/or the returns farmers can get from good quality land with irrigation and fertiliser use, as compared to returns from growing other crops. A number of projects being undertaken now will provide an assessment of these comparative returns within a few years[3].

Contrastingly, edible oils derived from rapeseed, sunflower and soybean, are being used as feedstock for producing biodiesel for example in the USA and Europe. However, food security is a national priority in India and therefore India cannot afford to use (or promote) either cereal grains for ethanol /biogas production or edible oils for biodiesel production, as is the current practise in other bioenergy producing countries (e.g. the E.U. and the USA). India is one of the leading importers of vegetable oil in the world, as demand outstrips domestic production. Furthermore, the production of food grains such as wheat, corn and coarse cereals, has been relatively stagnant in recent years, forcing India to import wheat in 2006, after having been an exporter for several years[4]. In India, as edible oils are in short supply, non-edible tree borne oilseeds (TBOs) such as *Pongamia pinnata* L. (Pongamia), *Jatropha curcas* L. (Jatropha) and *Azadirachta indica* A. Juss (Neem) are being considered as sources of Straight Vegetable Oils (SVOs) and raw material for biodiesel. Research on the use of SVOs in diesel engines shows that there are problems associated with their high viscosity and high flash point[5]. Given the great importance of edible oils for food consumption and the fact that India is a net importer of such oils, the fledgling Indian biofuel industry has focused on the development of inedible oilseeds.[6]

Several Government supported programs are currently ongoing in different states for an increased assessment of the potential of biofuels as an alternative source of energy. The following sections outline important policies and the role of implementing agencies for bioenergy at the national level.

1.1 The National Biofuel Policy

The Draft National Policy on Bio Fuels' formulated by MNRE has been approved by the Group of Ministers under the Chairmanship of the Union Minister of Agriculture and Consumer Affairs. The Biofuel Policy sets an indicative target of 20% blending of both bioethanol and biodiesel with production limited to wastelands and marg inal lands. There is a clear manifesto on discouraging the establishment of bioenergy plantations on fertile irrigated lands, and a strong focus on indigenous production of biofuel feedstock. As part of the strategy, Minimum Support Prices (MSP) and Minimum Purchase Prices (MPP) are provided to ensure fair prices for growers[7].

1.2 National Mission on Biodiesel

The Indian Government has developed a National Mission on Biodiesel, which aims to meet 20% of the country's diesel requirement by 2011-2012, from biodiesel derived from Jatropha[8]. The goals were planned to be achieved in two phases:

Phase I (2003- 2007) - in Phase I, the Government undertook demonstration projects of Jatropha plantations, covering both forest and non-forest lands in various states across the country. The projects focused on the viability of all activities including plantation establishment and management, seed collection, oil extraction, transesterification, blending, marketing and institutional arrangements. About 400,000 hectares of plantations were targeted, including marginal lands, hedging of fields and public lands alongside roads, highways, canals and railway tracks.

Phase II (2007- 2012) - Phase II envisages a self-sustaining expansion of Jatropha plantations, with an objective of establishing up to 11 million hectares of Jatropha on marginal land. This commercialization phase will also include the installation of more transesterification plants to meet the 20% target for blending with High Speed Diesel (HSD) by 2011-2012. Table 1 shows the national biodiesel demand, assuming an average productivity of 1.2 Mg of biodiesel per ha.

Table 1 Diesel and biodiesel demand and growing areas required for different blending rates

Year	Diesel Demand (x 10^6 Mt)	Biodiesel at 5% blend (x10^6 Mt)	Area for 5%blend (Mha)	Biodiesel at 10 % blend (x 10^6 Mt)	Area for 10% blend (Mha)	Biodiesel at 20% blend (x 10^6 Mt)	Area for 20% blend (Mha)
2001-02	39.81	1.99	NA	3.98	NA	7.96	NA
2006-07	52.33	2.62	2.19	5.23	4.38	10.47	8.76
2011-12	66.90	3.35	2.79	6.69	5.58	13.38	11.19

Source[8]

1.3 Biodiesel Purchase Policy

The Ministry of Petroleum & Natural Gas (MoP&NG) notified a *Biodiesel Purchase Policy* in October 2005, which prescribes that oil marketing companies buy standard quality biodiesel at 25 INR/litre (INR=Indian Rupees; including taxes, duties, transportation cost), starting in January 2006. 20 purchase centres in 12 states will supply a minimum capacity of 10,000 litres per tank of biodiesel, meeting prescribed specifications. Concessional loans to farmers for establishing Jatropha plantations on wastelands, with a repayment moratorium of 4 years, are considered.

1.4 Ethanol Policy

India is the largest producer of sugar in the world with an annual production of 280 million tonnes. Ethanol is primarily produced via the molasses route, which uses the remainder of sugar production after fermentation. In the Indian situation of scarcity of land and water, the available quantities of ethanol, when used as source for production of chemicals and potable alcohol, offer higher economic returns to the country rather than its use as an admixture with gasoline[3]. The commercial production and marketing of ethanol blended gasoline started in January 2003 with the first phase of the Ethanol Blended Petrol (EBP) program. The Policy mandated 5% blending of ethanol in gasoline in 9 states and 4 Union Territories (requiring 320-350 million L/yr). However, India is struggling to meet the 5% target, since sugar production is the priority of most farmers and less than 10% of sugarcane is diverted to ethanol production. Consequently, efforts to produce ethanol from other sources, such as sweet sorghum and sugar beet are ongoing. The government offers subsidized loans to sugar mills, for a maximum of 40% of the project cost, for setting up ethanol production units. Table 2 shows the projected ethanol demand in India. Possibilities of achieving up to 10-15% blending have been reported, if 25% of the current irrigated area is brought under drip irrigation with fertilizer application[9].

Table 2 Projected ethanol demand in India

Year	**Gasoline Demand (x 10^6Mt)**	**Ethanol Demand (Mt)**	**Ethanol Production**			**Utilization of Ethanol**		
			Molasses (Mt)	**Cane (Mt)**	**Total (Mt)**	**Potable (Mt)**	**Industry (Mt)**	**Balance (Mt)**
2001-02	7	324	1384	0	1384	505	468	411
2006-07	10	462	1794	1158	2952	597	554	1801
2011-12	12	590	1794	1158	2952	692	658	1602
2016-17	16	752	1794	1158	2952	801	782	1368

Source[8]

Notes:

1. Area under cane cultivation is expected to increase from 4.36Mha in 2001-02 to 4.96 in 2006-07 which would add additional cane production of around 50 x 106 Mt
2. About 30% of cane goes for making gur and khandsari. If there is no additional increase in khandsari demand, sugar and molasses production would increase.
3. The present distillery capacity is for 2900 x 106 L of ethanol and looks to be sufficient for 5% blend till 12th plan
4. A growth of 3% in potable use and a 3.5% in chemical and other use has been taken into account The chemical industry is a major driver of ethanol demand and expanding, perhaps should add a few words

1.5 Biodiesel Options in India

Research on biodiesel is receiving increasing attention. Concerted efforts are being made through the synergistic activities of several research organisations in the country. Crops suggested for biodiesel production in India are non-edible oilseed crops, such as Jatropha

(*Jatropha curcas* L.), Pongamia *(Pongamia pinnata* L.), Neem (*Azadirachta indica* A. Juss), Tung (*Vernicia fordii* Hemsl.), Mahua (*Madhuca longifolia*), Jojoba (*Simmondsia chinensis* (Link) C. K. Schneid), Wild Apricot (*Prunus armeniaca* Linn.) and Simarouba (*Simarouba gluaca*). However, the major focus is on cultivation of Jatropha due to its high oil content (30-35%), low water requirements, ease of cultivation, low gestation period and the potential value of Jatropha and its associated products (e.g oil for lighting/heating, soap and candle making etc.). The 'National Network on Jatropha and Pongamia' has been set up, with around 40 participating research institutions, across India. The government is involved in several promotional programs for both Jatropha and Pongamia. Targeted and already planted areas of the most important tree species are listed in Table 3.

Table 3 Current production of biodiesel: target species, target areas and achieved areas (by National Oilseeds and Vegetable Oils Development Board)

Plant Species	Target Area [ha]	Production Area [ha] (% of target area)
Jatropha	14,086	10,083 (72%)
Pongamia	2,378	1,292 (54%)
Neem	1,708	1,231 (72%)
Others		
Tung, Wild Apricot, Mahua and Simarouba	3,100	2,620 (85%)

Source[2]

The total potential of wastelands for Jatropha production is estimated to be 40 million hectares of land[2]. Research is focussed on plantation development, the production of high quality planting material through biotechnological approaches, developing agro-technology for different agro-climatic zones, and increasing the studies on oil quality and stability of biodiesel. Pongamia, the second favoured oilseed crop in India exhibits a comparable growth and yield potential in similar regions of the country as Jatropha.

The main advantages of planting Jatropha are the ease of establishment, quick growth and the potential of meeting domestic demands for oils needed for cooking and lighting. The trees can create additional environmental benefits/services such as the protection of crops or pasture lands, hedging for erosion control and as a source of organic manure[13]. Despite the potentials of Jatropha as a promising species, the utility of the crop is difficult to quantify, due to the small number of studies available and the absence of long term research results. The major concerns in spite of the large-scale promotion of Jatropha are the uncertainties in yield levels as well as the unknown differences in the growth and productivity in different agro-climatic zones[14]. Willingness of farmers to plant Jatropha and related costs and benefits are other important factors in determining the success of Jatropha. An initial estimate of costs indicates that the net expenditure of Jatropha plantation per hectare (2500 plants) after 14 years is 1305 USD and the corresponding net income (expected) is 2372 USD[15]. Costs and revenues may differ across regions and farming systems and these initial estimates can therefore be considered a first indicative estimate. Thus, considering the still large number of unknowns, providing recommendations for the cultivation of Jatropha is still difficult at this time. Additionally, large scale Jatropha monocultures might cause well known environmental (and economic) problems, such as increased risk of yield losses, and increased levels of pests and diseases and the subsequent increase in the use of agrochemicals with all associated health and other risks, potentially negative impacts on soil fertility, water resources and biodiversity[16] .

2. Land zoning and availability

In India, Agro-Climatic Regional Planning (ACRP) is considered as a distinctive planning approach applied to agriculture and related sectors. Based on soil properties, bioclimatology and geographic conditions, the country has been grouped into 20 agro-ecological regions (AER) with sub-divisions up to district level for developing long term land use strategies. The constraints and potentials of land, with appropriate ameliorative measures, have been described and suggested for each region. This is expected to aid the adoption of plans for cropping systems which will also help in minimizing the loss of land quality, controlled by soil physical conditions, nutrient availability and the organic carbon pool[17]. In most states such a planning procedure is already established for agricultural policies in the food sector, while biofuel cropping is yet to make headway, due to the lack of sufficient information about crop management and productivity in different agro-ecological zones.

The potential impacts of climate change on biofuel crops are also an important determinant in the success of the biofuel industry. Most biofuel crops in India, including Jatropha are likely to be grown under rain-fed conditions and thus shall be highly dependent on the Indian monsoon regime. Rising trends of extreme events and higher probability of natural hazards due to such events have already been predicted[18]. Results from simulation studies have indicated possibilities of droughts induced by a decline in winter rainfall in India under SRES ‘Marker’ scenarios[19]. According to the Department of Agriculture, 35% of net sown area is drought prone and rainfall is erratic during one of four years[20]. Apart from rising foodgrain prices as a direct outcome of drought, subsidies in diesel prices (for irrigation) as a relief measure for drought hit farmers[21] can indirectly tilt the economy of the biodiesel market. Temperature rise in the Indian sub-continent as an effect of climate change is likely to decrease the productivity of many food crops, including wheat and rice under different rates of temperature rise[22]. Although conclusive studies with respect to the effect of climate change on biofuel crops in India could not be located, assuming a similar trend as with foodgrains, biofuel crops, including Jatropha could be negatively impacted due to environmental change. Thus, climate change is a pertinent driver with several direct and indirect pathways that render sustained biofuel production vulnerable.

The most interesting category of land in India with respect to biofuel prospecting is ‘wasteland’. Wasteland is described as “degraded land which can be brought under vegetative cover with reasonable effort and which is currently underutilized and/or land which is deteriorating for lack of appropriate water and soil management or on account of natural causes”[23]. About 55.3 Mha of land in India are classified as wastelands, out of which, 32.3 Mha have been calculated to be suitable for Jatropha cultivation (Table 4). However, regional differences of the productivity of Jatropha plantations have to be seriously taken into account when estimating the land available for biofuel production. Wastelands in certain regions of India may be more suitable for the cultivation of other oil crops such as Pongamia or Neem. However, the allocation of a major fraction of wastelands for the establishment of Jatropha not only creates a significant dependence on wastelands for biofuel production, but also constrains the use of other potentially better suited species.

Another school of thought aims to strengthen efforts towards increasing the productivity of food crops. India witnessed a significant increase in crop yields and agricultural expansion as a result of the Green Revolution during the 1970s. As a result, India currently experiences surplus food production (20 million tonnes) and paradoxically, an increase in population that faces starvation (200 million). Currently, the major problem with respect to food security is not underproduction but inaccessibility of food, primarily due to prohibitive prices and lapses in the distribution system. However, it is expected that under current agricultural practices, India may face severe food shortages in the coming years[24]. Therefore at first glance, there seems to be no immediate demand for large new areas for growing food crops and it may be possible to allocate some current food growing areas to bioenergy crop production by further boosting the productivity of food crops. It is suggested that potential increases in yields of major crops might free up to one-third to one-half of the current croplands for production of bioenergy crops[25]. However, studies on changes in consumer preferences of food conclude that demand is growing for more resource intensive products such as vegetables, fruits and meat than the traditional choice of cereals[24, 26]. Hence it is expected that this shift in consumption patterns would increase both feed demand and non-grain crop demands in the country and future agricultural needs would involve crop diversification practices. Such diversification schemes may be challenged by increasing land degradation problems due to erosion (water and wind) and decreasing productivity of existing agricultural land due to nutrient imbalances and depletion, increasing salinity, little scope of irrigation expansion, changes in rainfall patterns and other adverse processes. Thus, considering the current and future trends of food production, pressure on available non-arable land or marginal lands shall increase and any ameliorative measures to counter land degradation by increasing productivity may also be seen as an opportunity to expand feed/non-grain production instead of biofuels.

Table 4 Category of wasteland suitable for Jatropha cultivation

A) Non-forest Culturable Wastelands	**Area (Mha)**
Gullied/Ravinous-Shallow (mainly Community, Govt.)	1.03
Land With Scrub (Government/Panchayats)	15.05
Land without Scrub (mainly Community, Govt.)	3.74
Saline/Alkaline-Slight (mainly private)	0.41
Shifting Cultivation – abandoned (community)	1.22
B) Degraded Forest Land	
Degraded Forest –Scrub	10. 84
Total	**32.29**

Source[31]

2.1 Forest Cover and Common Property Resources (CPRs)

The Forest Survey under the Ministry of Environment and Forests has been assessing forest cover in the country using remote sensing data in a two year cycle. The 10th assessment (2005) reports the total forest and tree cover of the country as 23.4% of the total area with an overall accuracy level of 92%[27]. Table 5 shows the change matrix between the 2003 and 2005 assessments.

The above statistics reveal that there is an increase of 191 km² of moderately dense and 65 km² of open forest to very dense forest. On the other hand, there has been a degradation of 121 km² of very dense forest to moderately dense forest. India aims to bring 33 % of her total land area under forests. Increase in forest cover aims at increasing carbon stocks as well as protecting biodiversity amongst several other advantages. 11.5 Mha of afforestation and tree planting will have to be carried out on lands outside recorded forests such as wastelands, state land, railways, military areas, public sector companies and agricultural lands[28]. The additional land required for an increase in forested area directly competes with land availability for bioenergy production. Strategies for Jatropha have been changing between the 10th and 11th Five Year Plans[29.] While bamboo plantations, medicinal plants and Jatropha were given adequate focus under the National Afforestation Programme (NAP)[30] under the Tenth plan (2005-2007), the recommendations in the Eleventh Plan (2007-2012) suggest that ecosystem based management must be given due importance to conserve biodiversity instead of establishing tree plantations. In biodiversity rich areas like the states of Chhattisgarh, Uttaranchal, Mizoram and Tripura, the introduction of large scale monospecific plantations of alien species like Jatropha were recommended to be immediately reviewed.

Besides competing with forests, bioenergy crops are also likely to compete for land with Common Property Resources (CPRs) e.g. village forests, marginal grazing lands, watershed drainage and rivulets etc. that support basic needs and provide services to vulnerable sections of the society. There are no official estimates of CPRs in India; however most of the degraded lands in the country are CPRs and a significant proportion of these lands are encroached upon for human settlement[31]. While CPRs are a matter of defining a particular type of property right on land, identifying a specific ecological characteristic for making a developmental programme for recovery of degraded lands, irrespective of property rights, is essential[32].

Table 5 Forest Cover Change Matrix for India (area in km^2)

Class	**VDF**	**MDF**	**OF**	**Scrub**	**NF**	**Total Area (9th cycle, 2003)**
VDF	54,313	121	23	0	61	54,518
MDF	191	331,878	777	19	1,191	334,056
OF	65	552	285,585	67	2,973	289.242
Scrub	0	5	145	38.150	1,774	40,044
NF	0	91	3,342	239	2,565,731	2,569,403
Total Area (10th cycle,2005)	54,569	332,647	289,872	38,475	2,571700	3,287,263
Net Change	51	-1,409	630	-1,569	2,297	

Source[27]

VDF- Very Dense Forest, MDF-Moderately Dense Forest; OF-Open Forests; NF-Non Forest

VDF- Lands with forest cover having a canopy density of 70% and above

MDF- Lands with forest cover having a canopy density between 40-70%

OF- Lands with forest cover having a canopy density between 10-40%

NF- Lands without forest cover

2.2 Land conversion and biofuels

In India the feasibility of the use of wastelands for afforestation is a major concern. Despite the government's strong promotion of the use of wastelands/marginal lands for biofuel plantations there are several uncertainties associated with these activities. It is important to accurately determine the technical, economic, environmental and social feasibility of wasteland afforestation projects. This also has global significance, since afforestation driven carbon sequestration is an important function of associated climate change. Afforestation projects are financially viable even when no environmental benefits are taken into consideration. It was found that afforestation of degraded forest lands that had some natural rootstock was cheaper than afforestation of totally degraded forest lands or barren lands that were devoid of any rootstock[33]. However, a research gap exists with respect to studies assessing the economic feasibility of biofuel plantations on wastelands. The current approach, which relies mostly on one new crop – in this case Jatropha - which is to be cultivated under harsh environments, might not the best suited for meeting the nation's biofuels goals and providing relief to the poor[34]. The food vs. fuel debate is pronounced in the country, as the pressure on land is enormous and steadily increasing with growing population. The plantation of large tracts of marginal lands for biofuel production is likely to be challenged by the discrepancies between government records and actual availability of land on the ground. Problems in wasteland acquisition for afforestation are further aggravated by non-availability of land, particularly in non-forest areas, where most lands are encroached, and thus used for various purposes. The process of evicting encroachers is both time consuming and expensive[35]. Besides, the removal of such encroachments also would render a considerable fraction of the poor population homeless and disarrayed.

The use of CPRs for biofuel plantation is facing numerous other challenges. The area under CPRs is steadily declining in the country. Although, one of the key benefits proclaimed from Jatropha systems is employment generation for the poor, it is in direct opposition to various already existing benefits of CPRs. The rural poor gather most of their fuel wood, fodder, food and fiber from such lands, services which cannot be replaced by Jatropha systems. Any conversion in CPRs would also imply a direct increase of pressure on forests for these supplies and may aggravate deforestation rates. Biofuel plantations can therefore have immediate and grievous consequences for the very low income group communities, and additionally generate pressure on forests for forest produce.

The introduction of new legislations (for e.g. Scheduled Tribes and other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006[36]), have the potential to be a driver of land conflicts. Enforcement of laws that provide direct ownership of natural resources to individuals, including land, can be a major driver of land use change. Biofuel projects initiated by the Government / private investors can now be challenged by civil communities beyond the realm of social activism. Although, effective implementation of such legislations may have far reaching effects towards equitable distribution of benefits between investors and local communities, the use (or misuse) of such laws shall play a deterministic role in the progress of biofuel projects.

The role of private investors in the biofuel sector is an important but less documented aspect. The liberalisation of the Indian economy has led to an attempt to attract Foreign Direct Investment (FDI), which has emerged as one of the major drivers of economic growth. FDI is allowed in all sectors, including the renewable energy sector (100% FDI allowance under certain conditions). As a consequence, investments in clean technology have grown by 12%, although globally, the biofuel sector is the only one to decline recently. Although the majority of investments are directed towards wind and solar energy, two large biofuel deals have contributed substantially to an increase in the total Venture Capital/Private Equity of the renewable energy sector. Steps to meet the official targets of biodiesel production up from currently negligible quantities[37], will involve amplifying feedstock production as well as increasing the capacity of, and/or setting up of new biodiesel plants. In both cases, land would be a key requirement and land acquisition is likely to be highly competitive. Currently both national (Tata Chemicals, Reliance Life Sciences Ltd) and international investors (BP, D1 Oils) are producing Jatropha based biodiesel, using contract farming as one of the pathways. Reliable documentation regarding the ownership, quality and land use history of such land parcels could not be found and hence it is difficult to assess the extent of land conversion involved in such ventures, however land conversion cannot be ruled out. In many cases, private investors utilise incentives of state governments to produce Jatropha seeds/biodiesel for export. This practice may prove detrimental to the main objectives of the Indian biofuel programme, unless adequate measures are taken to enforce the major share of the production to achieve domestic biofuel targets.

The carbon finance market is another rapidly expanding industry in India. India accounts for 32% of the registered Clean Development Mechanism (CDM) projects in the world, which has made it the most dominant CDM player[38]. However, India accounts for only 15% of the total emission credit volume, clearly revealing the small scale decentralised nature of the projects in the country. Biofuel projects currently have no contribution to the total number of CDM projects of the country, the major barrier being inadequate baseline and monitoring methodologies. With increases in investments in research towards life cycle assessments, it could be anticipated that that this knowledge gap would not be difficult to bridge in coming years. Various aspects of biofuel production (especially Jatropha / Pongamia based biodiesel) make it an attractive CDM option, viz., biofuel replacement of fossil fuel consumption and associated Greenhouse Gas (GHG) emission reduction potential, CO_2 sequestration potential, utility of by-products and income generation opportunities[38]. Therefore the CDM market for biofuels, once established, may trigger an impetus for higher production and in turn induce land use changes.

Another major challenge is the low level of inclination of farmers to grow biofuel crops, compared to better market oriented food crops supported by insurance schemes and subsidies from the government. The lack of a well established marketing mechanism, with adequate prices for biofuel crops, is a major hindrance to attracting long-term interest of farmers. Efforts to optimize the pricing structure for fuel sources, to ensure that there are sufficient incentives for the farmers to grow fuel crops on marginal lands, are necessary. In order to diminish the probability of food vs. fuel competitions, disincentives can be placed to prevent energy cropping on undesirable categories of land such as agricultural/forest. Non-price barriers, such as water availability, could be employed to enhance rotation between food and fuel crops over the agricultural calendar[39].

Notable from the above sections is that the range of the drivers of land conversions due to biofuels is large, interdisciplinary and ever increasing. The success of the biofuel programmes would largely depend on the elasticity of the planning process, which should be able to accommodate the changing dynamics and requirements of all sectors, while protecting the interests of the most vulnerable groups.

3. Case studies

In this section we briefly introduce four modelling studies at national/regional scale, highlighting different aspects of land availability and land-use change, related to potential yields of sugarcane and Jatropha. All case studies are mainly aiming at the improved usage of marginal lands, wastelands or natural land, unfortunately, all using different and partly overlapping definitions of these land categories.

National and sub-national level case studies are of high importance since global biofuel issues, albeit important, do not account for national or regional policy goals and ground conditions. Realistic estimates of land requirement vis-à-vis biofuel demands are much needed and indicate the importance of regional case studies, especially for highly heterogeneous agro-ecological conditions and production systems, characteristic of different parts of India. Typically, land-use modelling and related approaches provide a platform for taking into account several dimensions of the coupled socio-environmental systems, such as agricultural economics, demographic changes, regional environmental conditions, regional crop management and yields of food and bioenergy crops, as well as regional and larger scale policy goals. Potential pathways into the future are addressed with scenario analyses, which are an important method of generating projections using consistent assumptions of how the socio-environmental systems might unfold.

3.1 Study I: Potential of wastelands for intensified bioenergy production

A study at national scale was conducted focusing on the potential of the 85 Mha of wastelands (mostly dry shrub lands and savannas) for the production of energy-crops such as sugarcane[40]. In a gridded approach of 5 arc min spatial resolution, the DayCent Model[41] was employed to simulate the productivity of sugarcane in each wasteland grid cell. Three scenarios of increasing levels of land use intensity were developed, assuming the application of nitrogen (N) fertilizer (i) 50 Kg N, (ii) 100 Kg N and (iii) 100 Kg N + Irrigation. For the entire wasteland area, dry matter production summed up to 641 Mt, 1060 Mt and 1,150 Mt per year (Figure 1) respectively, representing 2.8 to 5.5 times the biomass produced by the natural vegetation cover[42]. However, large regional differences in simulated production and productivity (generally low in the North and North-West, Punjab, Himachal Pradesh, Rajasthan) highlight the need for thorough analysis of the limiting factors (in this study: temperature, water, soil fertility and added nutrients), as well as the need to analyse competing production systems based on different potential biofuel crops (see case studies presented in this paper). The three scenarios developed for this study clearly identify differences between nutrient limited and water limited production (e.g. comparing Figure 1 left and centre, all pixels south of the climate limited north are nutrient limited at the 50 kg N level; comparing Figure 1 centre and right, some regions e.g. in northern Karnataka or southern Maharashtra are water limited and increase productivity with irrigation, whereas others are not).

Depending on the conversion technology used, the total energy content of 11,300 - 20,400 PJ could translate into 900 – 1600 TWh of electrical energy using a steam engine pathway, or 240 – 430 TWh in a biogas pathway (conversion factors as in Jagadish 2003[42]). In the latter case, the N-rich organic material remaining after gasification would considerably reduce nutrient losses and the need for fertiliser application, if applied as organic fertiliser.

As in all sugarcane production systems, huge amounts of biomass are involved, requiring either efficient transportation infrastructure, or decentralised units for energy conversion, i.e. steam engines or biogas plants or both. Thus, the requirements to efficiently produce bioenergy on up to 85 Mha of wastelands, considerably differs from the actual setting of sugarcane plantations, which are currently clustered in relatively small, but intensively managed areas (mainly in Uttar Pradesh, Maharashtra, Tamil Nadu and Karnataka).

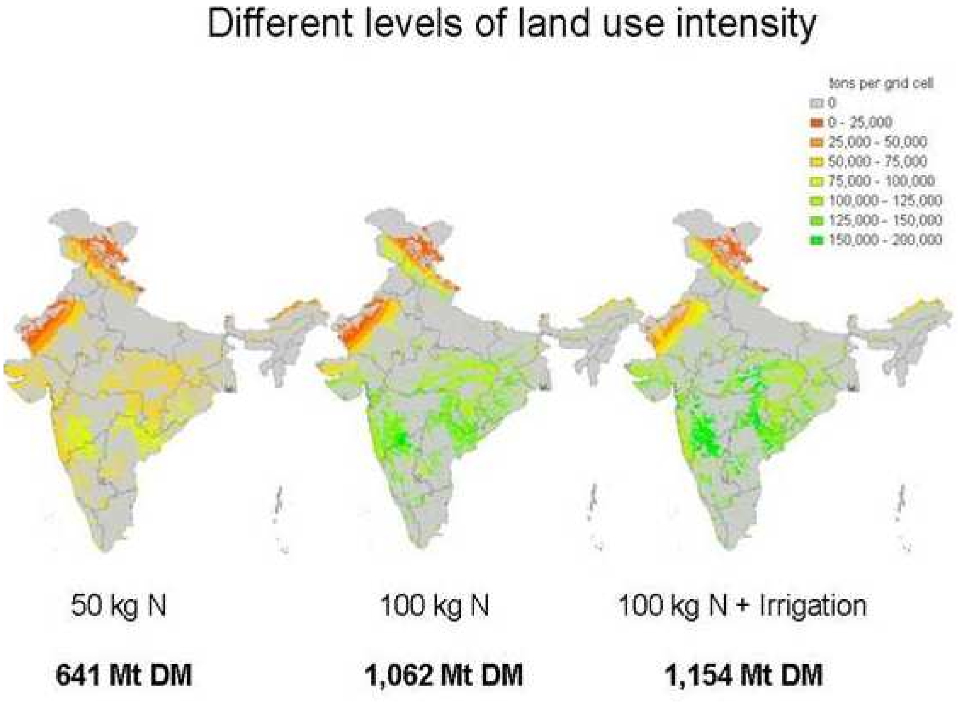

Figure 1 Sugarcane potential on marginal lands[40]

3.2 Study II: Potential land requirements for sugarcane and Jatropha to achieve national bioenergy policy goals

Land requirements and the potential productivity of sugarcane and Jatropha have been modelled for India and Brazil[43] (the current section reviews the India case study). The study was conducted using the well established process based model LPJmL. LPJmL uses Crop Fuctional Types (CFTs) and Plant Fuctional Types (PFTs). Sugarcane was parameterized as a CFT while Jatropha was parameterized as a PFT in the LPJmL framework. Potential yields were calculated assuming that each grid cell is available for sugarcane or Jatropha and averaged over 1971-2000 climate period under irrigated and rainfed conditions (Figure 2 and Figure 3). Results of productivity values were compared against available yields for sugarcane and very few observed data for Jatropha systems. Additional land requirements to achieve government targets for 2015 have been reported to be 1.7 Mha for rainfed sugarcane (increase of 43% in the area under sugarcane cultivation) and 1 Mha for irrigated sugarcane. From the results, an additional 21.2 Mha of land shall have to be brought under Jatropha (rainfed) cultivation, with an average productivity of 2.2 Mg ha^{-1}, in order to achieve government targets of the National Mission. If only high productivity areas (5.2 Mg ha^{-1}) are utilised, additional land requirements considerably lessen to 9.5 Mha. The study showed that spatial variation of yields under irrigated conditions is low, since most of India attains similar productivity with an average of 5.89 Mg ha^{-1}. Under irrigated conditions 7.9 Mha of additional land would be sufficient to achieve targets. The dependence of the national goals on stable monsoons and/or irrigation expansion is largely reflected in the results of this study. Spatial analysis of the heterogeneity of productivity regimes of Jatropha across the country makes it an interesting baseline for planning processes.

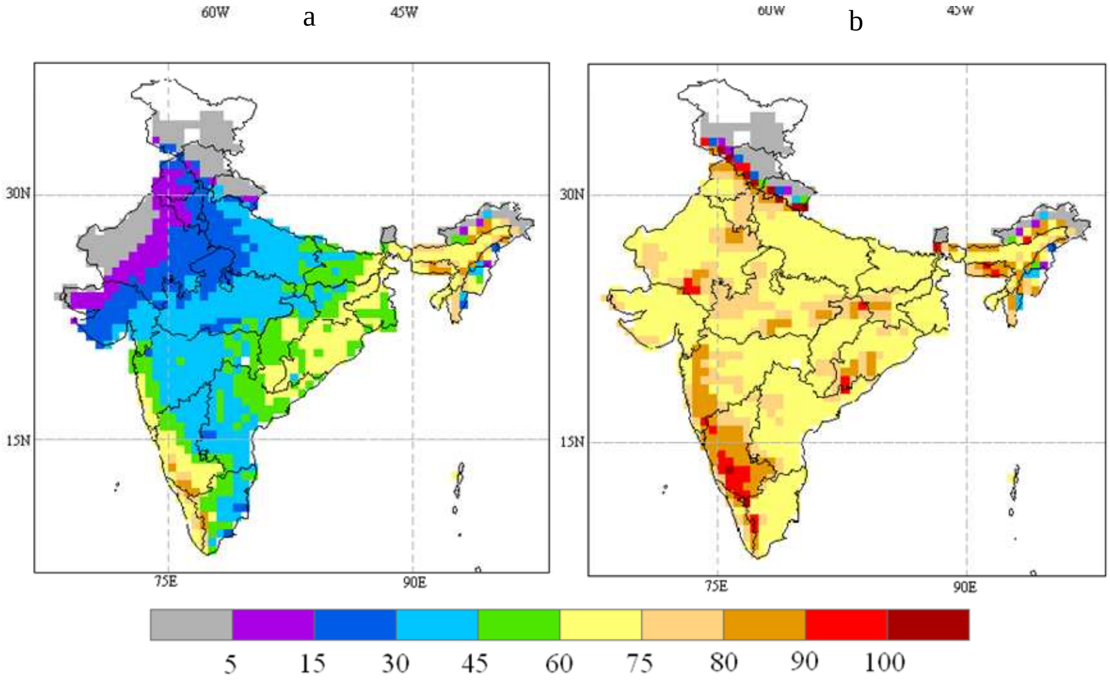

Figure 2 Sugarcane potential yields (Mg ha-1) in India under rainfed (a) and irrigated (b) conditions averaged for 1971-2000 climate[43]

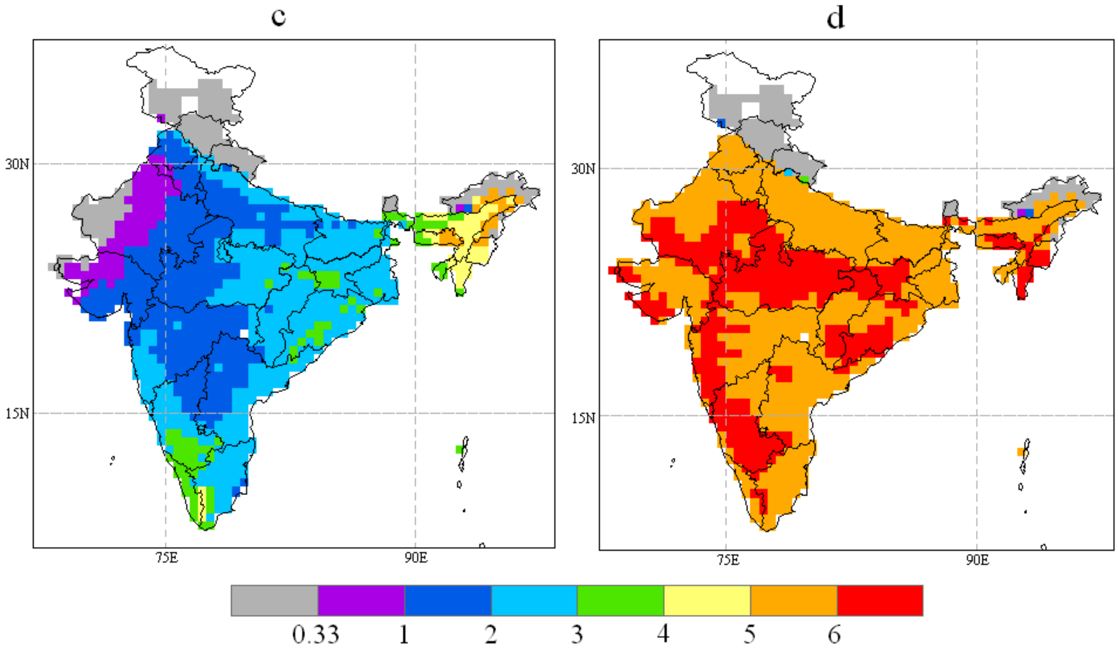

Figure 3 Jatropha potential yields (Mg ha^{-1}) India under rainfed conditions (c) and irrigated (d) conditions averaged for 1971-2000 climate

3.3 Study III: Assessment of potential productivity of Jatropha at sub-national scale

Various aspects of the potential of Jatropha as an agrodiesel crop on wastelands were assessed for the state of Karnataka (South India)[44]. The DayCent model, embedded in the SITE (SImulation of Terrestrial Ecosystems) framework[45] was used to simulate Jatropha at a resolution of 2 x 2 km. Based upon available literature, the shrub was parameterized as a 'Tree' type in DayCent. CRU[46] climate data was used for a thirty year time period (1971-2000) for simulations and only rain-fed conditions were considered since irrigated Jatropha was assumed to be unfeasible. Recognising that Jatropha production is aimed at marginal lands/wastelands, potential yields were calculated for the four major categories of wastelands (75% of total wasteland area) that are suitable for Jatropha growth. The production potential was estimated at district level for all relevant wasteland categories. The results indicate that the average potential productivity of Jatropha is ranging from 0.8 Mg ha^{-1} to 1.7 Mg ha^{-1} (Figure 4). Additionally, the study assessed the total potential oil production from Jatropha, using various reported levels of oil content in seeds (30%, 35% and 40%) and different extraction efficiencies (57%, 68%, 81% and 100%) as parameters. It was found that depending on combinations of oil content and extraction efficiency, it is possible to generate 40% to 93% of the targeted amounts of biodiesel. As a consequence, conversion of 1-7% of agricultural land for energy production would be sufficient to meet current targets, considering Jatropha as the only species in use. This broad range reflects that conversion can be restrained to very low levels by increasing the total efficiency of the agrodiesel production chain. The study concludes that Jatropha has a significant potential for agrodiesel production on the state's wastelands. Further interventions in improving extraction efficiency can raise the potential considerably, especially in conjunction with efforts to increase oil content via selection, breeding or other means of improvements. The importance of spatially explicit regional estimates of potential yields as an important base information for further planning and management has clearly been demonstrated. Improvements in estimates/data on the actual availability of wastelands were recognised as a critical gap that needs to be filled, if targets have to be met.

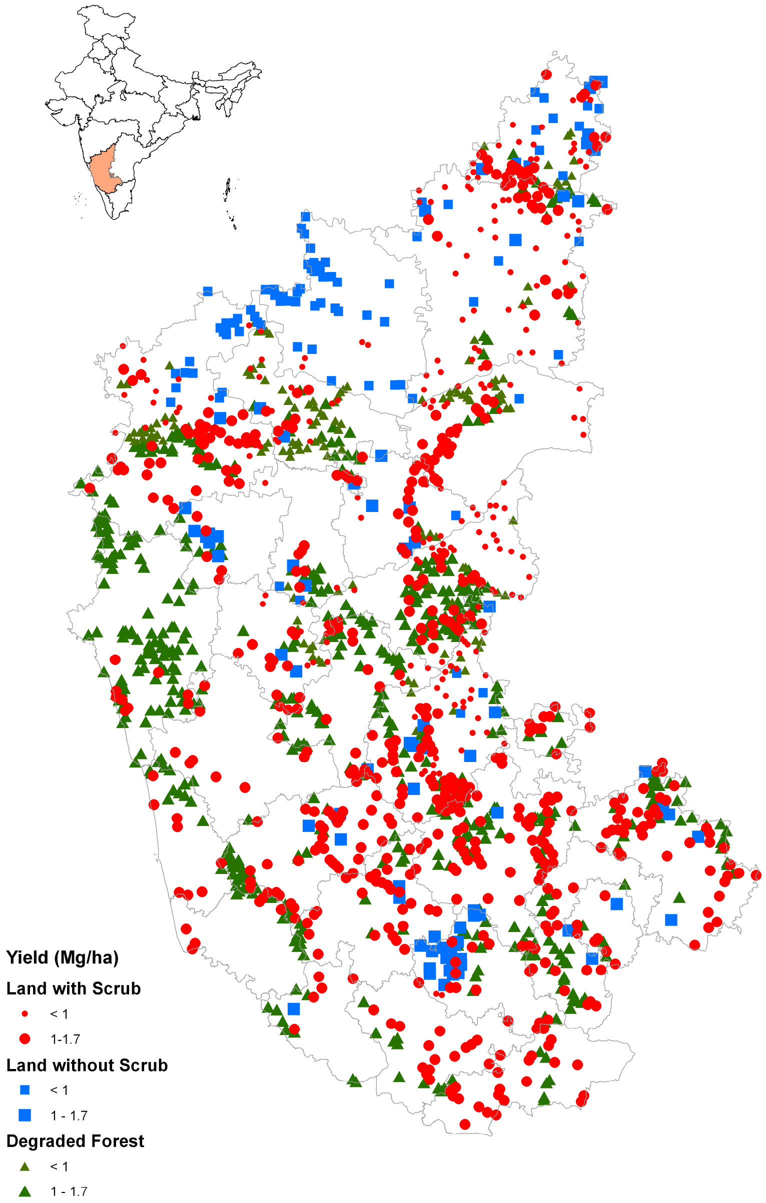

Figure 4 Potential yields of Jatropha in wastelands of Karnataka

3.4 Study IV: Biofuel Blending Scenarios

In this study[47] the major focus was on analysing the spatial impacts of blending petrol with sugarcane derived ethanol. The “Order from Strength” scenario of the Millennium Ecosystem Assessment (MEA) served as a baseline scenario. Biofuel policies of blending between 5% and 20% of the petrol demands up to 2030 were translated into the corresponding demands for additional sugarcane production (132 – 158 Tg). The spatially explicit LANDSHIFT model was employed to simulate competition between different land use types and to estimate the additional amounts of land needed to match blending goals. In the simulations it was assumed that forests and other protected areas will be strictly protected in the future and were thus excluded from land conversion. As the size of the human population (MEA scenario assumption) and their demand for food crops grew faster than crop yields (results from the IMPACT model[48] used as input for LANDSHIFT), urban and cropping areas in all cases increased considerably at the expense of natural lands, which are mainly marginal lands with low suitability for agricultural production (e.g. too steep, too dry, too high, unsuitable soils and other constraints). It is noteworthy that the major fraction of the conversion of natural land (43%) was attributed to increased food production, and only between 3% and 8% were caused by the additional demands for ethanol (see Table 6).

Table 6 Simulated land use in 10-year time steps. Sugarcane and cropland used for food production are listed separately

	2000 [Mha]	2010 [Mha]	2020 [Mha]	2030 [Mha]	2000 - 2030 [%]
			MEA base scenario		
Settlement	186.6	22.5	25.6	30.2	62
Cropland	159.7	167.2	182.1	191.0	20
Sugarcane	4.5	4.7	5.0	5.1	14
Natural land	80.3	74.9	57.3	45.8	-43
			5% ethanol blending		
Cropland	159.7	167.3	180.3	191.3	20
Sugarcane	4.5	5.3	5.9	6.6	46
Natural land	80.3	74.1	58.1	44.1	-45
			10% ethanol blending		
Cropland	159.7	167.4	180.2	191.3	20
Sugarcane	4.5	6	6.9	8.1	79
Natural land	80.3	73.5	57.2	42.7	-47
			20% ethanol blending		
Cropland	159.7	167.3	181.8	192	20
Sugarcane	4.5	7.3	9	11.1	144
Natural land	80.3	72.3	53.5	39.3	-51

Source[47]

4. Discussion

The role of bioenergy in India is primarily important in the transport sector (biodiesel/bioethanol) and in rural electrification (biomass, biogasification). Various estimates of the net share of diesel consumption by the transport sector show a wide range, from 59 %

to 85% of the total diesel consumption of the country[49]. A closer look at statistics makes it apparent that biofuels are still to make a significant contribution in the total energy consumption. However, in the near future, biodiesel can reduce fossil fuel components of the transport sector that are most likely to run on conventional sources of energy i.e. mainly diesel consumption in road, railroad and partially water traffic (of passengers and freight), less in air traffic and large ocean vessels.In this context, the role of biofuels should not be underestimated, as the demand from the transportation sector cannot be easily fulfilled by other forms of renewable energy commonly used such as wind, solar energy or hydro-power. Use of biofuels in the transportation sector is therefore inevitable, unless other alternative forms of energy (e.g. fuel cells) prove technically and economically feasible. Rising oil prices, depleting national petroleum reserves and rising oil demands (motorized mobility has grown by 888% between 1970 and 2000[49] and continues to grow) are motivating policy makers and planners at the state and national level, to include biofuel options and establish ambitious biofuel production targets.

In the context of energy security, which is directly competing with food security (both of which are part of the Millennium Development Goals), the effect of biofuels may show different trends over time. Food distribution is a Herculean task, as 1,200,000 bags (50kgs each) of food-grains are transported each day from regions of surplus production to food deficient zones[24]. Food supply to remote parts of the country (e.g. mountainous regions) which are not linked by railways is usually achieved by road transport. In the near future, enhanced biodiesel/bioethanol production may aid food distribution (See Section 2) by strengthening the public distribution system. However, over longer periods of time, energy crops have the potential to cause an imbalance in the agricultural system by competing with food crops for scarce land and water resources, the latter already now being overexploited[11].

India has also initiated research and trials for alternative feedstock. Bioethanol, which was traditionally produced and delivered by the sugarcane industry, is now finding new pathways from crops such as tropical sugarbeet and sweet sorghum. Cellulose/lignocellulose sources of bioethanol are also currently under research. A useful combination of various sources of alternative fuels may reduce dependence on a single crop/source, but in turn requires investments in multiple technology and competence enhancement.

Comprehensive studies on land use changes, including biofuel production and related impacts, are not yet available. Land use planning and management has already become an ever increasing challenge, as globalisation, climate change and increasing mobility tend to increase the range of land-use drivers, often across multiple sectors. The environmental heterogeneity and large regional imbalances contributes to the complexity of the task. Unsustainable use of land has led to large scale land degradation (143 Mha). Extension of cultivation to areas with low production potential has also been identified as a driver of further land degradation [24]. Although, Indian policies do not advocate any energy production on agricultural/fertile land, the pressure on marginal lands is also increasing exponentially. A wide range of activities are planned on wastelands, ranging from afforestation projects by Forest Departments to several forms of renewable energy. Such competing interests on wastelands (including various government agencies) reflect the severe limitation of suitable land-resources. The current situation can proliferate into an internal ‘land grab’, manifestations of which are already visible in several parts of the world[50].

Land use change – potentially including changes resulting from biofuel production - may considerably contribute to GHG emissions and thus become a major driver of climate change. Over the last decade, India has intensified efforts to reduce GHG emissions. However, with the share of the energy sector in national emissions being largest (61%)[51], there is little room for additional emissions induced by changing land use patterns (currently 1% of total emissions). GHG levels of bioenergy production systems are still largely unknown, as is the carbon sequestration potential of various bioenergy crops. Prioritization of bioenergy cropping should therefore also include GHG emission reduction goals, as carbon offsets in one sector could be overridden by another sector.

5. Conclusion

India faces the challenge of ensuring the use of biofuels is sustainable. The boon of suitable climatic conditions to use new and promising oilseeds, such as Jatropha and Pongamia and crops, such as tropical sugarbeet, is challenged by the bane of ever growing pressure on land for food and fuel production and other competing sectors. The broad range of options presented in the selected case studies clearly highlights the need to consider multiple options, in order to identify crops, management systems, technologies and energy conversion pathways which are apt to match the widely differing environmental and socio-economic conditions in the various agro-ecological zones and states of India. Ensuring energy and food to all sections of the society, while fulfilling international commitments towards climate change, provides an opportunity for the strengthening of the existing linkages between science and policy. Besides direct benefits as fuels, indirect benefits of biofuels, such as employment and income generation, contribution to national GDP, land reclamation and carbon sequestration, can be additionally gained.

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7. References

1. Draft Report of the Expert Committee on the Integrated Energy Policy, Planning Commission, New Delhi (2005)
2. M. S. Punia, Editor. 3 rd R& D Report on TBOs, National Oilseeds and Vegetable Oils Development Board, Ministry of Agriculture, Government of India , (2007-08)
3. Draft Report of the Expert Committee on the Integrated Energy Policy, Planning Commission, New Delhi (2006)
4. S. K. Singh, India Bio-Fuels Production Report, GAIN Report No: IN6047, (2006)
5. N. Kukrika, Vegetable Oil based Biofuels in India : An Overview Of The Value Chain Analysis Of Biofuels' Pro Poor Potential', Harvard University, (2008)
6. TERI, Liquid Biofuels for Transportation: India country study on potential and implications for sustainable agriculture and energy. Report prepared for the Duetsche Gesellschaft fur Technische Zusammenerbeit (GTZ) GmbH, New Dehli, October, (2005) www.gtz.de/de/dokumente/en-biofuels-for-transportation-in-india-2005.pdf
7. Ministry of New and Renewable Energy Press Release, http://mnes.nic.in/press-releases/press-release-12092008.pdf, (2008)
8. Planning Commission, Government of India, New Delhi 'Report of the Committee on the Development of Biofuel' (2003)
9. Ministry of Petroleum and Natural Gas, Government of India, Biodiesel Purchase Policy (2005) Available at http://www.petroleum.nic.in/
10. FAO Statistics Division, Major food and agricultural commodities and producers (2009) http://www.fao.org/es/ess/top/commodity.html
11. M. Rodell, I. Velicogna and J. S. Famiglietti, Satellite based estimation of ground water depletion in India, Nature, doi:10.1038/nature08238 (2009)
12. A. Bharadwaj, R. Tongia and V. S. Arunachalam, Scoping technology options for India's oil security: Part I – ethanol for petrol, Current Science, Vol 92 (8) (2007)
13. R. S. Kureel, Prospects and Potential of Jatropha curcus for Biodiesel Production, Proceedings of the Biodiesel Conference towards Energy Independence – Focus on Jatropha, (2006), Hyderabad, India

14. V. Dange, D. Suthar and P.S Reddy, Biodiesel through Jatropha curcus- A Critical Analysis. Proceedings of the Biodiesel Conference Towards Energy Independence – Focus on Jatropha, (2006), Hyderabad, India
15. R. S. Kureel, C. B. Singh, A. K. Gupta and A. Pandey, Jatropha an alternate source for biodiesel, (2007),NOVODB, Gurgaon, India
16. BAIF Institute for Rural Development, Karnataka, The Biofuel hype: Chance or Challenge for Sustainable Agriculture, in, Micro Gaul, Jatropha curcus production systems for small farmers: Research, Demonstration and Information Exchange, GTZ- Sustainet, Eiscshborn, (2005)
17. K. S. Gajbhiye and C. Mandal, Agro-Ecological Zones, their Soil Resource and Cropping Patterns, Status of Farm Mechnization in India, Department of Agriculture and Cooperartion, Government of India, accessed (2009) (http://agricoop.nic.in/Farm%20Mech.%20PDF/05024-01.pdf)
18. B. N. Goswami, V. Venugopal, D. Sengupta, M. S. Madhusoodanan and P. K. Xavier, Increasing trend of extreme rain events over India in a warming environment, Science Vol 314, (2006)
19. M. Lal, T. Nozawa, S. Emori, H. Harasawa, K. Tukahashi, M. Kimoto, A. Abe-Ouchi, T. Nakajima, T. Takemura and A. Numaguti,, Future climate change: Implications for Indian summer monsson and its variability, Current Science 81 (9), (2001)
20. Crisis Management Plan - Drought (National), Ministry of Agriculture, Government of India (2009)
21. Ministry of Agriculture, Government of India communication to states, Diesel subsidy in drought and deficit rainfall affected areas (2009). Available at http://agricoop.nic.in/Diesel%20subsidy4809.pdf
22. N. Kalra, P. K. Agarwal, S. Chander, H. Pathak, R. Choudhary, A. Choudhary, M. Sehgal, H. K. Rai, U. A. Soni, A. Sharma, M. Jolly, U. K. Singh, O. Ahmed and M. Z. Hussain, Impacts of Climate Change on Agriculture, in Climate Change and India, Vulnerability Assessment and Adaptation, Edited by P. R. Shukla, S. K. Sharma, N. H. Ravindranath, A. Garg, S. Bhattacharya, (2003), University Press, Hyderabad
23. Ministry of Rural Development and National Remote Sensing Agency, Government of India, Wastelands Atlas of India (2005)
24. State of Environment Report, India, Ministry of Environment and Forests , Government of India , (2009)

25. N. H. Ravindranath, Land for Food or Fuel? in D. Ahuja, J. Alcamo ,Joint Indo-German Research Workshop 'Will Competition for Land and Water Hinder Energy Development in India? 7-8 March. (2006), pg 12
26. U. A. Amarsinghe, T. Shah and O. P. Singh, Changing Consumption Patterns: Implications on Food and Water Demand in India, International Water Management Institute (IWMI) Research Report 119, (2007), Sri Lanka
27. State of the Forest Report, Forest Survey of India, Ministry of Environment and Forests (2005)
28. Report of The Working Group on Forests for the Environment and Forest Sector, for the Eleventh Five Year Plan (2007-2012), Government of India, Planning Commission, (2006)
29. Five Year Plans, Planning Commission, Government of India, (2009) Available at http://planningcommission.gov.in/
30. Annual Report, Ministry of Environment and Forests (MOEF), New Delhi, (2004-2005), p76
31. D. Ramakrishanaih, Land Availability for Biofuel Plantation, Proceedings of the Biodiesel Conference towards Energy Independence – Focus on Jatropha, (2006), Hyderabad, India
32. Ministry of Environment and Forests (MOEF), New Delhi, Status of Desertification-Volume I, National Action Programme (NAP) to Combat Desertification, (2001)
33. K. Balooni, Economics of wastelands afforestation in India, a Review. New Forests 26: 101–136, (2003)
34. D. Rajagopal, Implications of India's biofuel policies for food, water and the poor, Water Policy 10 Supplement 1 95-105 (2008)
35. K. Balooni and K. Singh, Prospects and problems of afforestation of wastelands in India: A synthesis of macro- and micro-perspectives. Geoforum 38 1276–1289 (2007)
36. The Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, (2006), The Gazette of India, Registered No. DL- (N)04/0007/ 2006-08,Ministry of Law and Justice, Government of India
37. R. Boyle, C. Greenwood, A. Hohler, M. Lierbreich, V. S. O' Brien, A. Tyne and E. Usher, Global Trends in Sustainable Energy Investment, UNEP, ISBN: 978-92-807-2939-9, DTI/1066/PA (2008)

38. S. J. A. Bakker, CDM and biofuels: Can the CDM assist biofuel production and deployment? Energy Research Center of the Netherlands (2006)
39. S. Srinivasan, The food v. fuel debate: A nuanced view of incentive structures. Renewable Energy. 34 950–954 (2008)
40. J. A. Priess and M. Heistermann, Modelling the Potential of Biofuel Crops in India: An example of sugarcane production in Will competition for land and water hinder energy development in India, NIAS workshop, March (2006), Bangalore, India
41. W. J. Parton, M. Hartman, D. Ojima and D. Schimel, DAYCENT and its land surface submodel: description and testing, Global and Planetary Change 19(35-48) (1998)
42. K.S. Jagadish, Bioenergy for India: prospects, problems and tasks. Energy for Sustainable Development, 7/1, 28-34. (2003)
43. D. M. Lapola, J. A. Priess and A.Bondeau, Modeling the land requirements and potential productivity of sugarcane and Jatropha in Brazil and India using the LPJmL dynamic global vegetation model. Biomass and Bioenergy. 33 8: p. 1087-1095. (2009)
44. S. Das and J. A. Priess, Shedding some light on Karnataka’s blind date with Jatropha, Journal of Environmental Management, under review (2009)
45. M. Mimler and J. A. Priess, Design and Implementation of a generic modeling framework- a platform for integrated land use modeling. Center for Environmental Systems Research, Kassel University Press, University of Kassel, Germany (2008)
46. T. D. Mitchell and P. D. Jones, An improved method of constructing a database of monthly climate observations and associated high resolution grids. International Journal of Climatology. 25 p. 693-712. (2005)
47. R. Schaldach, J. A. Priess and J. Alcamo, Simulating the impact of bio-fuel development on country-wide land-use change in India. Biomass and Bioenergy, under review (2009)
48. M. W. Rosegrant, X. Cai and S. A. Cline, World water and food to 2025: Dealing with Scarcity. International Food Policy Research Institute, Washington, D.C., (2002)
49. Nan Zhou and M. A. McNeil, Assessment of historic trend in mobility and energy use in India transportation sector using bottom-up approach, Journal Of Renewable And Sustainable Energy 1, 043108 (2009)
50. J. v. Braun and R. Meinzen- Dick, Land grabbing by Foreign Investors in Developing Countries : Risks and Opportunities, IFPRI Policy Brief, (2009)

51. Ministry of Environment and Forests, National Communication to UNFCCC, India (2004) Available at http://www.natcomindia.org/natcomreport.htm

3 Zig-zagging into the future: the role of biofuels in India[2]

Abstract

India announced a long awaited and much needed national biofuel policy in December 2009 with a mandate of achieving 20% blending of bioethanol and biodiesel by 2017. However, while the determination of specific time-bound targets is a crucial step in the Indian biofuel program, several aspects of the guidelines reflects uncertainty that may render the 20% target unachievable. This paper traces the rapid changes in political strategies of biofuels in India over the last decade and reviews significant scientific progress, achieved in the same period. Our observation indicates that biofuel policies in India have followed a zigzag course interspersed with several positive initiatives, severely discouraging advocacies and occasional neglect of biofuels. The multiplicity of related policies, each partially addressing biofuel issues have amounted to increasing ambiguity. We present an analysis of the tenets of the current policy with respect to land availability, related land use, and economic and marketing institutions, which are some of the important determinants of success for the Indian biofuel program. Some recommendations emanating from the analysis are (i) to estimate available land and land use change effects, (ii) to build resilience for energy crops towards climate change and (iii) to strengthen marketing and financial mechanisms at grass-root level. In conclusion we emphasise the need for timely scientific assessments and the subsequent incorporation into policy formulation to enable India to achieve overall goals of sustainable biofuel production.

Key words: Bioenergy, Jatropha, Biofuel Policy, landuse

1. Introduction

Oil imports that amount to 73% of domestic demands have become a commonplace figure that has been cited in research articles, government documents and white papers.[1, 2, 3] India has registered an overwhelming increase of 63% in the import of crude oil from 2001 to 2008.[4] Alternative energy from wind (10,925 megawatt (MW)), small hydro power (2558 MW), biomass power + bagasse cogeneration (2136MW) and solar (2 MW) power has made some considerable progress hitherto.[5] Additionally, agro-residues, photovoltaic systems, solar lanterns and solar cookers have contributed to renewable energy outputs. On the energy demand side, the expanding transport sector has experienced a compound annual

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[2] Das S and Priess JA (2011) Zig-zagging into the future: the role of biofuels in India, *Biofuels Bioproducts and Biorefining* **5,** 18-27

growth rate of vehicle population of 11% from 1951-2002. Petrol and diesel demands in this sector grew at 7.3% and 5.8 % from 1980- 81 to 2004-05.[6] After several biofuel initiatives (2003 - 2010), which we will discuss in more detail in section 2, actual achievements in terms of production or contributions to the transport sector are still missing in national statistics, leading to the conclusion that blending targets have not been achieved. In contrast to other sources of renewable energy, there are no records available that document the area used, technical achievements, installed capacity of biofuel production or extent of blending being undertaken. While India has recorded an annual growth rate of 6.7 % GDP in 2008-2009 [7] rise in both food and fossil fuel prices have captured national, political and civil interest. Prices of all essential commodities including most food-grains have witnessed the highest ever price advance in 2009. While primary food prices went up to 18%, fuel prices had increased 10% in 2009.[7]

Against this background of increasing fuel demands and prices, it is vital for India and other countries facing similar challenges, to explore the potential opportunities presented by biofuels and analyse the obstacles in the biofuel production process. The potential of biofuel production from different feedstocks (eg., sugarcane, sweet sorghum, Jatropha, Pongamia) in India has been assessed by several international bodies[8, 9] and scientists.[10-14] In this context, it is also imperative to anticipate potential positive and negative economic, environmental and social impacts of biofuels. This paper aims at tracing the rapid changes in political strategies over the last decade and reviewing significant scientific achievements over the same time period. Further, we discuss some of the challenges and possible strategies for sustainable biofuel production in India in the light of the policy framework upto 2010.

2. Recent biofuel policies and related science in India

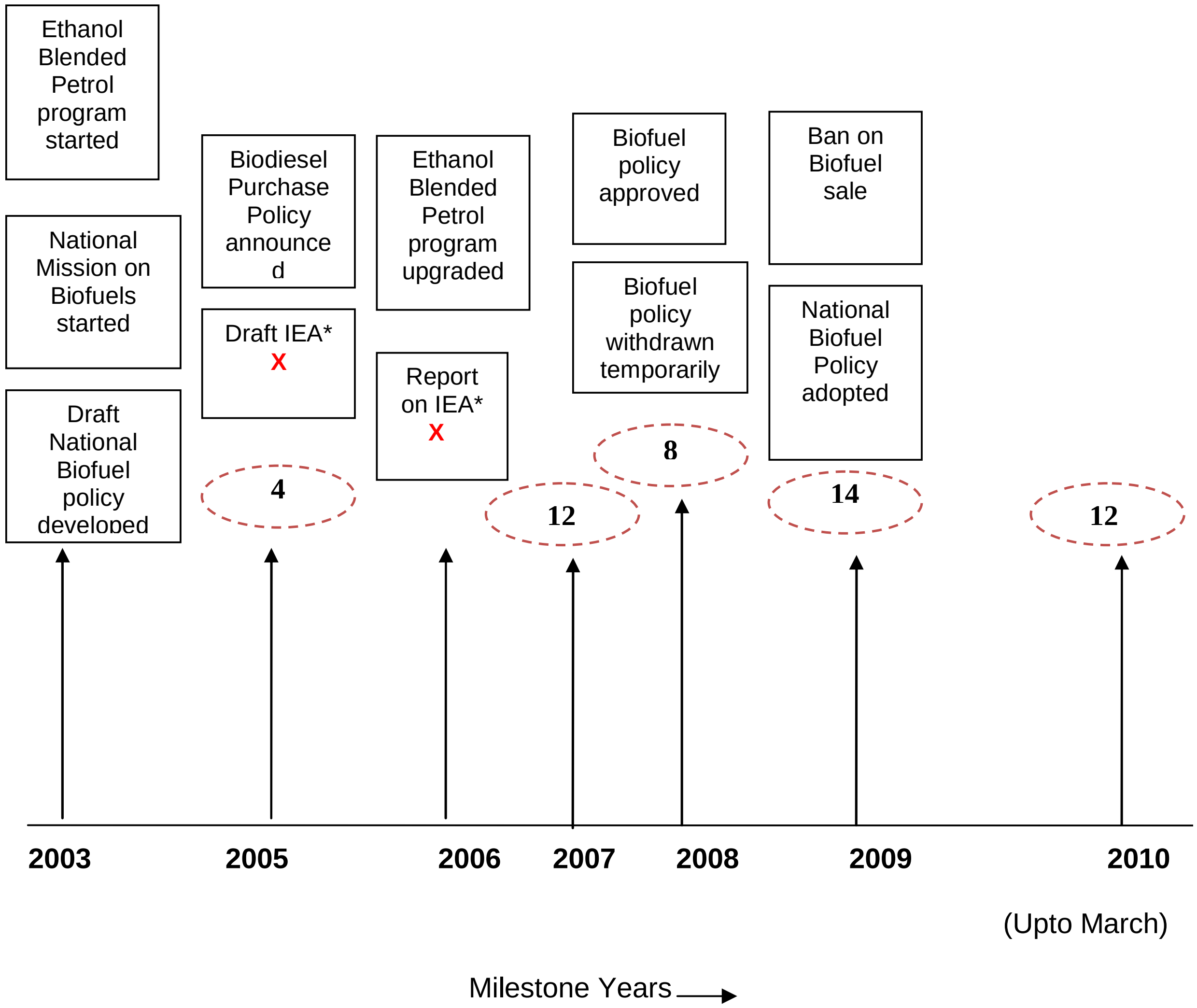
Figure 1 depicts the sequence of various policy strategies adopted in India over the last decade. India’s Ethanol Blended Petrol (EBP) programme first mandated a blending target of 5% for 10 states and 4 union territories.[15] The policy was later modified to 5% blending for the entire country in 2006.[4] This target could only be partially achieved due to the very high sensitivity of the ethanol industry to large fluctuations in sugarcane production as well as restrictive pricing mechanisms. Currently, the 5% EBP programme is still in the stage of implementation in 16 out of 29 states and 3 out of 4 union territories.[4] At the time of writing this article, no detailed data was available for estimates on the extent of implementation. The initial blending targets could not be achieved. One of the major reasons for the failure could be related to unstable levels of production of sugarcane, which is first of all required to meet national sugar/ sweetener demands. Sugar production, distribution and sale in India is strictly regulated under the domain of several laws[16-18], and only 10% of the sugarcane production is diverted to ethanol.[10]

The need to support blended gasoline with biodiesel first found its way into the planning reports of the government in 2003.[2] Consolidation of the alternative pathways of transport fuels was envisaged with the commencement of the 'National Biofuel Mission' that focused on the use of non edible oils as a source of biodiesel, primarily from the shrub *Jatropha curcas*. Meticulous planning was exhibited in the outline of the programme, which had foreseen a testing phase (2003-2007) and a subsequent self sustaining production phase (2007-2012). Targets were set to a (over-) optimistic 20% blending of biodiesel 2011-2012.[2] Research projects were initiated with more than 35 participating institutions, aiming at studying a multitude of aspects of oilseed based biodiesel production (such as: plant physiology, oil content variability, development of high oil yielding varieties, improved oil extraction technologies, efficient industrial processes, economic viability, developing market mechanisms). As a result of the research activities (in India mainly from 2003 to 2007), significant scientific progress was made in India and elsewhere (for a detailed list of publications from Indian studies see Table 1). [12, 19, 20]

Since the first years, biofuels have been politically addressed at national scale; the most striking element of biofuel policies is the indecision that presided over the formulation of a national biofuel policy, highlighted in Figure 1. A Draft Biofuel Policy was developed and presented in 2003 which was first approved by the Union Cabinet in February 2008. [21] It was subsequently withdrawn for further consideration. The National Policy on Biofuels, (2009) (henceforth referred as 'Biofuel Policy') was finally adopted by the Cabinet of Ministers in December 2009.[22]

The Biofuel Policy prescribes 20% blending of both bioethanol and biodiesel by 2017. The assumptions, estimates or data, on which the policy has been based are unknown and have not been mentioned in the political documents. Interestingly, while it took more than six years from the first draft to the final adoption of the policy, two forms of an 'Integrated Energy Policy' were circulated, both granting only sparse reference to biofuels, in contrast to solar, wind, hydro and traditional biomass based systems.[23,24] In spite of ambitious blending targets, plans for 2007-2012 [25] included biofuels / bioenergy as an important research area for technology development. Funds to the tune of 35 million USD have been planned for research activities in bioenergy which is less than both solar (95 million USD) and wind (47 million USD) energy research. Furthermore, no funds have been allocated for installing or advancing installed capacities for bioenergy such as in the case of solar power (47 million USD), small hydro (1.6 billion USD) or wind power (17 million USD).[25] Finally the report also does not estimate the physical potential of biofuels whereas the total potential of renewable energy has been calculated to be 84,776 Megawatt equivalents covering wind, small hydro, cogeneration and waste to energy conversion.

Well before a general biofuel policy was adopted, a biofuel purchase policy was invoked in 2005.[26] The purchase policy aimed at establishing purchase centers for biofuels by the Oil Marketing Companies (OMCs) and fixed the purchase price at 25 INR (~ 0.40 €) per litre. The policy did not provide regulatory measures for the sale of biofuels by producers beyond the OMCs. In September 2009, the government introduced a circular that banned unauthorized sale and possession of biofuels. The ensuing confusion of the producers was only exacerbated by the absence of a national level biofuel policy.[27] The Biofuel Policy includes several mechanisms to strengthen the marketing infrastructure and relies upon the OMCs to shoulder the storage, distribution and marketing of the biofuels, but opens the door for speculation with the introduction of a dynamic Minimum Purchase Price (MPP) without recommendations for changes in the existing purchase policy. The existence of dual regulations with regard to the MPP without specifications on their pre-conditions of applicability is likely to increase uncertainty and confusion among producers.



Note: Boxes indicate policy moves

Dashed circles indicate number of scientific papers published in the year, year 2005 corresponds to the period 1985-2005

*IEA- Integrated Energy Policy

X indicates insufficient significance of biofuels in the reports

Figure 1 Milestones in policy and science initiatives in biofuels in India

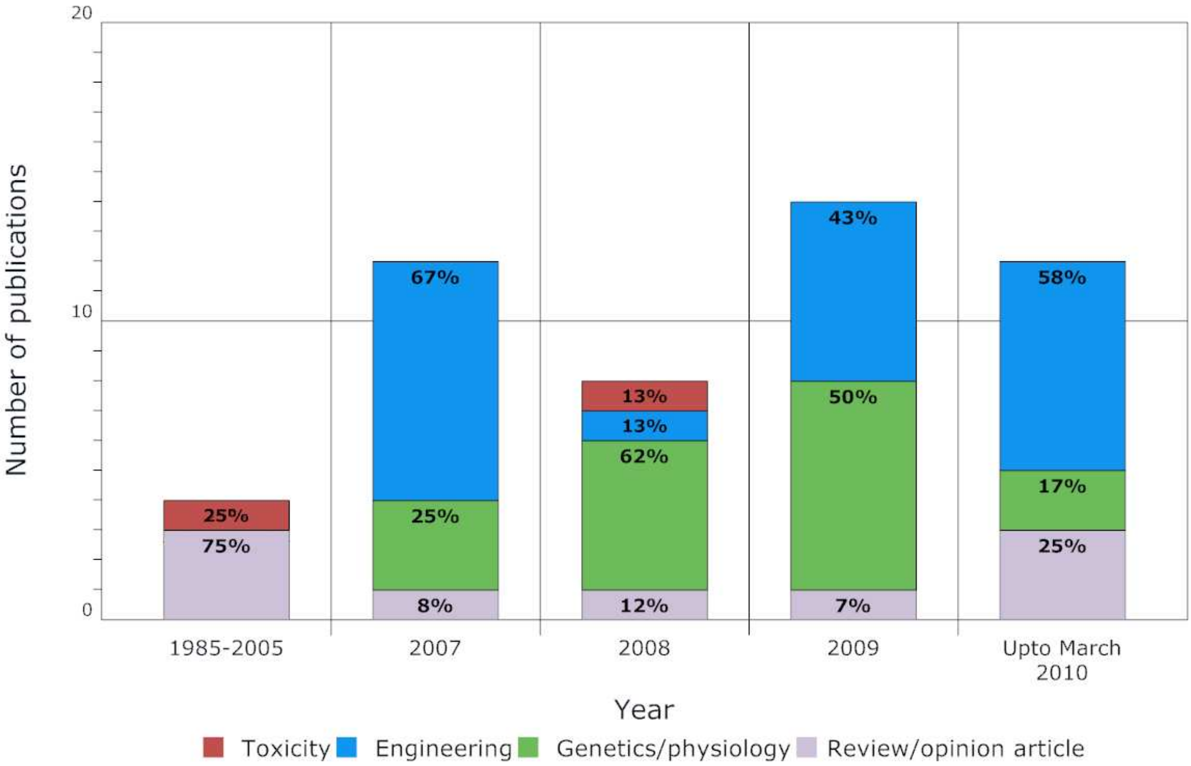
While charting the course of development of policies on biofuels, reviewing the progress of scientific achievements for the corresponding time frame reveals considerable (neglected) progress. Since Jatropha biodiesel has been on the forefront of the research agenda in India, we only consider articles concerning Jatropha based biodiesel production in this paper. In the beginning, the lack of solid information was often claimed by researchers (and politicians) across the world. [12 ,19, 28] After the Biofuel Mission was announced in India, massive research was undertaken on oilseeds, with a special focus on Jatropha. Since peer reviewed journal articles are the worldwide accepted yardstick for originality and scientific rigour, we consider only such articles here. We searched the portal www.sciencedirect.com using the keywords “Jatropha”, “India” and “biodiesel”, the results of which are tabulated in Table 1. Based on the main discipline of the study we further categorized the articles into four broad groups- Toxicity (toxic components of seeds), Engineering (trans-esterification, optimization, thermodynamics, biodiesel plants, life-cycle analysis) Genetics/ physiology (population genetics, DNA markers, root-shoot growth, LAI, water requirements) and Review/ opinion articles (perspectives). Prior to 2007, articles focusing on biofuels essentially reviewed and outlined the significance of oilseeds and / or Jatropha. It is not until 2007 that scientific articles characterizing the growth, physiology, industrial processing and life-cycle analyses of Jatropha systems under Indian or similar conditions were published (Figure 2, Table 1). Resulting from the Biofuel Mission, comprehensive reports covering several aspects of oilseeds were published.[19] While this type of reporting is suitable to back political decisions, scientific communities tend to downplay the significance of such reporting and term them as ‘grey literature’ due to the lack of an independent review process.

As evident from Figure 1, a credible scientific knowledge-base could not have been part of the Indian planning process prior to 2007. Comparing the progress (or regress) of policy vis-à-vis the progress in scientific knowledge / research activities for the time period in question, we observe that policy and science have remained grossly disjunctive. Since policy formulation partly preceded scientific publication, the benefits of the increasing knowledge base could not be used. Thence the observation that India has missed most targets of blending and production is not surprising, as they were formulated without prior estimation of production potentials and markets.

Table 1. List of published articles on Jatropha studies in the Indian context

	Authors	**Reference**
Prior to 2007	Banerji R, Chowdhury AR et al.	Biomass **8(**4): 277-282(1985)
	Banerji R	Biomass Bioenergy **1(**4):247(1991)
	Mujumdar AM, Misar AV	J.Ethnopharmacol **90(**1):11-15 (2004)
	Subramanian KA, Singal SK et al.	Biomass Bioenergy **29 (**1): 65-72 (2005)
2007	Basha SD, Sujatha M.	Euphytica **156**:375–386, (2007)
	Kaushika N, Kumar K et al.	Biomass Bioenergy **31**: 497–502 (2007)
	Bharadwaj A, Tongia R et al.	Curr. Sci., **92**(9): 1234-1241 (2007)
	Devanesan MG, Viruthagiri T et al.	Afr. J. Biotechnol. **6**(21): 2497-2501 (2007)
	Pradeep V,Sharma RP	Renewable Energy, **32(**7): 1136 1154(2007)
	Agarwal D, Agarwal AK	Appl. Therm. Eng. **27**(13): 2314-2323(2007)
	Shah S, Gupta MN	Process Biochemistry, **42**(3): 409-414 (2007)
	Vyas DK, Singh RN	Renewable Energy, **32**(3): 512-517(2007)
	Goud VV, Patwardhan AV et al.	Chem. Eng. Sci. **62** (15): 4065-4076 (2007)
	Namasivayam C, Sangeetha D.	Process Saf. Environ. Prot. **85**(2): 181-184(2007)
	Tiwari AK, Kumar A et al.	Biomass Bioenergy, **31**(8): 569-575 (2007)
	Rathore V, Madras G	Fuel, **86** (17-18): 2650-2659 (2007)
2008	Garnayaka DK, Pradhana RC et al.	Ind. Crops Prod. **27:** 123–129(2008)
	Sunil N, Varaprasada KS et al.	Biomass Bioenergy **32**: 198– 202(2008)
	Ranade, SA, Srivastava AP et al.	Biomass Bioenergy, **32**(6): 533-540(2008)
	Rakshit KD, Darukeshwara J. et al.	Food Chem. Toxicol. **46**(12): 3621-3625(2008)
	R.N. Singh, D.K. Vyas et al.	Renewable Energy **33**(8):18681873(2008)
	Das B, Ravikanth B et al.	Phytochemistry **69**(14): 2639-2641(2008)
	Banapurmath NR, Tewari PG	Renewable Energy **33**(9):19821988(2008)
	Kumar A and Sharma	Ind.Crops Prod.**28** (1):1-10(2008)
2009	Srinivasan S	Renewable Energy **34**:950–954 (2009)
	Basha Sd and Francis G	Plant Science **176**(6):812-823(2009)
	Sahoo PK and Das LM	Fuel **88(**6): 994-999(2009)
	Tatikonda L,Wani SP et al.	Plant Science**176**(4): 505-513(2009)
	Sarin A, Arora R. et al.	Energy**34(**9):1271-1275 (2009)
	Vyas AP, Subrahmanyam N et al.	Fuel **88 (**4):625-628 (2009)
	Mishra DK	Biomass Bioenergy **33**(3): 542 545(2009)
	Sharma DK,Pandey AK et al.	Biomass Bioenergy **33(**1): 159 162(2009)
	Ganapathy T, Murugesan K et al.	Applied Energy **86**(11):2476-2486 (2009)
	Das B, Reddy KR et al.	Bioorg. Med. Chem. L.**19**(1):77-79 (2009)
	Jamil S, Abhilash PC et al.	J.Hazard. Mater. **172** (1): 269-275(2009)
	Sahoo PK, Das LM	Fuel**88**(9):1588-1594(2009)
	Sharma A, Arora A et al.	New Biotechnol.**25 (**Supp1): S248(2009)
	Pradhana RC, Naika SN	Ind.Crops Prod.**29**(2-3): 341-347(2009)
2010	Behera SK, Srivastava P et al.	Biomass Bioenergy **34** :30-41(2010)
	Biswas PK, Pohit S et al.	Energy Policy **38:** 1477–1484(2010)
	Divakara BN, Upadhyaya HD et al.	Applied Energy **8:** 732–742(2010)
	Jindal S, Nandwana BP et al.	Appl.Therm. Eng.**30**(5): 442-448(2010)
	Kumar D, Kumar G et al.	Ultrason.Sonochem.**17**(5): 839-844(2010)
	Jain S and Sharma MP	Renewable Sustainable Energy Reviews **14**:763–771(2010)
	Behera SK, Srivastava P et al.	Agricultural and Forest Meteorology **150**: 307–311(2010)
	Michael S, Zah G et al.	Biomass Bioenergy **34:**347 355(2010)
	Singh A, Reddy MP	Ind. Crops Prod.**31**(2) :209-213(2010)
	Pradhan RC, Naik SN et al.	Applied Energy **87**(3):762-768(2010)
	Sarin A, Arora R et al	Energy **35** (5):2333-2337(2010)
	Puhan S, Saravanan N et al.	Biomass Bioenergy **34**(8): 1079-1088(2010)

*Note: This table gives a comprehensive collection of Jatropha related studies in India and may not be treated as a complete list of published articles



Note: For a detailed list of references of papers used in this figure, please refer to Table 1

Figure 2. Trends in publication of Jatropha biofuel research based in India

The Biofuel Policy seems to have fallen short of utilising the results of the research undertaken over the past couple of years. While the blending targets for both bioethanol and biodiesel have been proposed to a degree of 20% it has not been made mandatory for biodiesel, leaving it ‘recommendatory in the near term’.[22] This recommendation hints at the level of (perceived) uncertainties associated with production capacities. One of the major aims of the National Mission on Biofuels (in 2003), was to arrive at potential yields of oilseeds under different biophysical conditions and to assess the performance (productivity) of these crops grown on degraded lands.[2] The level of uncertainty has neither been eliminated nor diminished in the last seven years since the Biofuel Policy retains the same questions it posed already in 2003. Specific targets set by governments are important benchmarks of exploration of the potential of a technology, in this case, biofuels. The absence of such specific targets or the presence of over ambitious targets, which are dismantled in the short time span of three to four years, neither encourages science nor agriculture. To date, one major reason of the sub-optimal realization of biofuels as an energy alternative in India is the failure of policymakers to provide stable directions for scientific assessments. Most research in India is funded through centralised agencies whereby funds allocated to any field of research (in this case, biofuel research) is largely determined by the direction provided by the union government. The propensity of the government towards increasing scientific capacity is often adjudged in terms of policy moves. Unstable policy therefore adversely affects research by way of unsure means of funding. Investments in scientific research (be they measurements or simulations) can yield appropriate returns only in the event that aims and related assumptions at the conceptualization of a piece of research hold until the completion of the project.

3. Current challenges and adaptive strategies

Summarising available literature and the above sections of the paper, we conclude that there has been severe indecision amongst policymakers compounded by a tendency to retract from previously developed agendas and targets. It is essential in this context to analyse some of the probable issues that have inspired the insipid progress of biofuel production. The plethora of challenges to be faced by biofuel initiatives include crop selection and improvement, land suitable for energy plantations, optimizing industrial processes, developing marketing mechanisms, climate change adaptation, formulating fiscal incentives. In the following sections, we examine the current policy status, implications and plausible strategies for three of the major issues or obstacles in India: land availability and land allocation, climate change and economic framework.

3.1 Land availability and land allocation

Biofuel production in India is based on the use of degraded lands or wastelands that cover 17.45% of the geographical area [29] to avoid competition between food production and (large scale) energy plantations. Increasing discussions about the productive potential of wastelands led to the first national level remote sensing based quantification of wastelands in 2005. The classification of wastelands is mostly based on the underlying causes of land degradation (e.g. salinity, alkalinity, forest degradation, agricultural degradation), into 13 major categories thereby consolidating land-use planning. However, the actual availability of the wastelands e.g. for energy crops has long been debated.[30] It has been argued that the acquisition of wastelands for public projects or private companies is severely challenged by encroachments. Most areas quantified as wastelands by virtue of their biophysical limitations may actually be unavailable because they are in use for habitation, grazing or agricultural production by landless or indigenous people. Land records are often limited in their capacity to either reflect the encroachment or oppose it, thus making it virtually impossible to arrive at realistic estimates of available wasteland areas. [31] However, as the entire national biofuel concept is based on wasteland availability, it is critical to analyse whether or to what degree the assumption holds.

Land acquisition for developmental projects in India has a significant history that needs to be borne in mind while formulating new projects that are largely dependent on wasteland availability. Renowned environmental experts Gadgil and Guha have described several conflicts dating from 1990 to 2002 about water, land, and forests, mostly originating from marginalisation of the poor.[32] One of the most rigorously contested land acquisition attempts has been that of the ‘Sardar Sarovar Project’, a multipurpose river valley project in the Narmada catchment in Central India. The possible displacement of several thousand people due to the flooding of villages led to a nation-wide protest over several years incurring losses of lives, finance and other negative impacts. Other prominent examples of mass protests of land acquisition are the Chipko movement, the Silent Valley project and the Doon valley mining project. The most recent incidence to have come to the fore is in Singur, in the eastern state of West Bengal. An attempt by Tata Motors, one of India’s prominent industrial groups, to build a car factory for the world’s cheapest car – Nano, on fertile state-lands was heavily opposed by social groups, farmers and environmental activists. Large scale unrest resulted in the loss of several lives and more than 300 million USD, culminating in the retreat of Tata Motors.[33] Similar land acquisition issues for iron and steel projects have been documented in the states of Andhra Pradesh and Orissa. [34]

In many instances, the legal ownership and rights of large parcels of land remain unclear. The introduction of the Forest Rights Act [35] is a promising step of the government to protect, legalize and document the rights of indigenous tribal populations by granting them the opportunity of legally owning forested land. Under the new scheme, more than 700,000 titles claimed have been disposed off to tribals up to March 2010. [36] The update of land records and subsequent accurate quantification of available wastelands are therefore vital parameters of the formulation of biofuel policies, and a key indicator of the success of implementation. Also, strategies that involve absolute dependence on wastelands for bioenergy production need to be revisited.

3.2 Biofuels and climate change

India can ill afford to neglect issues related to food security, climate change or greenhouse gas (GHG) emissions, thus making it imperative that any policy on biofuels includes an assessment of potential consequences and impacts. While the issues of net emissions have been briefly mentioned in the Biofuel Policy, threat to food security has been completely ruled out, based on the argument that only non-food feedstock on non-agricultural land shall be utilized for energy production.[22] While it is true that there has been no advocacy for food crops as energy feedstock in India, land use change related to biofuels definitely have the potential to affect the production of food crops and hence challenge food security. The tenets of the policy allows the corporate sector to use contract farming as a means to produce biofuels but there is no specified scheme for restricting / prohibiting such contract farming on productive lands. If wastelands are unavailable or difficult to acquire, it is safe to assume that restraint exercised in using ‘undegraded’ (fertile) land by corporate giants would be minimal. Hence, food security measures definitely need ample attention. Currently net emissions from agriculture constitute 17% of the total emissions of India, while land use change and forestry (LULUCF) have been reported to be a net sink of CO_2 .[37] However, these calculations are based on land use change matrices derived from various national level sources and therefore fail to capture intrinsic regional level land use changes. A high level of associated uncertainty has been reported.[37] While much research is required to address the issue of net emissions from (large scale) plantations of biofuels, it would be important to place mechanisms to track and quantify resultant land use changes and emissions associated with these changes, e.g through contract farming. Such challenges that have been addressed by scientists seem to have escaped the attention of Indian policymakers. [38, 39]

Besides considering the direct and indirect impacts of land use change, resilience with respect to future climate variability / change needs to be built into biofuel policies. Lowered crop productivity under rising temperatures and changes in precipitation patterns has been predicted for wheat, rice and maize in India [40], other crops might be affected in different ways. O’ Brien et al. [41] have developed district level spatial information for India for climate change vulnerability. Amongst several factors, biophysical, socioeconomic and technological attributes were used to calculate a net climate vulnerability index for each district. Further the authors of the study note that the approach helps in identifying locations where policy intervention (e.g. alternative crops, access to irrigation, credit systems.) is most critical. Any short and long-term deviations from expected yields of energy crops will unavoidably affect national energy independence and energy security. Hence, productivities of all relevant energy crops need to be studied under varying management and climate conditions using approaches already developed (as above) or by developing similar tools .The multitude of other aspects related to energy security are beyond the focus of this paper.

3.3 Financial and marketing institutions for biofuels

The success of biofuel production largely depends on economic incentives at farm and industrial levels. The positive financial mechanism that currently support biofuels are 100% foreign equity for biofuel projects, exemption of biodiesel from excise duties and concessional excise duties for bioethanol. In June 2010 the Indian government started to deregulate fuel prices thereby step by step opening competitive markets for fossil and biofuels. [42] A market-determined pricing mechanism may be useful for encouraging biofuels if manufacturers succeed in marketing biofuels at a lower price than fossil petrol / diesel. However, financial incentives that directly impact farmers (e.g. microfinance, loans at low rates of interest) are not binding elements as proposed in the Biofuel Policy. The policy prescribes ‘active involvement’ of rural development banks and agencies (IREDA, NABARD) but fails to specify the extent and level of support to be provided. [22]

Oilseed crops such as Jatropha and Pongamia, which have not been among the traditional crops grown by Indian farmers, need pro-farmer policy interventions. Glaring examples of past follies need to be judiciously analysed while introducing new plants. One of the most prominent examples of hasty introduction and irrevocable consequences thereof is that of Bt Cotton in India which is believed to have played a significant role in the rise of farmer suicides in the country that now stand at an alarming number of 17,000 annual deaths.[43] Many small scale farmers in India are completely dependent on the success of the crop, to repay their often substantial debts / loans. The interest of such farmers has to be adequately protected by policy initiatives. In this context, the Biofuel Policy advocates the introduction of a Minimum Support Price (MSP) for oilseeds and a raise in the Statutory Minimum Price (SMP) for sugarcane, both of which are strong protective measures. However, both MSPs and SMPs have been integral part of agricultural policies of the country for more than three decades and also existed for BtCotton.[43,44] Clearly, this mode of protectionism needs to revisited and strengthened in order to ensure and raise farmers’ interests.

Secondly, while retail marketing is to be undertaken by OMCs, establishing marketing linkages for farmers is vital. India is characterized by a large number of farmers who lack the ability or know-how of selling their produce directly to the local markets.[45] However, India has had several successful experiences with cooperative marketing. One of the most remarkable examples is that of the dairy cooperative marketing system as part of the White Revolution (1970).[46] Other notably successful cooperatives operate for horticulture, floriculture, sugarcane and fish across the country. A similar attempt has great potential of success with respect to biofuels and initial steps towards such an exercise are underway through the Rural Biofuel Growers Association, Karnataka.[47] Enabling farmers to sell their produce directly at local markets through an organised sectoral approach not only can increase farmers’ confidence in new crops but also improves livelihood and income generation.

4. Conclusions

We conclude that at its current state, biofuels remain an “underexplored” area of renewable energy and deserve more stringent and conclusive efforts, both in terms of scientific studies as well as policy initiatives. The course of biofuel development in the country demonstrates a zigzag pattern. For policy to function as an instrument of biofuel development in India, stability in directives and legislation seems to be essential. Frequent vacillations in targets and objectives are likely to slow down or hamper India's path to sustainable energy. There is large scope to replicate/ modify aspects of previous processes related to other forms of renewable energies, marketing systems and crop introduction. Additionally, biofuel development in the country can avail of latecomer advantages such as established technologies, strong cooperation with countries like Brazil that have vast experience in the biofuel industry and best practices for agriculture that have been formed for energy production.

Considerable investments already made in the research and development of biofuels should be harnessed as direct inputs to planning by improving the linkages between scientific outputs and policy formulation. Critical knowledge gaps in all aspects of biofuel production and use need to be addressed in the near future. While it is encouraging that research in second or third generation biofuels is already underway, it seems to be a matter of decades before they can be fully established. Thus, a hasty writing-off of first generation biofuels ignores their social, economic and environmental potential on the way to reduce fossil fuel dependencies. With its rise in economic capacities and fast increasing energy demands, India cannot afford to overlook or 'under-implement' the existing potential of biofuels, rather strengthen the role of biofuels for sustainable energy independence.

Acknowledgements

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References

1. Ghosh S, Future demand of petroleum products in India. *Energy Policy* **34** pp 2032-2037 (2006).
2. Report of the Committee on Development of Bio-Fuel, Planning Commission, Government of India, New Delhi, (2003).
3. Singh SK, India Bio-fuels Annual, Global Agriculture Information Network, GAIN Report Number IN7047, USDA Foreign Agricultural Service, New Delhi, (2007).
4. Annual Report, Ministry of Petroleum and Natural Gas, Government of India, New Delhi, (2008-2009).
5. Annual Report, Ministry of New and Renewable Energy, Government of India, New Delhi, (2009-2010). Available at http://mnre.gov.in/annualreport/2009-10EN/index.htm [Accessed May 19, 2010].

6. The Working Group Report on Road Transport for the Eleventh Five Year Plan, Planning Commission, Government of India, New Delhi, (2007). Available at http://www.planningcommission.nic.in/plans/planrel/11thf.htm[Accessed May 19, 2010].

7. Economic Survey, Ministry of Finance, Government of India, New Delhi, (2009-2010). Available at http://indiabudget.nic.in/es2009-10/esmain.htm, [Accessed May 19, 2010].

8. The State of Food and Agriculture, Biofuels: prospects, risks and opportunities, ISBN: 978-92-5-105980-7, Communication Division, FAO (2008).

9. Brittaine R and Lutaladio N, Jatropha: A Smallholder Bioenergy Crop, The Potential for Pro-Poor Development, Integrated Crop Management 8, FAO, Rome (2010).

10. Bharadwaj A, Tongia R and Arunachalam VS, Scoping technology options for India’s oil security: Part I –ethanol for petrol. *Curr. Sci.* **92**(8) pp 1071-1077 (2007).

11. Das S and Priess JA, Biofuel options for India- perspectives on land availability, land management and land-use change. *J. Biobased Mater. Bioenergy* Accepted (2010).

12. Lapola DM, Priess JA and Bondeau A, Modeling the land requirements and potential productivity of sugarcane and Jatropha in Brazil and India using the LPJmL dynamic global vegetation mode*.* *Biomass Bioenergy*, **33**(8) pp 1087-1095 (2009).

13. Prasad S, Singh A, Jain N and Joshi HC, Ethanol Production from Sweet Sorghum syrup for utilization as automotive fuel in India. *Energy Fuels* **21** (4) pp 2415–2420 (2007) DOI: 10.1021/ef060328z.

14. Mukta N, Murthy IYLN and Sripal P, Variability assessment in Pongamia pinnata (L.) Pierre germplasm for biodiesel traits. *Ind. Crops Prod.* **(29)** pp 536-540(2009).

15. Notification, Ministry of Petroleum & Natural Gas, F.No: P-45018/28/2000-CC, Government of India, New Delhi, (2004).

16. Essential Commodities Act,1955, Gazette of India, Government of India

17. Sugar Cess Act, 1982, Act No.3 of 1982, Gazette of India, Government of India

18. Sugar (Control) Order, 1966, Gazette of India, Government of India

19. Punia MS, 5th R&D Report on Tree Borne Oilseeds (2009-2010) Edited by Kureel RS, Kumar V and Pandey A, National Oilseeds and Vegetable Oil Development Board, Ministry of Agriculture, Government of India, Gurgaon (2010). Available at http://www.novodboard.com/ [Accessed June 7, 2010].

20. Maes WH, Trabucco A, Achten WMJ and Muys B, Climatic growing conditions of Jatropha curcas L. *Biomass Bioenergy* **(33)** pp 1481-1485(2009).

21. Sharma AB, Draft National Bio-fuel Policy sent for approval, The Financial Express, (2008). India. Available at http://www.financialexpress.com, [Accessed May 19, 2010].

22. National Policy on Biofuels, Ministry of New and Renewable Energy, Government of India, New Delhi (2009).

23. Expert Committee, Draft Report on Integrated Energy Policy, Planning Commission, Government of India, New Delhi, (2005).

24. Expert Committee, Report on Integrated Energy Policy. Planning Commission, Government of India, New Delhi, (2006).

25. XI Plan Proposals for New and Renewable Energy, Ministry of New and Renewable Energy, Government of India, New Delhi, (2006).

26. Bio-diesel Purchase Policy, Ministry of Petroleum and Natural Gas, Government of India, New Delhi, (2005).

27. The Economic Times, 'Biodiesel demand, ban come together' 2009. Kolkata. Available at http://economictimes.indiatimes.com [Accessed May 19, 2010].

28. Jongschaap REE, Corre WJ, Bindraban, PS and Bradenburg WA, Claims and Facts on Jatropha curcas L. Report 158.Plant Research International B.V., Wageningan, The Netherlands (2007).

29. Wasteland Atlas of India, Ministry of Rural Development (New Delhi) and National Remote Sensing Agency (Hyderabad), Government of India (2005).

30. Balooni K and Singh K, Prospects and problems of afforestation of wastelands in India: A synthesis of macro- and micro- perspectives. *Geoforum* **38** (6) pp 1276-1289 (2007).

31. Burns T, Land administration: indicators of successes, future challenges, Agriculture and Rural Development Discussion Paper No. 37, World Bank (2007).

32. Gadgil M and Guha R, Ecological Conflicts and the Environmental Movement in India. *Development and Change* **25**, pp 101-136, (1994).

33. Srivastava M, Why Indian farmers are fighting Tata's Nano? Business Week, New Delhi, (August 27, 2008).

34. Balagopal K, Land unrest in Andhra Pradesh-II Impact of grants to industries, *Economic and Political Weekly*. September 29 (2007).

35. The Scheduled Tribes and other Traditional Forest Dwellers (Recognition of Forest Rights), Act, Gazette of India, No: DL- (N) 04/0007/2006-08, Ministry of Law and Justice, Government of India, New Delhi (2006).
36. Status report on implementation of Scheduled Tribes and other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006 for the period ending 31st March, 2010, Ministry of Tribal Affairs, Government of India, New Delhi (2010). Available at http://www.fra.org.in/index.htm [Accessed June 7, 2010].
37. India: Greenhouse gas emissions 2007, INCCA Indian National Network for Climate Change Assessment, Ministry of Environment and Forests, Government of India (2010).
38. Fargione J, Hill J, Tilman D, Polasky S and Hawthrone P, Land Clearing and the Biofuel Carbon Debt, *Science*. **319** pp 1235-1238, (2008).
39. Lapola DM, Schaldach R, Alcamo J, Bondeau A, Koch J, Koelking C et al, Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proc. Natl. Acad. Sci. U.S.A., Early Ed.*, **107** pp 3388-93, (2010).
40. Lal M, Singh KK, Rathore LS, Srinivasan G and Saseendran SA, Vulnerability of rice and wheat yields in NW India to future changes in climate. *Agriculture and Forest Meteorology* **89,** pp 101-114 (1998).
41. O' Brien K, Leichenko R, Kelkar U, Venema H, Aandahl G, Tompkins H et al., Mappine vulnerability to multiple stressors: climate change and globalization in India. *Global Environmental Change*, **14** pp 303-313 (2004).
42. Press Information Bureau, Petrol Prices Deregulated, June 25, 2010, Ministry of Petroleum & Natural Gas, Government of India, New Delhi Available at http://pib.nic.in/release/release.asp?relid=62834 [Accessed August 30, 2010].
43. Report of Fact Finding Team on Vidarbha, Regional Disparities and Rural Distress in Maharashtra with particular reference to Vidarbha, Planning Commission, Government of India, New Delhi (2006).
44. Agarwal NL, Price Policy and Parity Issues in *Agricultural Prices and Marketing in India*, Mittal Publication, New Delhi (1986).
45. Singh DV, Role of Agricultural Co-operative marketing societies in marketing of fruits and vegetables: a case study of successful society in Himachal Pradesh in *Indian Agricultural Marketing- emerging trends and perspectives* , Edited by Jagdish Prasad and Arbind Prasad, Mittal Publications, New Delhi (1995).

46. Bellur VV, Singh SP, Chaganti R and Chaganti R, The White Revolution- how Amul brought milk to India. *Long Range Planning*, **23** (6) pp 71-79 (1990).
47. Gowda KN, Rebuilding the confidence of farmers- experiences of an innovative extension project. *Indian Research Journal of Extension Education*, **9**(3) pp 6 - 8 (2009).

4 Study area and the modeling framework “SITE - Karnataka”

4.1 Study Area

The study was conducted for the state of Karnataka (11.31°-18.45° N; 74.12°-78.40° E) situated in southern India (Figure 1). Karnataka is the eighth largest state in India in terms of area, covering 191,791 km^2. The state extends 750 km from north to south and 400 km from east to west, and is surrounded by the states Maharashtra and Goa on the north and north-west, by the Arabian Sea on the west, Tamil Nadu and Kerala in the south and Andhra Pradesh in the east. Bangalore, situated in the south of the state is the capital, which has developed into India’s largest and most thriving ‘software city’.

Figure 1 Location of the state of Karnataka in India

4.1.1 Physiography and climate

Karnataka forms part of two major macro regions of India- the Deccan plateau and the Coastal Plains. Topographically the state covers mountains, plateaus, hills and coastal areas. In terms of physiography, the region may be divided into three zones, all forming part of the Deccan plateau- Northern, Central and Southern Plateau area. The Northern

Karnataka plateau is mostly a treeless expanse with elevation ranging from 300-600 meters. The Central Karnataka Plateau represents the transitional area between the Northern plateau and the Southern plateau with most of the area being part of the large Tungabhadra river basin. The Southern plateau has an average elevation of 600-900 meters and is part of the Cauvery basin. The western part of the Southern Plateau is flanked by the Western Ghats forming a divide between the coastal and the plateau region. The coastal region of the state lies between the edge of the Western Ghats on the east and the Arabian Sea on the west. This region has two districts with a rugged terrain full of rivers, creeks, waterfalls, peaks and ranges. The coast line of Karnataka stretches about 260 kilometers from north to south (Bhatt and Bhargava 2006).

The average annual rainfall in the region is 1189 mm with large variations ranging from 300mm / year (north and central regions) to 2500 mm/year (coastal zone and the Western Ghats) across the state. Common soil types of the state are red and black with loams or sandy texture. Lateritic soils, coastal soils and forest soils are also found (Department of Economics and Statistics 2007).

4.1.2 Land use

Almost 53% of the area is used for agriculture while 16% is under forests (Directorate of Economics and Statistics 2011). The state has ample mineral resources such as high grade iron ore, copper, manganese and bauxite. Non-agricultural land includes urban areas, infrastructure (such as roads and railways), natural and man-made lakes and mines (Purushothaman and Kashyap 2010). 7% of the area is covered by wastelands (NRSA and DOLR, 2005). The agricultural sector still provides almost 56% of the jobs and is characterised by diverse crops and cropping systems, subject to several structural changes over the last four decades (Purushothaman and Kashyap 2010; Planning and Statistics Department 2006). Net sown area is increasing at the expense of fallow land. Area under oilseeds, maize and pulses has increased due to several technology development programmes such as the “National Oilseeds Mission” (Purushothaman and Kashyap 2010). Agriculture is dependent on the occurrence of monsoon rains and only 25-30% of the agricultural area is irrigated (Planning and Statistics Department 2006). Urbanization is one of the main drivers of land use change in the state, with the capital city of Bangalore having grown tremendously in the last two decades and other cities also having experienced expansion.

4.1.3 Demography

The population of Karnataka was 53 million in 2000 (Census of India 2001) with a growth rate of 1.7% per year. Population structure shows that the state has a large fraction of working population (about 60%), followed by “young population” (< 14 years) which constitutes 32% while only 8% of the population is “old” (> 60 years) (Planning Commission 2007). About 66% of the population lives in rural areas (Planning and Statistics Department 2006), but the proportion of the population living in urban areas is higher than in the other Indian states. There are 237 towns and about 30,000 villages in the state. Bangalore, the state capital, alone accounts for 24% of the urban population of the state and attracts most of the migrants. About 87% of migrants move between or within districts, while only 12.5 % of migrants come from other states. The state reported 67% literacy in 2001, (marginally higher than the national average), but with clear rural-urban and gender gaps in literacy levels.

4.1.4 Economy

Karnataka is the country’s fourth fastest growing state with a growth rate of 5.7% p.a (1999-2006). The economy of Karnataka was predominantly agrarian in character in earlier decades, but changed significantly since 1980-81.The share of the primary sector in the state GDP (Gross Domestic Product) dropped from 60% in 1956 to 18% in 2006-07. Although agriculture remained the largest sub-sector in terms of jobs, it has the lowest growth rate (1.4% p.a). Manufacturing, banking & insurance, real estate and business as well as the service sector now contribute much more to the economy, all showing growth rates of more than 9% per annum. Although the population employed in the agricultural sector did not decrease in the last decade, its contribution to the state GDP almost halved, indicating that in this sector the economic output per capita is low and decreasing compared to other sectors. Agricultural productivity has not increased significantly in the state and the average size of farm land has decreased (> 70% rural households own land less than 1 hectare land). The focus of policy makers in Karnataka is therefore to achieve a better sectoral output-employment ratio (Karnataka State Planning Board 2008).

4.2 A generic framework for land-use modelling- SITE[3]

Abstract

In this paper we present the generic modelling system SITE (SImulation of Terrestrial Environments), a software package to develop and apply models simulating regional land-use dynamics. The modelling system includes (i) a framework managing the model generics and (ii) code templates for the development of rule-based land-use and land-cover change (LUCC) models. SITE comprises built-in methods for e.g. map-comparison, model optimisation and environmental scenarios.

Keywords: Integrated framework; Map comparison; Genetic algorithm; Cellular automata; Land-use model

Software availability

Name of Software: SITE – SImulation of Terrestrial Environments

Developers: Mimler M., Priess J.A., Schweitzer C., Das S.

Contact address:

Helmholtz Centre for Environmental Research- UFZ

Department Computational Landscape Ecology,

Permoserstrasse 15, D-04318 Leipzig, Germany.

christian.schweitzer@ufz.de

Year first available: 2007

Hardware required: PC

Software required: Python 2.3, MySQL, Win32

Program language: C++, Python

Program size: 6 MB (Windows installer – including example Python scripts, example data)

Availability: free (upon request)

Software Homepage: http://www.ufz.de/index.php?en=19080

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[3] Schweitzer C, Priess JA and Das S, A generic framework for land-use modelling- SITE, *Environmental Modelling and Software*, *accepted February 2011*

1. Introduction

Modelling land-use, land-cover and environmental change is a field of increasing importance and a broad range of models has been developed for this discipline (Haase and Schwarz 2009, Schaldach and Priess 2008). For numerous modelling approaches the development or adaptation of the appropriate software is a crucial step for successfully answering research questions, a step strongly constrained by financial resources and time available for model development. In order to overcome this problem, researchers often tend to modify existing or create new software, which may be functional, but often not very intuitive in terms of applicability and transferability. For users with little or no programming skills the application of such models is difficult and a reason for little or no interest in those approaches. To address this problem, modelling frameworks try to bridge this gap by providing convenient user interfaces that communicate with the complex software generics. A ‘framework’, as it is used in our context, is defined as generic software that can be reused for custom applications, with the advantage that the software can be developed several times faster than without the framework (Fayad et al. 1999). In this manuscript we present the key features of the SITE framework and show an implementation example for a rule-based land-use model, in which land allocation is based on a multi-criteria analysis and regional preferences and constraints.

2. Modelling system

From the beginning, a core objective of the SITE developers was to facilitate maintenance and reuse of components within the entire software package, as the tool was intended to be applicable in more than one case study (Mimler and Priess 2008). SITE consists of two main parts (i) the system domain (SD), which includes optimized methods, procedures and essential tools for the modelling process, implemented in C++ and (ii) the application domain (AD), which is a Python interface designed for the implementation of modelling routines and decision rules to address land-use modelling issues (Fig. 1).

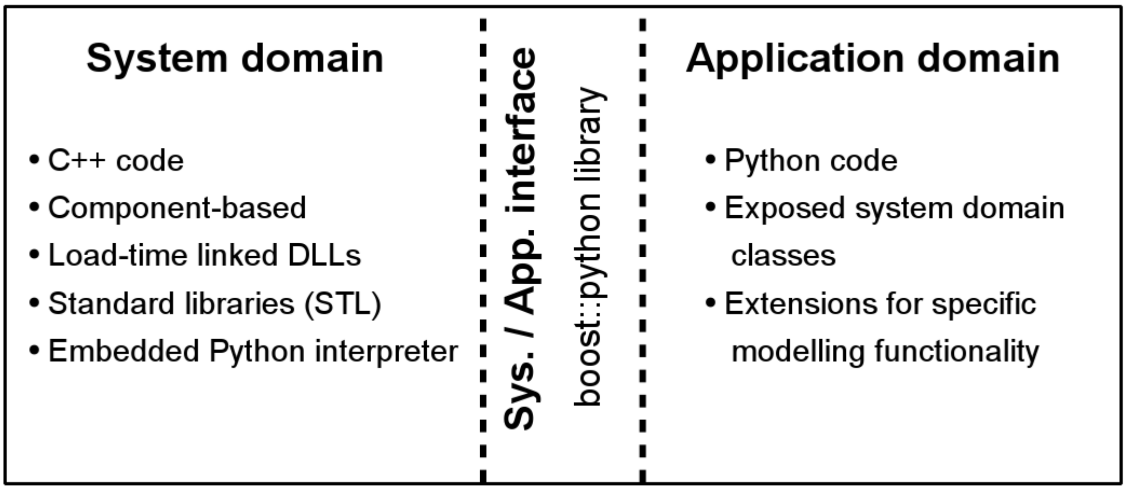

Fig. 1. Software aspects of the system and application domain. The system domain includes generic software components that handle and execute models, while case-study specific code is located in the application domain (Mimler 2007).

SITE currently uses the concept of cellular automata (CA) models, which are defined as spatially and temporary discrete systems consisting of cells arranged in a lattice of *n* (>1) dimensions. The cells represent a discrete moment in time and change their current state due to a set of rules, mostly deterministically formulated in a local transition function taking into account the current state of neighbouring cells (Schiff 2010). Theoretically it is possible to represent land-use decisions in SITE with spatial non-CA models such as multi-agent systems (Berger et al. 2006) or CLUE-type regression equations (Veldkamp and Fresco 1996), although in the latter case much of the flexibility of rule-based approaches would be lost.

SITE has been applied for three case studies addressing different land-use related research questions. The first application investigated the land use dynamics of tropical rainforest margins in Sulawesi, Indonesia (Priess et al.2007). The second and third case studies, which are under advanced stages of development, analyse the impacts of LUCC on water resources and impacts of wildfire in Mongolia (Priess et al.2010, Schweitzer and Priess 2010) and the potential of bioenergy crops and food-fuel conflicts in South-India (Das et al.2010) respectively. Figure 2 presents a generalized view of the SITE components used in previous studies. A detailed description of the software implementation is given in Mimler (2007)and Mimler and Priess(2008).

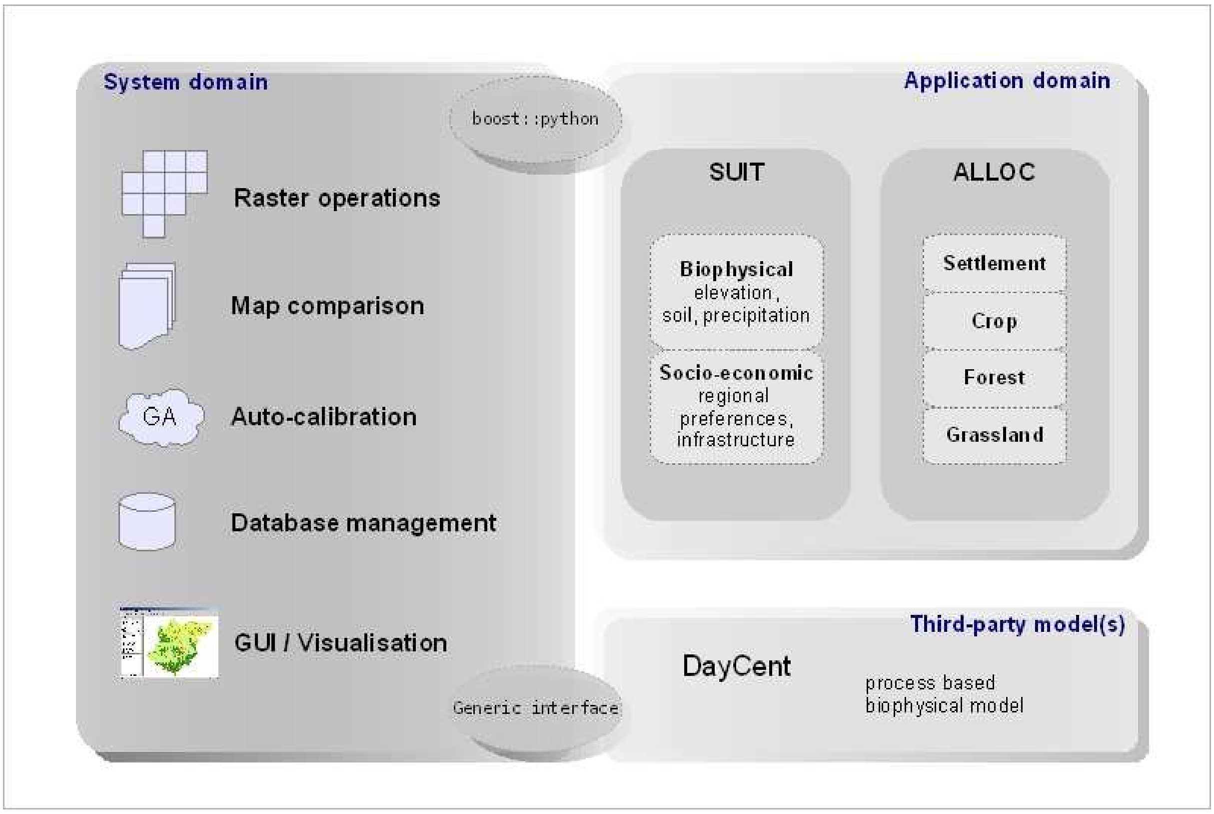

Fig. 2. Main components of the SITE modelling system. The system domain represents the core engine of the framework, providing necessary modelling functionalities. Within the application domain user-specific decicion rules are developed. A generic interface provides the possibility to link third-party models. Note that the external model DayCent is not a standard component delivered with the SITE software.

2.1 System domain

The SD comprises the generic aspects in SITE and handles the grid system, cell-attributes, cell-/cluster-iterators and other components. The latter integrates methods for model testing and calibration using map comparison algorithms, distance and neighbourhood operations and clustering procedures. SITE includes a graphical user interface (GUI), which supports the execution of land-use models and visualisation of simulation results. A 3-D view offers the possibility to freely assign (and combine) x/y- and z-axis with cell attributes (e.g. ‘crop x’ and ‘distance to market’). Additionally, a command line is available for consecutive runs, e.g. during sensitivity analysis or model calibration.

The coupling of third party models is enhanced by providing a generic interface that allows the implementation of feedbacks between different framework components and different processes, which are considered an essential aspect of integrated approaches (Verburg 2006). In recent studies we linked the biophysical model DayCent (Parton et al.1998), to simulate carbon dynamics, biomass and crop yields (Priess et al.2007, Priess et al.2010, Schweitzer and Priess 2010, Das et al.2010). The integration is based on a client-server solution in which SITE acts as client distributing modelling jobs (= annual simulations for cells or clusters) to the DayCent server. The interface can configure and execute jobs and handle incoming simulation results.

2.2 Application domain

The AD is designed as a scripting interface to access functionalities and methods implemented in the SD. Setting up a new model in the AD requires minimally the use of the two functions *Initialize()* and *SimulationStep()*, in which the model’s scheduling has to be included. The sequence of sub-module calls reflects the model’s scheduling hierarchy. Potential users benefit from the existing case studies, which already provide a set of sub-modules, in different Python files that can be modified to cover new research objectives. Figure 3 presents a generalized scheduling structure that can be executed by SITE, based on the ones we use in current studies.

```
def Initialize(grid):
      # initialize the grid system
      grid.SetGeoreference(x,y,resolution)
      # calculate cluster-layer
        ConfigClusterLayers()
      # count neighbour cells for all lu/lc-types
      NghbCount()
      # calculate distances
      CalcDistances()
      # run DayCent to calculate potential yields
      DayCent.CalcPotYields()


def SimulationStep(grid,step):

      # perform suitability assessment
      CalcSuitabilities()
      # allocate lu/lc
      Settlments.Allocate()
      Crops.Allocate()
      Forest.Allocate()
      Grassland.Allocate()
      # run DayCent to calculate current yield
      DayCent.CalcCrntYields()
```

Fig. 3. Example of a main Python file used in SITE. The function *Initialize()* generates the simualtion grid and intialises all attribute values, including operations required for further model simulation. *SimulationStep()* includes the model’s scheduling that will be repeated every time step.

2.2.1 Initialization

Initialize() first generates the simulation grid, followed by operations setting the cells to an initial status with cell-specific attribute values (e.g. count the number of neighbour cells, perform distance calculations etc.). To reflect identical or almost identical biophysical properties of grid cells and simultaneously reduce the high runtime requirements of DayCent, the cluster algorithm of SITE groups cells of the same LUCC type to derive units of uniform geographical and biophysical properties, comparable to hydrological response units - HRUs, a concept often applied in hydrological studies (Flügel 1995). Cluster definitions (and resulting cluster size) usually depend on data quality, research question and may apply any cell attribute present in the case study.

2.2.2 Simulation step

In *SimulationStep()*, land-use decisions are simulated typically once a year following a three step process: (i) suitability analysis based on a multi-criteria approach, (ii) execution of allocation modules, that are driven by the demand for commodities (e.g. space for housing, food, wood) and (iii) calculation of plant growth, biomass and trace gas fluxes both for natural vegetation and agro-ecosystems, currently using DayCent.

Suitability analysis

The task of the suitability module (SUIT) is the generation of dynamic suitability maps for each of the LUCC classes expected to change. SUIT employs a multi-criteria approach which is transparent, flexible and has the capacity to integrate large amounts of heterogeneous data (Eastman et al.1995). SUIT is subdivided into functions computing biophysical suitabilities (e.g. elevation, terrain slope, soil fertility, precipitation) and suitabilities based on socio-economic factors, if necessary (e.g. gross margins, accessibility, farmers’ preferences). All suitability values are normalised to a range between 0 (not suitable) and 1 (perfectly suitable) following the equation:

$$s_{kl} = \underbrace{\left(w_B \sum_{i=1}^{m} \beta_i s_{Bikl} + w_E \sum_{i=1}^{n} \varepsilon_i s_{Eikl} \right)}_{\text{suitability}} \cdot \underbrace{\prod_{j=1}^{o} c_{Bjkl} \prod_{j=1}^{p} c_{Ejkl}}_{\text{constraints}} \qquad (1)$$

with $w_B + w_E = 1;\ \sum_{i=1}^{m} \beta_i = 1;\ \sum_{i=1}^{n} \varepsilon_i = 1;\ s_{Bikl}, s_{Eikl}, c_{Bjkl}, c_{Ejkl} \in [0, 1]$

The calculation of the overall suitability value s_{kl} for each grid cell k and land-use type l consists of two terms. In first part (suitability) the mean value of the partial suitabilities s_{Bikl} for biophysical and s_{Eikl} for socio-economic criteria are weighted using the partial weights β_i / ε_i, where *m/n* represent the total number of criteria included. The advantage of this approach is the possibility to assign one weighting factor for the entirety of the biophysical (w_B) versus the socio-economic suitability components (w_E). Constraints may reduce the overall suitabilities by applying *o/p* constraints c_{Bjkl}/c_{Eikl} to each class or land-use type. Constraints can be used to simulate limitations or restrictions, e.g. land-use in protected areas, steep terrain, etc. The determination of reasonable suitability factors usually involves a preliminary selection of the competing factors, studying empirical information and by the application of a correlation analysis. Criteria weights are derived from model calibration or can be achieved using approaches like the Analytical Hierarchy Process (Saaty 1980, Chen et al.2010).

Land allocation

The set of maps calculated by SUIT serves as the basis for the land-use change decisions implemented in the allocation module (ALLOC). ALLOC includes a set of modules allocating settlements, crops, forest etc. The hierarchy in ALLOC follows the sequence of regional land allocation preferences, and may differ between case studies. Rules for the allocation are usually implemented in the form of a decision tree. In current studies the allocation of settlement areas has the highest priority and is therefore executed first. At the next hierarchy level demand for agricultural products steers the allocation of different crop types and so on. Next we provide an example for a demand-driven competition for land between different crops. If a cell is selected as change-candidate (e.g. current land use is low-yielding or unprofitable), the algorithm identifies the most suitable crop for this cell. In the crop module, decision criteria are evaluated consecutively, starting with the crop-type with the largest difference between current production and demand. Note that the algorithm switches between crops to avoid allocating the most favourable cells to just one crop. If current crop production is higher than the demand, cells are either converted to other land uses, or to fallow if below a productivity limit (defined as < x % of mean yield in a region or administrative unit). Allocation criteria vary between case studies, but are always based on crop-specific SUIT results (ranking of all cells with a suitability > 0), using actual productivity, profitability or potential productivity if a certain crop has never been grown in a cell. Furthermore, ALLOC employs a conversion-matrix, which bars conversions that do not occur in the study area (e.g. conversion of agricultural land to forest or urban to village land).

Simulation of plant growth

In a last step, DayCent calculates carbon and nitrogen dynamics of plants and soils within the respective clusters. Results are fed back to the SUIT and ALLOC modules, updating dynamic attributes (e.g. carbon, nitrogen, biomass, yields), and thus informing subsequent land-use decisions.

2.3 Validation methods and automated calibration

The SD includes model calibration and model validation components based on a map comparison toolkit for categorical maps, comprising spatial statistics like Kappa (Pontius 2002), Figure of Merit (Pontius et al.2008) and moving window approaches (Kuhnert et al.2005). All implemented algorithms are suitable to assess the similarity of simulated maps (model output) against a reference map derived from independent sources, using identical sets of LUCC classes.

An automated optimization algorithm is included to identify the best parameter values using a genetic algorithm (GA) (Wall 1996), which has been shown to be an efficient optimization tool in recent studies (Holzkämper and Seppelt 2007). The GA works through the *n*-dimensional search space, and assesses the optimal parameter setting (*n:* number of calibration parameters). Note that parameters used in DayCent and parameters used in the AD can be calibrated simultaneously, to account for the fact that yield levels may have a strong impact on both land-use areas and patterns.

2.4 Environmental scenarios

A major objective in many land-use studies is to assess potential consequences of future land-use options, or development pathways (Alcamo et al.2008). SITE provides structures to simulate and analyse quantitative scenarios driven by socio-economic and biophysical changes. The GUI provides an interactive scenario dialog-box, an additional feature through which users can directly edit and change scenario data e.g. to respond to implausible land-use changes discovered during simulations, and re-run the scenarios.

3. Conclusions

In this paper we presented the SITE modelling framework, which is designed for spatially explicit regional land-use modelling. SITE uses modular software concepts to enable users to focus on advancing the state of the art of land-use modelling. The GUI supports the execution and analysis of land-use models, facilitating the active participation of researchers / stakeholders / policymakers with limited capacity or prior experience in modelling. The built-in flexibility and adaptability contributes to shorten the process of identifying or developing adequate model constellations, which is usually a very challenging task, especially if the research is embedded in a multi-stakeholder setting (Sterk et al.2009) with potentially conflicting interests. In this context, SITE supports the increasing number of (participatory) land-use studies, providing fast iterators available for cell, cluster and neighbourhood analyses, without ignoring important system feedbacks or oversimplifying the complexity of terrestrial systems. Time-consuming calculations can be parallelized making use of the built-in client-server solution.

The use of a scripting language for the AD offers a large degree of freedom for model developers with respect to complexity, for example to simulate land-use decisions, or competition for land, processes typically requiring multiple variables and structures to characterize them. Additionally, this type of programming language provides a user-friendly facility to interact with the complex software generics, advantages also seen by other environmental modelling groups (Kraft et al. 2011).

The next steps include an improved integration of wildfire simulations, for which first results have already been published (Schweitzer and Priess 2010). In this context it is also envisaged implement a standard model interface such as the Open Modeling Interface and Environment (OpenMI 2009) and migrate to a platform independent and open source version.

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References

Alcamo, J., Kok, K., Busch, G., Priess, J., 2008. Chapter four. Searching for the future of land: Scenarios from the local to global scale. In: Alcamo, J. (Ed.), Environmental Futures - The Practice of Environmental Scenario Analysis. Vol. Volume 2. Elsevier, pp. 67–103.

Berger, T., Schreinemachers, P., Woelcke, J., Apr. 2006. Multi-agent simulation for the targeting of development policies in less-favored areas. Agricultural Systems 88 (1), 28–43.

Chen, Y., Yu, J., Khan, S., Dec. 2010. Spatial sensitivity analysis of multi-criteria weights in gis-based land suitability evaluation. Environmental Modelling & Software 25 (12), 1582–1591.

Das, S., Priess, J., Schweitzer, C., 2010. Biofuel options for India - perspectives on land availability, land management and land-use change. Journal of Biobased Materials and and Bioenergy 4, 243–255.

Eastman, J., Weigen, J., Kyem, P., Toledano, J., 1995. Raster procedures for multi-criteria / multi-objective decisions. Photogrammetric Engineering and Remote Sensing 61 (5), 539–547.

Fayad, M., Schmidt, D., Johnson, R., Sep. 1999. Building Application Frameworks: Object-Oriented Foundations of Framework Design, Wiley Computer Publishing.

Flügel, W. A., 1995. Delineating hydrological response units by geographical information system analyses for regional hydrological modelling using prms/mms in the drainage basin of the river Bröl, Germany. Hydrological Processes 9 (3-4), 423–436.

Haase, D., Schwarz, N., 2009. Simulation Models on Human - Nature Interactions in Urban Landscapes: A review including Spatial Economics, System Dynamics, Cellular Automata and Agent-based Approaches. Living Reviews in Landscape Research 3.

Holzkämper, A., Seppelt, R., 2007. A generic tool for optimising land-use patterns and landscape structures. Environmental Modelling & Software 22 (12), 1801 – 1804.

Kraft, P., Vaché, K. B., Frede, H.-G., Breuer, L., 2011. A hydrological programming language extension for integrated catchment models. Environmental Modelling & Software, In Press.

Kuhnert, M., Voinov, A., Seppelt, R., 2005. Comparing raster map comparison algorithms for spatial modeling and analysis. Photogrammetric Engineering & Remote Sensing 71(8), 975–984.

Mimler, M., 2007. Design, implementation and application of a generic framework for integrated regional land-use modeling. Ph.D. thesis, University of Kassel, Germany.

Mimler, M., Priess, J. A., 2008. Design and implementation of a generic modeling framework - a platform for integrated land use modeling. CESR-Paper 2. Kassel University press.

OpenMI, 2009. The open-mi life project website. http://www.openmi-life.org/.

Parton, W. J., Hartman, M., Ojima, D., Schimel, D., 1998. Daycent and its land surface submodel: description and testing. Global and Planetary Change 19, 35–48.

Pontius, R., 2002. Statistical methods to partition effects of quantity and location during comparison of categorial maps at multiple resolutions. Photogrammetric Engineering & Remote Sensing 68, 1041–1049.

Pontius, R. B., Wideke, Castella, J.-C., Clarke, K., de Nijs, T., Dietzel, C., Duan, Z., Fotsing, E., Goldstein, N., Kok, K., Koomen, E., Lippitt, C., McConnell, W., Mohd Sood, A., Pijanowski, B., Pithadia, S., Sweeney, S., Trung, T., Veldkamp, A., Verburg, P., Mar. 2008. Comparing the input, output, and validation maps for several models of land change. The Annals of Regional Science 42 (1), 11–37.

Priess, J., Schweitzer, C., Wimmer, F., Batkhishig, O., Mimler, M., 2010. The consequences of land-use change and water demands in Central Mongolia - an assessment based on regional land-use policies. Land Use Policy 28, 4–10.

Priess, J. A., Mimler, M., Klein, A.-M., Schwarze, S., Tscharntke, T., Steffan-Dewenter, I., 2007. Linking deforestation scenarios to pollination services and economic returns in coffee agroforestry systems. Ecological Applications 17 (2), 407–417.

Saaty, T. L., 1980. The Analytical Hierarchy Process. McGraw Hill.

Schaldach, R., Priess, J., 2008. Integrated models of the land system: A review of modelling approaches on the regional to global scale. Living Reviews in Landscape Research 2 (1).

Schiff, J. L., 2010. Cellular Automata: A Discrete View of the World. Wiley Computer Publishing.

Schweitzer, C., Priess, J., 2010. Linking wildfire behaviour and land-use modelling in Northern Mongolia. Proceedings of the 2010 International Congress on Environmental Modelling and Software, Modelling for Environments Sake, Ottawa, Canada.

Sterk, B., Leeuwis, C., van Ittersum, M., Feb. 2009. Land use models in complex societal problem solving: Plug and play or networking? Environmental Modelling & Software 24 (2), 165–172.

Veldkamp, A., Fresco, L. O., Nov. 1996. Clue-cr: An integrated multi-scale model to simulate land use change scenarios in costa rica. Ecological Modelling 91 (1-3), 231–248.

Verburg, P. H., 2006. Simulating feedbacks in land use and land cover change models. Landscape Ecology 21 (8), 1171–1183.

Wall, B., 1996. A genetic algorithm for resource-constrained scheduling. Ph.D. thesis, Massachusetts Institute of Technology.

4.3 SITE-Karnataka – new components

4.3.1 Economic components

Several authors have observed the importance of including socio-economic drivers while modeling land use change (Veldkamp and Lambin 2001; Turner *et al.* 1995; Musters *et al.* 1998). Incorporation of social, economic and political factors in land use models is often hampered by lack of data and methodological difficulties which is a possible reason that few published papers deal with ecological and economic integration in a spatially explicit way (Veldkamp and Lambin 2001; Münier *et al.* 2004). Bioenergy system components (such as feedstock production, conversion technology and energy allocation) are often embedded in several social, economic and environmental contexts that are ignored when bioenergy planning is done focussing on a single component (Buchholz *et al.* 2009). Moreover, all new developments in the energy sector are dependent on the willingness of investors, developers and suppliers to the market (Elghali *et al.* 2007) and subsidies, therefore substantiating the necessity of incorporation of market based economic criteria while studying land use change in the context of bioenergy.

This study added new modules to the SITE framework by integrating and simulating the impact of the regional components of agricultural / biofuel marketing systems (spatial location of markets, cost of cultivation, prices and profit margins). The following sections describe the most important aspects of the current agricultural marketing framework in Karnataka (which also applies to the national scale), details of costs and prices involved in producing agricultural goods (also biofuel commodities) and the implementation of the economic components in SITE- Karnataka.

4.3.2 Agricultural marketing in Karnataka

In India, traditionally agricultural produce was sold by farmers to (i) moneylenders / village traders (ii) village markets and (iii) unregulated wholesale markets. The establishment of a regulated marketing system was one of the measures taken up by the government to prevent exploitation of farmers by middlemen (Haque and Sirohi 1986). In Karnataka, as in other parts of India, Agricultural Produce Marketing Committees (APMCs) play a regulatory role in the functioning of the markets and are governed by the APMC Act. Most of the wholesale and village markets come under the purview of the APMC. The regulated markets consist of principal markets and sub-yards. The regulated marketing system ensures increased transparency in price structures and more order in the market places. Infrastructural developments such as construction of approach roads that link primary and secondary wholesale markets also improve farmer access.

In Karnataka there are a total of 204 APMCs (Ministry of Agriculture 2004), each of which has members from all representative sections of the society. The Karnataka State Agricultural Marketing Board (KSAMB) was established in 1972 as a liason agency between the APMCs and the Government of Karnataka. Through an online Marketing Information System (MIS), it is possible to get detailed information on each APMC on 25 different parameters such as income – expenditure details, market charges, credit given and borrowed, transportation, market arrivals etc (KSAMB 2011).

The agricultural price policy in India aims at building an intervention in the agricultural markets to influence the level of fluctuations in prices and price-spread from farm-gate to the retail level (Ministry of Statistics and Programme Implementation 2010). The main tiers of prices in India are-

(i) Producer Prices (Farm Harvest Prices): This is the price realised by the farmers at the farm-gate. The cost of transporting agricultural produce from the farm to the market or the first point of sale off-farm and of selling it there (by the farmer himself or by specialized agents) is not to be included in the farm-gate price.

(ii) Wholesale Prices: This refers to the price at which a relatively large transaction, generally for further sale is effected. After an agricultural product leaves the farm-gate it may pass through one or more wholesale markets (primary or secondary) and a chain of middlemen.

(iii) Retail Prices: These prices are established in transactions in which quantities dealt with are relatively smaller than in wholesale transactions and in which the final consumers of the agricultural product participate as buyers. Among other uses, they are used in constructing consumer price indices and are useful in determining agricultural wages.

Cost of Cultivation (COC) forms an important part of the agricultural economics profile in India. Intensive surveys for data generation on the various inputs are carried out by the Central Statistics Organisation in India (Central Statistical Organisation 2008). All input data is obtained by direct inquiry from the farmer. A “Comprehensive Scheme for Cost of Cultivation of Principal Crops” was designed in 1970-71 which was subsequently modified to meet changing requirements. The current design follows a three stage stratified random sampling design whereby each state is demarcated into homogenous agro-climatic zones based on biophysical characteristics. A village is the smallest administrative unit of survey and data is collected from selected villages at 5 different farm-size classes.

4.3.3 Implementation in SITE- Karnataka

Marketing is the final stage where the farmer converts his efforts and investments into profits. With the modernization of agricultural systems, increasing cost-consciousness has been observed in south India. Moreover, the financial success of farmers depends not only on returns they receive from a particular enterprise but also the location that they sell their produce in (Jyothi and Raju 2003). To improve the representation of economic components of agricultural production and biofuel development, this study used net profit margins as a key criterion in the suitability assessment of crops. The two major assumptions of the approach are – (a) all agricultural produce is sold, i.e subsistence agriculture was not considered (b) all agricultural produce is sold at the wholesale market. The lack of time series data on marketable surplus and adequate price information were the reason for these assumptions.

In the first step, a spatial database of markets (APMCs) was developed with details of 204 APMCs across Karnataka (available at the online MIS portal- (http://www.ksamb.gov.in/). As shown in Figure 2, a careful analysis of available qualitative information was transformed into detailed spatial information to be used as an input to the model. While all other commodities are traded in regulated APMCs, sugarcane trade takes place directly at sugar mills, hence for the purpose of this study, all sugar mills were assumed as “sugarcane markets” (Maps of India 2010). No information on established markets for jatropha biodiesel could be located as the development of the marketing network for biodiesel is still at a nascent stage. Therefore, the location of existing commercial biodiesel processing units (K1 Oils and Labland Biodiesel Pvt. Ltd.) and government owned oil refineries (at Bangalore and Mangalore) were used as “jatropha markets”. Detailed information on commodities traded at each of these 204 APMCs was incorporated into the database using the Directory of Markets (Ministry of Agriculture 2004). According to our analysis 33 “commodity specific markets” (i.e. markets that trade only in one crop (rice or maize etc.)) operate in the region. Nearly 50% of the markets trade 3 commodities and only 6 out of 204 markets trade all six major crops in the region. There is large variation in the items traded across the network of APMCs, 38 combinations of traded items were used in this study (Figure 2). This level of detailed representation of the interaction between markets and commodities was selected in order to capture the importance of spatial distribution of the markets.

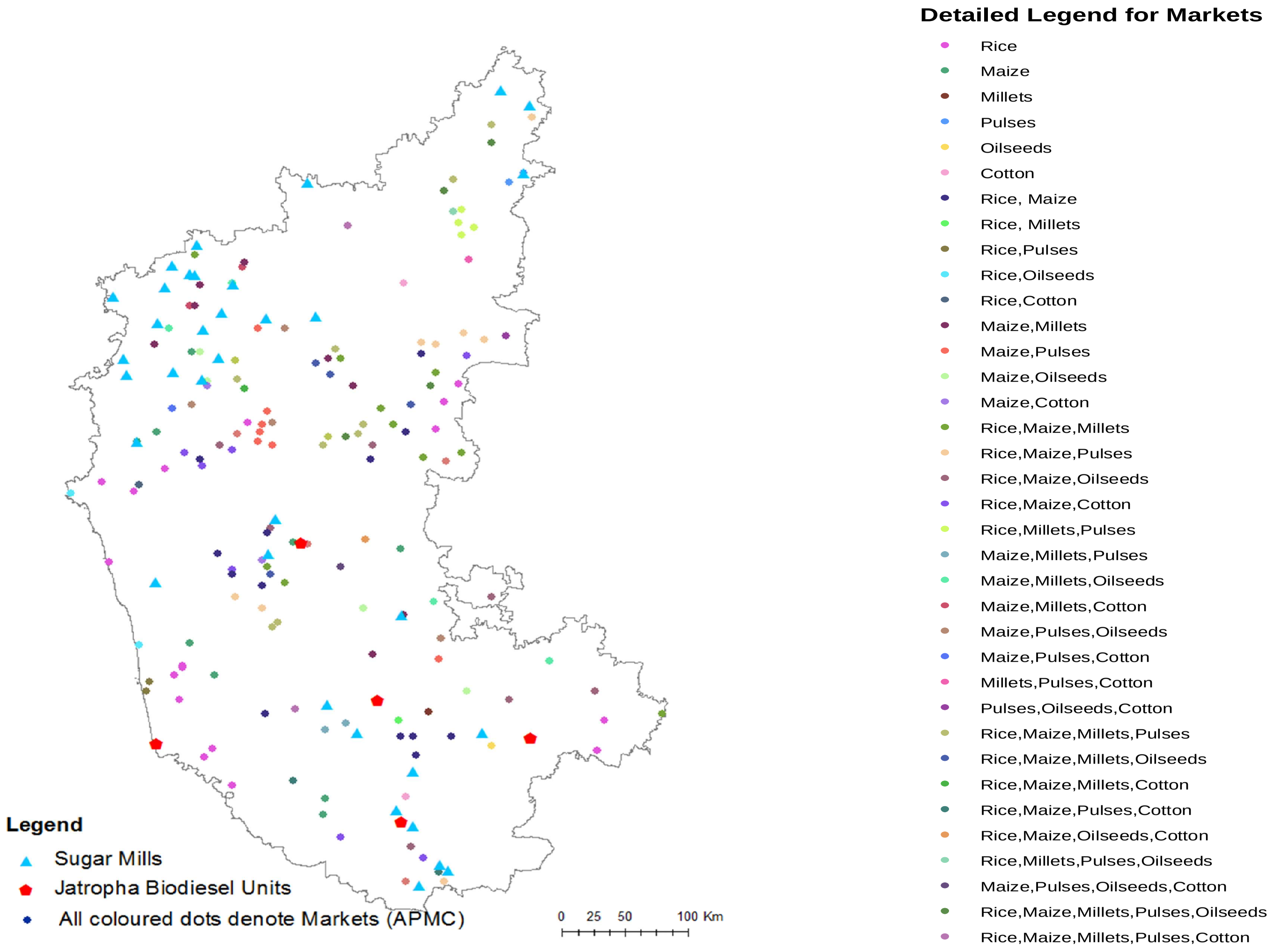

Figure 2 Agricultural Markets in Karnataka with details of commodities traded

In the next step, the distance function of the SITE framework was used to calculate distance of a crop pixel to its nearest market (see examples in Figure 3 and 4). Since time series of wholesale prices (corresponding to APMCs) was unavailable, time series of Farm Harvest Prices (FHP) was used (Directorate of Economics and Statistics, 2007) and travel costs were added to the prices by using a cost surface.

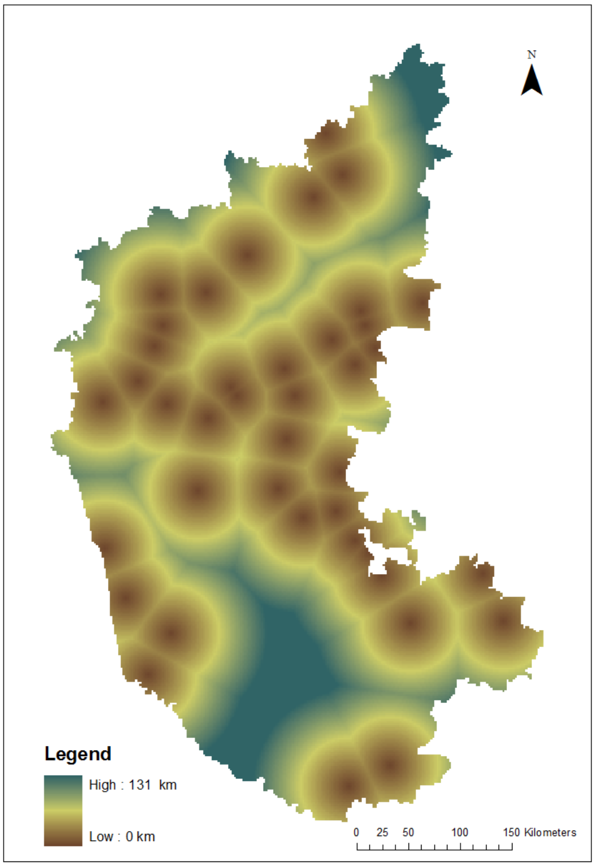

Figure 3 Distance to Oilseed markets

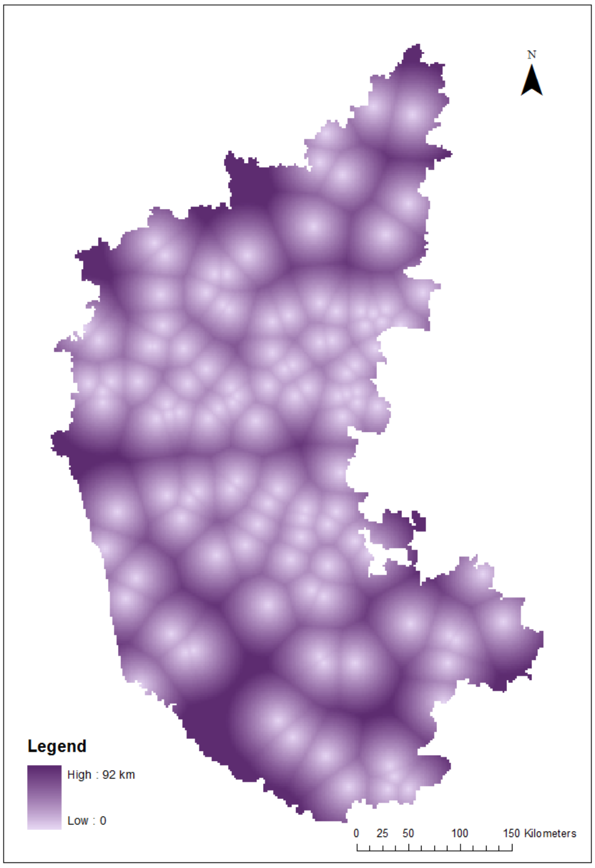

Figure 4 Distance to Maize markets

A database for the cost of cultivation (COC) of each crop was created from the available data (Directorate of Economics and Statistics, 2007). The underlying components of the COC for crops (Rice, Maize, Millets, Pulses, Oilseeds, Cotton and Sugarcane) are given below (for more details see Directorate of Economics and Statistics 2007) - “Cost of Cultivation of Principal Crops in India”)

1. Operational Costs- (Human labour, family, casual)
2. Labour costs - (Bullock labour (hired/ owned), machine labour (hired/ owned), Seed)
3. Fertilizer costs + Manure costs + Irrigation charges + Insecticides

4. Fixed costs (Rental value of owned land / rent paid for leased-in-land/ land tax/ depreciation on implements and interest on fixed capital)
5. Miscellaneous

The COC of jatropha based biodiesel included the following components (NOVODB, 2007)

1. Site preparation (cleaning, levelling, alignment)
2. Digging of pits
3. Cost of plants during first year of planting + cost of replanting
4. Weeding and soil working
5. Harvesting of fruits/seeds
6. Miscellaneous

Net profit margin that was used as a suitability criterion in the MCA and was calculated for each grid cell based on Equation 1:

$$\text{Net Profit} = (\text{Crop Yield} * \text{Cell Size} * \text{Wholesale Price}) - \text{COC} \qquad \text{(Equation 1)}$$

where:

Crop Yield = crop yields calculated by DayCent (t/ha)

Cell Size = size of grid cell (400 ha)

Wholesale Price = FHP + travel costs to nearest market (INR / t)

COC = Cost of Cultivation (INR / ha)

5 Production and processing of biofuels in South India[4]

Abstract

The management of degraded lands or wastelands for alternative energy production is a strategy that has been widely propagated in Indian environmental policies. However, gaps in productivity estimates have been a challenge to the implementation of these policies e.g. in the form of bioenergy plantations. This paper examines the potential of *Jatropha curcas* as an energy crop in southern India. Besides potential energy production, Jatropha systems are also known for various environmental co-benefits. We estimated potential yields of Jatropha on degraded lands of southern India through a spatially explicit modelling approach. Our results indicate productivity ranging from 0.1 Mg ha^{-1} yr^{-1} to 1.7 Mg ha^{-1} yr^{-1} on four types of wastelands and hence present a modest potential as an alternative energy feedstock. The range of agricultural land conversion to meet energy requirements has been estimated at 1-7%, depending on the oil content of Jatropha seeds and oil extraction technologies. Besides contributing to energy management and planning at the state or district levels, the study also identifies the need to improve estimates of wasteland availability and oil extraction technologies as two major determinants of successful Jatropha based bioenergy production.

Keywords: Biodiesel, biofuel, crop yield, South India, SITE land-use model, DayCent model, oil extraction technology

1. Introduction

India faces the critical challenge of meeting an increasing energy demand, ranking 6th in the world in terms of energy requirements. The primary energy supply is assumed to increase by 3-4 times from 2003-04 levels in order to sustain daily energy requirements of 2031-2032 if the current GDP increase of 8% per year continues (Planning Commission 2006). Currently India imports 73% of its total oil demand, while 27% is derived from domestic sources (Kureel 2006). There has been an increased commercial and research interest in biofuels as a renewable energy option in India since 2002-03, especially from non-edible oilseeds such as *Jatropha curcas, Pongamia pinnata, Azadirachta indica, Simarouba glauca, Madhuca indica* etc. Efforts to explore the possibilities of oilseed based biofuels were intensified with the launch of the 'National Mission of Biodiesel' by the Indian government in 2003 to be undertaken in two phases until 2012, and has been followed by the adoption of the National

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[4] Das S and Priess JA, Production and processing of biofuels in South India, *Environmental Management*, *submitted March 2011*

Biodfuel Policy (Ministry of New and Renewable Energy 2010). According to the policy, blending targets for both biodiesel and bioethanol have been set at 20% until 2017 while targets for biodiesel can be recommendatory. The Indian Railways and the Karnataka Road Transport Corporation (KSRTC) have demonstrated the large scale applicability of biofuels (Ministry of Railways 2008, Megharikh and Rao 2006).

This paper has three aims – (i) to demonstrate a modelling approach to estimate potential yields (in terms of seeds) of Jatropha in South India, (ii) estimate potential production (in terms of oil), considering oil content of seeds and oil extraction methodology as main parameters and (iii) calculate additional land requirements to achieve existing political biodiesel targets. The methodology presented in this paper is applicable in all 29 states of India, based on district level estimates of biodiesel production (from Jatropha or other crops) for the entire country (see following paragraphs).

Jatropha plantations have been recorded in several states of India, viz. Maharashtra, Karnataka, Uttaranchal, Chhattisgarh, Andhra Pradesh and parts of the North-East. Some of the assumptions/ advantages that have led to an increase in the interest in Jatropha in India are-

1. The high seed yield of the plant even under sub-optimal environmental conditions of semi-arid to arid climates. It has been reported that Jatropha can grow under a range of rainfall regimes (300mm to 1500 mm per annum) with the ability to withstand extended drought conditions (Benge 2006).
2. Amelioration of degraded soils under Jatropha (Kureel 2006).
3. Potential improvement of the livelihoods of rural people through Jatropha production systems (Altenburg and others 2009, BAIF 2006).

Reliable reports of yields of Jatropha are crucial for further estimation of the total potential of biodiesel production. To date, the lack of reliable knowledge on potential yields of Jatropha under sub-optimal or marginal conditions has constrained the establishment of large-scale plantations (Jongschaap and others 2007). The absence of scientific information has also been identified as the severest drawback by farmers in India (Meena and Sharma 2006). Though more drought tolerant than many other crops, Jatropha responds with reduced yields to low water and nutrient levels of soils, but these aspects of marginal lands are only poorly documented, as only few experiments have been conducted on degraded lands (FAO 2008).On experimental plots, Jatropha intercropped with red gram, onions and wheat have been reported to yield 0.6 Mg ha^{-1}, 1.6 Mg ha^{-1} and 1.0 Mg ha^{-1} of seeds respectively, while intercropping with lentils produced only negligible yields (Punia 2009). However, only few reliable estimates for seed yields of mature plantations are available to date, because systematic yield monitoring started only recently (Achten and others 2008). On drylands in India, some individual field studies have aimed at estimating seed yields, methane potential and energy flows in Jatropha systems. It has been demonstrated that the total seed yield (35% oil content) was 1.4 Mg ha^{-1} in the state of Tamil Nadu (Gunaseelan 2009).

In Karnataka, currently only 11.5 % of the total energy is derived from renewable energy sources, which is aimed to be scaled up to 20% by 2014 (Government of Karnataka 2009). Biodiesel production programmes from non-edible oilseeds have been planned by the government in India only on wastelands and degraded forest lands (Government of Karnataka 2007, Ministry of New and Renewable Energy 2010). The wasteland fraction in Karnataka comprises of 7.1% of the total area (NRSA and DOLR 2005). Spatially explicit information on distribution of potentially high and low yielding zones have been provided by employing vegetation and crop models, such as DayCent (Stehfest and others 2007) or LPJmL (Lapola and others 2009). Results from Lapola and others (2009), provide potential yields at national levels for Brazil and India. Although such national estimates are useful indicators of total potential, they are limited in their capacity to be directly utilised for implementation, as they estimate yields at rather aggregated levels (~ 100 km^2 pixels) and do not consider nutrient or other environmental limitations. Since many biofuel programmes are developed by state, district or village administration, more detailed estimates are needed to support regional scale decision-making. Our study aims to amplify convergence of the scale of research with the scale of implementation by providing district level data. Another distinctly significant attribute of this paper is the use of spatial wasteland data for yields which has not been previously used in other studies. Due to the varying nature of limiting factors, yield levels may vary considerably across different categories of wastelands. Using a nationally adopted wasteland classification is necessary while reporting potential yields, because legal ownership of wastelands is crucial to the planning process. Maintenance of an established classification system also allows for clarity of legal status of the land and associated rights for potential biofuel projects.

This paper further aims at improving accuracy of biofuel estimates from Jatropha by considering climatic and soil fertility constraints, various levels of oil content in Jatropha seeds, as well as major extraction technologies commonly used in India

2. Methods

2.1 Study area

This study was conducted in Karnataka (11.31°-18.45°N; 74.12°-78.40°E). The area of Karnataka is 192,000 km^2 with an elevation ranging from 300 – 900 m.a.s.l. The state has a population of 53 million (2001), with 66 % of the population living in rural areas (Planning and

Statistics Department 2005). The major physiographic regions of the state are the Deccan plateau which forms part of the peninsular plateau of India extending southwards and the coastal plain region on the western boundary of the state, popularly known as the Western Ghats. The region receives almost 80% of rainfall from the southwest monsoons during June – September and 20% from the northeast monsoon during October - December. The average annual rainfall is 1189mm with large variations ranging from 300 mm/ year to 2500 mm/ year across the state (DES 2007). Broadly, the soils of the area can be classified into red and black soils with loamy and sandy textures. Soils on degraded lands suffer from high salinity. Although the role of agriculture in the economy of the state has diminished over the last two decades, it remains the largest source of employment with more than 60% of the working population involved in agriculture. The agricultural sector is characterised by diverse crop systems and is highly dependent on monsoons, struck by the frequent occurrence of droughts (Planning and Statistics Department 2005, Karnataka State Agriculture Department 2010).

2.2 Modelling framework for potential yield calculation

Some of the recent integrated modelling frameworks offer the advantage of simulating crop yields under different conditions, including soils, management, landscape and agro-climatic parameters, and resulting land requirements (Stehfest and others 2007, Lapola and others 2009).

We determined potential yields of Jatropha in Karnataka with the DayCent model (Parton and others 1998), which is simulating the physiological growth of the plant. DayCent employs a daily land surface submodel wherein plant growth, nutrient cycling, evapotranspiration are calculated as a function of daily weather, plant, soil and management parameters, etc. (Parton and others 1998). It is noteworthy to mention here that in contrast to LPJml that does not constitute a nitrogen cycle (applied by Lapola and others 2009), DayCent encompasses nitrogen cycling through its Nitrogen Submodel (Stehfest and others 2007) thus enabling nitrogen limitation in plant growth. The model is embedded within the SITE framework (Mimler and Priess 2008, Schweitzer and others 2011) for spatially explicit representation of the study area, the state of Karnataka. SITE (SImulation of Terrestrial Ecosystems) was developed as a land-use modelling framework specifically for regional applications. SITE is a generic platform, which facilitates developing land use models for different study areas addressing various environmental questions (Priess and others 2007, Priess and others 2010).

In the current study, we used a spatial resolution of 2 x 2 km. The DayCent parameterization of Jatropha was developed using available literature based on field experiments in India and elsewhere (see electronic supplement). Jatropha is a shrub growing up to 8-10 m

(Department of Biotechnology 2007) and therefore was parameterised as a ‘tree’ plant type in DayCent. Minimal management practices were assumed since the promotion of Jatropha has been based on the potential of the plant to grow under low management (= low to no input) conditions. We used FAO soil data (FAO 2009), which was scaled down to the required resolution in ArcGIS. CRU climate data (Precipitation, Maximum temperature, Minimum temperature) (Mitchell and Jones 2005) was used for daily weather calculations. Potential yields were calculated averaged over a 30 year time period for 1970-2000 climate conditions.

2.3 Estimation of wasteland availability

In Karnataka 1,353,700 ha are classified as wastelands, which account for 7% of the total area (NRSA and DOLR 2005). Out of the 28 sub-classes of wastelands in India, few are suitable for the cultivation of Jatropha (Ramakrishnaiah 2006). Barren rocky lands, areas with steep slopes, sands, mining and industrial wastes and similar land categories are not suitable for cultivation, due to extremely limiting growth conditions (Parikh 2008). The categories of land suitable for Jatropha and the corresponding area available as calculated from the Wasteland Atlas are given in Table 1. The wasteland map (NRSA 2005) was rescaled to the required resolution for spatial distribution of suitable wastelands. 75% of the total wasteland area in the state is theoretically suitable for Jatropha cultivation.

Table 1 Different types of wasteland suitable for Jatropha cultivation

Wasteland Category	Area Available in Karnataka (ha)	% of Total Wasteland Area
Land with scrub	409,800	31
Land without scrub	73,000	5
Saline /Alkaline Lands	16,600	1
Degraded Forests	524,000	38
Total	1,023,400	75

2.4 Seed oil content and oil extraction technologies

Total biodiesel production from Jatropha depends on oil content of the seeds, extraction efficiency of the oil from the seeds, and blending ratios with high speed diesel. The oil content largely depends on the variety / genotype of Jatropha plants being used. Oil content has been known to vary over a wide range of 19% - 45% (Kureel and others 2007, Meena and Sharma 2006, Kandpal and Madan 1995, Pratibha and others 2009, Kumar and Sharma

2008).We calculated oil yields based on commonly reported 30%, 35% and 40% oil content in seeds.

In India and elsewhere, oil from Jatropha seeds is extracted by various means. The choice of the method for oil recovery is important for the final quantity and quality of biodiesel production and thus the economic viability biofuel production. There are a range of recovery methods available. In India, a large fraction of the recovery process is dependent on the traditional ‘Ghani’ method. A Ghani is fundamentally a mortar-pestle mechanism, in which the oilseeds are held in a circular mortar made of wood or stone and a rotating pestle. A load beam rides around the outside of the pit and is yoked to two animals. Variations in Ghani designs exist across India, in the south, large Ghanis made of granite have a capacity of 35-40 kg of seeds (Acharya 1994). The efficiency of a Ghani has been reported to be 57% for Jatropha (Punia 2009). In the absence of other options, under most circumstances local farmers use Ghanis for oil extraction, ‘Power Ghanis’, an electrical version of the traditional Ghani are also being used for which experimental studies are ongoing for evaluation of efficiency. A faster and more efficient option is the use of Mechanical Expellers. In the absence of expellers specifically designed for Jatropha, traditionally available expellers are currently being used, the efficiency of which for Jatropha seeds is 68%. Research for designing a mechanical expeller for Jatropha has been undertaken and a lab scale expeller is reported to have an efficiency of 81% (Punia 2009). Industrial extraction by solvent extraction techniques have the highest efficiency, reported to reach 100% (Punia 2009). We have examined the total potential of Jatropha crude oil production under four assumptions of oil content and extraction efficiency.

3. Results

3.1 Modeling results for potential seed yields

We calculated potential seed yields from different categories of wastelands, using the wasteland map (NRSA 2005). The spatial distribution of the three major classes of wastelands and corresponding potential yields under rainfed conditions are shown in Fig. 1. The average yield calculated is 0.8 Mg ha^{-1} with a maximum of 1.7 Mg ha^{-1} on degraded forest lands. Districts covering the Western Ghats- Uttara Kannada, Udupi and Dakshina Kannada (see Supplement Fig.3 for a district map) have the highest yield potentials averaging 1.5 Mg ha^{-1} on wastelands while the dry northern Karnataka districts of Bagalkote, Bidar, Gulbarga and Raichur have significantly lower yields ranging from 0.25 – 0.85 Mg ha^{-1}. Our results indicate that potential yields are low during the first seven years of growth (0.4 – 0.8 Mg ha^{-1}) and stabilise after the 8th year of growth to 0.8 – 1.0 Mg ha^{-1} (see Fig. 1, Supplement). In Karnataka, a strong climatic gradient exists from West to East with declining amounts of rainfall. Yields are correlated to rainfall ($R^2 = 0.6$) and are in the range of 0.7-1.0 Mg ha^{-1} under precipitation regimes of 500- 1000 mm. At higher precipitation (> 2000 mm) yields increase to 2.5 Mg ha^{-1}(see Fig. 2, Supplement).

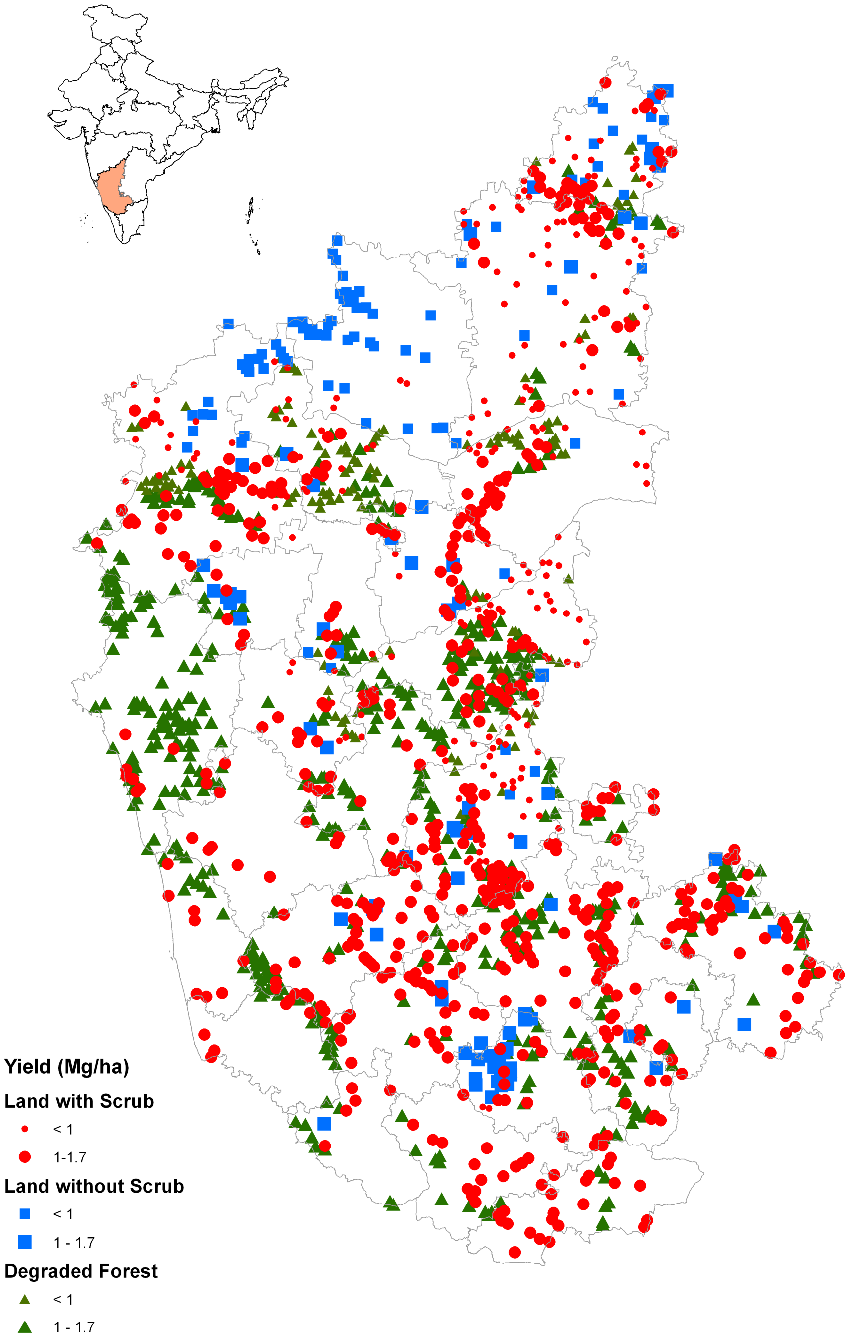

Fig. 1 Potential seed yields of different wastelands

3.2 Calculation of potential oil yields

Table 2 gives the potential oil yield calculations in different categories of wastelands for the entire state. We have calculated oil yields assuming 30%, 35% and 40 % oil content in seeds. Relevant types of wasteland areas per district and corresponding potential yields are presented in the electronic supplement. Figure 2 shows the overall wasteland areas per district and the average potential yield of Jatropha seeds (Mg ha^{-1}) in each district.

Table 2 Potential oil yield from Jatropha at different oil content

Wasteland category	**Total Area in Karnataka (ha)**	**Seed Yield (Mg ha^{-1})**	**Potential Oil Yield (30%) (tons)**	**Potential Oil Yield (35%) (tons)**	**Potential Oil Yield (40%) (tons)**
Degraded Forests	524,000	628,812	188,643	220,084	251,524
Land with scrub	409,800	463,102	138,930	162,085	185,240
Land without scrub	73,031	58,425	17,527	20,448	23,369
Saline/Alkaline Lands	16,743	10,045	3,013	3,516	4,018
Total	1,023,609	1,160,385	348,115	406,135	464,154

Note-Oil yield values are based on 100% oil extraction efficiency

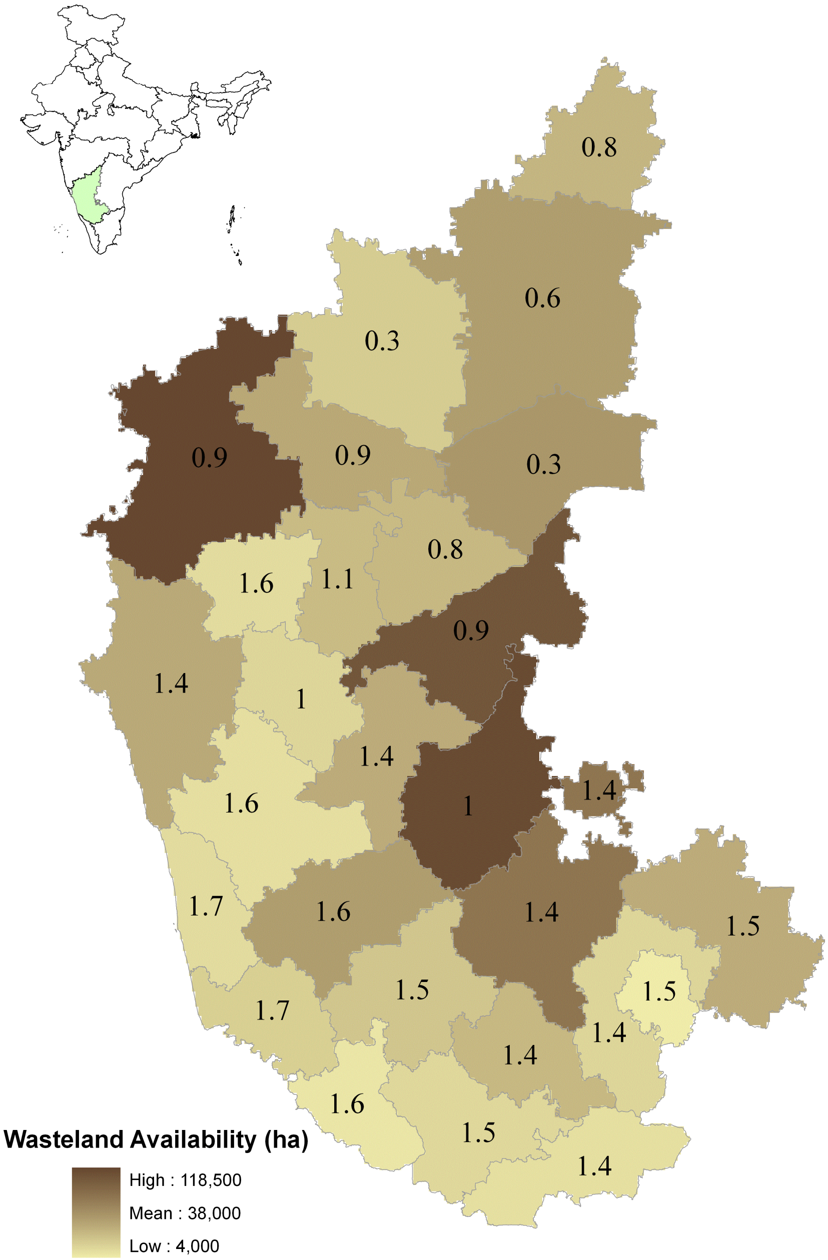

Fig. 2 Current wasteland area (colour scheme) and average seed yields per District(numbers)

Table 2 shows potential oil yields assuming 100% extraction efficiency. However, the net oil production is highly dependent on various techniques applied during the processing chain, one of the most crucial being the method of extraction, as discussed in Section 5.3.2. Table 5.3 shows the total potential oil production under four scenarios with varying oil content and extraction efficiency.

Table 3 Potential oil yields resulting from different extraction technologies

Oil Content of Seeds (%)	**Extraction Efficiency (%) and Technology**			
	100 **(industrial solvent extraction)**	**81** **(IIT* technology mechanical expeller)**	**68** **(traditional mechanical expeller)**	**57** **(tradtional Ghani oilpress)**
30	348,115	281,974	236,719	198,426
35	406,135	328,969	276,172	231,497
40	464,154	375,965	315,625	264,568

* IIT – Indian Institute of Technology, New Delhi

3.3 Calculation of additional land requirements

The political biodiesel target is to produce 500,000 tons oil (Karnataka Renewable Energy Development Limited 2008). This value does not refer to Jatropha only, but includes all other potential biodiesel sources. We have used 500,000 tons for further calculations of additional land requirements, assuming that all biodiesel is produced from Jatropha. From Table 2 and Table 3, it is clear that Jatropha has a high potential of contributing substantially to the 0.5 million ton target. Depending on Jatropha varieties and extraction technologies in use, between 40% and 93% of the desired amount can be produced on Karnataka's wastelands. In consequence, additional land would be required to fulfil current political targets. The total agricultural area in Karnataka is is 12.88 Mha (DES 2007). We calculated Jatropha production for six land use scenarios, based on the average simulated productivity of 2.0 Mg ha^{-1} on agricultural land. Note that the productivity of agricultural land is 67% higher than the one of wastelands. The potential production under different rates of conversion of agricultural lands is shown in Table 4. The difference between the targeted 0.5 M tons and the potential production is 35,846 tons - 301,574 tons, for which approximately 1% - 7% of agricultural land would be needed for rainfed Jatropha production. Under ‘Low’ conditions (=low oil content AND low extraction efficiency) approximately 7% of agricultural land would be required to meet biofuel targets. Under ‘High’ conditions almost the entire targeted amount could be produced on wastelands, and only 1% of additional agricultural land would be needed (Table 4). Note that all calculations assume 100% availability of the three wasteland categories suitable for biofuel production.

Table 4 Potential oil production on agricultural land

Area Converted for Jatropha (%) (Area in ha)	Oil Production (tons) Low[1]	Oil Production (tons) High[2]
1 % (128,870)	44,047	103,096
5% (644,350)	220,368	515,480
7% (902,090)	308,515	721,672

[1] Low: 30% oil content + 57% extraction efficiency. [2] High: 40% oil content + 100% extraction efficiency

4. Discussion

Recent reports from the state of Andhra Pradesh (South India) indicate that yields for a 3 year old plantation sum up to meagre 0.1 Mg ha $^{-1}$ under 780 mm of rainfall. It has been further anticipated that at the end of the 6th year, yields shall increase to 1 Mg ha $^{-1}$ (Brittaine and Lutaladio 2010). From the neighbouring state of Tamil Nadu (South India), yields under rainfed conditions have been reported to be 0.45 Mg ha $^{-1}$ and 0.75 Mg ha $^{-1}$ under irrigated conditions for a 3 year old plantation Ariza-Montobbio (2010). In Maharashtra (Western India), average yields after seven years stabilized at 1.25 Mg ha $^{-1}$ (Gokhale 2008), whereas in Chhattisgarh (Central India), in a 2 year old plantation yields of 0.5kg /plant have been reported (Gmünder and others 2010). In the absence of reported values of plantation density in the latter example, yields can be calculated to be 1 Mg ha $^{-1}$ (assuming 2000 plants / ha). The agreement of our simulation results to the above reported values strongly supports our parameterization of Jatropha in DayCent (for more details see Table 2, in the electronic supplement).

Using political targets as a measure for comparison, we deduce that Jatropha has a moderate to high potential for biofuel production in South India. Our results indicate that it can be utilised as a promising biofuel crop even under rainfed conditions. However, current political biofuel targets overestimate the biophysical potential (including the technical potential) by 7% to 60%, indicating either the need for additional land, intensified Jatropha production, improved Jatropha varieties, optimal extraction facilities or a mix of the four factors influencing biodiesel production from Jatropha or similar oil crops. Similar over expectations were reported by Ariza-Montobbio 2010, who found that the actual yields from the field were ten times lower than previously expected yields. Research has already shown that yields can be significantly enhanced under irrigated conditions and/or with the application of fertilisers (Punia 2009). Irrigation at 30 day intervals has been considered essential under arid and semi-arid ecosystems (average annual rainfall of 800- 900 mm) in tropical countries (Behera and others 2010). However, it would not be feasible to assume adequate water availability for biofuel production, as currently only 30% of the gross cropped area in the state is irrigated (DES 2007). In order to avoid that scarce water resources are diverted from food crops to biofuel production, estimates of the potential productivity of Jatropha need to be based upon yields under rainfed conditions. Other management optins such as intercropping with food crops have been suggested by some researchers. However, intercropping also may cause competition for resources (water, nutrients) between crops, resulting in unintended decreasing yields of the food crop component. Intercropping experiments currently being conducted may provide adequate guidelines on the potential of Jatropha as an intercrop on agricultural lands (Punia 2009, Behera and others 2010, Gokhale 2008).

The merits of Jatropha are based on its ability to grow under various climatic and soil conditions. Our study shows that although it can grow and also produce seeds under drier conditions, the productivity is in the range of 0.1 - 1.7 0 Mg ha^{-1}. Thus, allocation of Jatropha plantations e.g. in the dry districts of northern Karnataka and the neighbouring states, or the wetter regions of the Western Ghats, needs thorough planning. It is noteworthy that the potential productivity of Jatropha is lower in the districts where wasteland availability is higher. For example, in the districts of Bellary, Belgaum and Chitradurga where almost 27% of the total wastelands are located, the average productivities are 0.9, 0.9 and 1.0 Mg ha^{-1} of seeds respectively. Thus, enhancing the productivity of the wastelands of these three districts may prove much more efficient than in other regions of South India. However, as indicated by other researchers (Behera and others 2010, Achten and others 2008, Foidl and Kashyan 1999) simultaneous reclamation of wastelands and high biofuel productivity on wastelands without the use of fertilisers and irrigation may not be realistic.

Comparable to the allocation of biofuels, land availability has been reported to be the major limitation for afforestation / reforestation projects, not just in India, but all over Asia (Zomer and others 2008). The decision to utilise only wastelands for biofuel production in India, is driven by the target of averting diversion of agricultural land to other production purposes i.e. to avoid a competition for space with food crops. However, the actual availability of wastelands, which is based on government records and statistics, is debatable. Wasteland availability has always remained a concern for example in major afforestation projects in India and should be a concern when establishing biofuel plantations in Karnataka and other Indian states. Actual available wasteland areas may be far less than official estimates and thus biofuel production from marginal lands much lower than assumed. Encroachment of wastelands by the poor for habitation is a well known fact in Karnataka and other states. However, in the absence of clearly defined land rights, the poor may increasingly face the risk of losing parcels of land they currently live on, as a result of expanded biofuel production or other production targets. Degraded patches of forest land, for example, currently are (at least partially) used by tribal forest dwellers who may oppose the idea of converting forests into plantations (Balooni and Singh 2007). In consequence, the political and scientific challenges are to develop production systems aiming at the integration of the interests of local communities with biofuel production. This goal may be achieved e.g. by generating employment opportunities, improving existing technologies (decorticators; oil extraction), as well as approximating equity in benefit sharing from Jatropha production. Incidentally, Jatropha plantations in India are very labour intensive, the tasks of picking the fruits and washing and drying of seeds are generally performed by illiterate to semi-literate women and children in rural areas (BAIF 2006). Apparently, the labour aspect makes Jatropha and similar oil crops attractive for rural areas, increasing opportunities to generate income, but on the other hand rendering the largely female and child worker population highly vulnerable to reported toxic effects of Jatropha (Brittaine and Lutaladio 2010). We conclude that keeping the uncertainties and potential limitations in mind, biofuels like Jatropha and others can contribute to reduce GHG emissions and fossil fuel dependency and to improve rural livelihoods, solve land availability issues and reduce potential land conflicts.

According to our study, a 1% - 7% allocation of agricultural land to biofuel production may be needed to reach the targeted 500, 000 tons of oil, depending on the oil content of seeds and extraction efficiency. Adapted Jatropha varieties or hybridization techniques may further enhance the oil content of the seeds even beyond 40% or improve seed yields, thus increasing the overall productivity (Punia 2007, Saikia and others 2009, Leduc and others 2009). It is noteworthy that the largest gain (> 40%; see Table 3) could be achieved by improving local extraction technologies. However, small scale local farmers may not always have access to industrial processes or technologies and thus be compelled to use locally available ‘Ghanis’ for oil extraction. In the absence of efficient oil extraction facilities transportation of seeds to the nearest factory for extraction, will cause additional costs (Leduc and others 2009) and induce a negative effect on the financial viability of oil production. Thus, a large fraction of the potential oil yield may remain unutilised. To summarize, the potential competition between cropping areas for food /cash crop production and land needed for biofuels can be minimized or even completely avoided by improving Jatropha varieties and especially local oil extraction technologies.

We agree with Benge, who emphasised that “Strategies based on a single source of oil, such as that from Jatropha, which produces an unsure yield of nuts only during a short period of time and eventually may not produce optimal yields for several years, are risky and potentially unsustainable” (Benge 2006). In order to reduce risks as well as to optimise financial gains from biofuel production, more than a single oilseed crop needs to be considered. There are a range of other non-edible oilseeds as options for biofuel production, the most pertinent being *Pongamia pinnata*. Pongamia or others would not only reduce the dependence on a single species, but also reduce potential negative effects of monocultures. However, it is important to consider the technical feasibility of such diversification. The steps in the production chain of each type of oilseed may differ considerably between crops and technical requirements may be higher, if required to support a range of different oilseeds. It has been seen that Jatropha oil extraction methods can vary from traditional Ghani based techniques (+: easy to use & maintain, no electricity required; -: low efficiency of 57%) to modern oil expellers and solvent extractors (+: high efficiency of 100%; -: technical infrastructure & electricity required, higher costs). If a variety of oilseeds are simultaneously used to generate biofuels, the total potential of each of the oilseeds may not be reached as post-harvest techniques are crop-specific in parts of the processing chain.

We conclude that Jatropha has a significant potential as a source for biofuel in South India. Under optimal conditions, current political targets are matching the biophysical and technical potential. However, under more realistic assumptions i.e. cultivation of mixed varieties and use of locally available extraction technologies, much smaller than the targeted amounts can be produced on wastelands. The remaining amount would require the conversion of 1% - 7% of agricultural land, potentially causing land-use conflicts with food production. A second source of land use conflicts may arise from wasteland areas officially considered as available, but actually inhabited or used by someone. Given the scale of planned cultivation, and the lack of experimental data, detailed spatially explicit estimates of potential yields are important ingredients of any planning process at district, state or regional level. As reflected in the results, oil content and efficiency of oil extraction are important factors when comparing potential biodiesel production against national or sub-national targets. This study provides insight into the potential of wastelands in terms of suitability for biofuel production, but the potential of wastelands in terms of actual availability is a critical information gap that needs to be bridged before biofuel strategies can contribute to secure future energy demands and reduce GHG emissions in India.

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6. References

1. Acharya K T (1994) Ghani: A Traditional method of oil processing in India. Food, Nutrition and Agriculture, FAO publication 11.
2. Achten WMJ, Verchot L, Franken YJ, Mathjis E, Singh VP, Aerts R, Muys B (2008) Jatropha bio-diesel production and use, Biomass and Bioenergy. 32 12 1063-1084.
3. Altenburg T, Dietz H, Hahl M, Nikolidakis N, Rosendahl C, Seelige K (2009) Report-Biodiesel India- Value Chain Organisation and Policy Options for Rural Development, Deutsches Institut für Entwicklungspolitik , Bonn, Germany.
4. Ariza-Montobbio P, Lele S, Kallis G, Martinèz-Alier J (2010) The Political Ecology of Jatropha plantations for biodiesel in Tamil Nadu, India, The Journal of Peasant Studies 37, 875-897
5. BAIF Institute of Rural Development (2006) The biofuel hype- Chance or challenge for sustainable agriculture in Sustainable Agriculture in A Pathway out of Poverty for India's Rural Poor, SUSTAINET- Sustainable Agriculture Information Network.
6. Balooni K and Singh K (2007) Prospects and problems of afforestation of wastelands in India: A synthesis of macro- and micro-perspectives, Geoforum 38, 1276-1289.
7. Behera S K, Srivastava P, Tripathi R, Singh J P, Singh N (2010) Evaluation of plant performance for Jatropha curcas L. under different agro-practices for optimizing biomass – A case study, Biomass and Bioenergy 34, 30-41.
8. Benge M (2006) Assessment of the potential of Jatropha curcas, (biodiesel tree,) for energy production and other uses in developing countries - in house working document, USAID
9. Brittaine R and Lutaladio N (2010) Jatropha: A Smallholder Bioenergy Crop- The Potential for Pro Poor Development, Integrated Crop Management, Vol. 8. FAO, Rome.
10. Department of Biotechnology (2007) Agrotechnology Packages for Bioenergy Crops, Ministry of Science and Technology, Government of India, New Delhi.
11. DES (Department of Economics and Statistics) (2007) Government of Karnataka Statistical Abstract of Karnataka, 2001-02 to 2004-05, Bangalore.

12. FAO (2008) The State of Food And Agriculture Biofuels: prospects, risks and opportunities, Food and Agriculture Organization of the United Nations.
13. FAO (2009) Digital Soil Map of the World and Derived Soil Properties, Available at www.fao.org [Accessed 19 April, 2010].
14. Foidl N and Kashyap A (1999) Exploring the potential of Jatropha curcas in rural development and environmental protection, Rockefeller Foundation, New York.
15. Gmünder SM, Zah R, Bhatacharjee S, Classen M, Mukherjee P, Widmer R (2010) Life cycle assessment of village electrification based on straight jatropha oil in Chhattisgarh, India, Biomass and Bioenergy 34 347- 355.
16. Gokhale D (2008) Jatropha: Experience of Agro- Forestry and Wasteland Development Foundation, Nashik, India. In: International Consultation on Pro-poor Jatropha Development. 10-11 April, 2008, Rome, IFAD (Available at http://www.ifad.org/events/jatropha/),[Accessed on April 19, 2010].
17. Government of Karnataka (2007) Draft Biofuel Policy of Karnataka, Bangalore.
18. Government of Karnataka (2009) Karnataka Renewable Energy Policy, Karnataka Renewable Energy Development Limited, Bangalore.
19. Gunaseelan VN (2009) Biomass estimates characteristics, biochemical methane potential, kinetics and energy flow from Jatropha curcus on dry lands, Biomass and Bioenergy. 33 4589-596.
20. Jongschaap REE, Corre WJ, Bindraban PS, Brandenbug WA (2007) Claims and Facts on Jatropha curcas L.Plant, Research International, Wageningen, Netherlands.
21. Kandpal J B and Madan M (1995) Jatropha curcus : a renewable source of energy for meeting future energy needs. Renewable Energy, 62 159-160.
22. Karnataka Renewable Energy Development Limited (2008) Draft Renewable Energy Policy of Karnatka, , Government of Karnataka, Bangalore.
23. Karnataka State Agriculture Department, Bangalore (2010) Available from www.raimitra.nic.in [Accessed on April 19, 2010].
24. Kumar A and Sharma S (2008) An evaluation of multipurpose oil seed crop for industrial uses (Jatropha curcas L.): A review, Industrial crops and products. 28-1,1-10.
25. Kureel R S, Singh C B, Gupta A K, Pandey A (2007) Jatropha -An alternate source for biodiesel, National Oilseeds & Vegetable Oils Development Board, Ministry of Agriculture, Govt. of India.

26. Kureel RS (2006) Prospects and Potential of Jatropha curcas for Biodiesel Production, in Biodiesel Conference towards Energy Independence – Focus on Jatropha, Hyderabad.
27. Lapola DM, Priess JA, Bondeau A (2009) Modeling the land requirements and potential productivity of sugarcane and Jatropha in Brazil and India using the LPJmL dynamic global vegetation model. Biomass and Bioenergy 33(8) ,1087-1095.
28. Leduc S, Natarajan K, Dotzauer E, McCallum I, Obersteiner M (2009) Optimizing biodiesel production in India, Applied Energy. 86 Supplement 1,S 125- S131 doi:10.1016/j.apenergy.05.024.
29. Meena H R, Sharma F L (2006) Constraints in Jatropha Cultivation Perceived by Farmers in Udaipur District, Rajasthan, International Journal of Rural Studies 13.
30. Megharikh NS and Rao PSA (2006) Driving further on greener fuel- biofuel blends in KSRTC's buses in India, Public Transport International, Bangalore, 26-28.
31. Mimler M and Priess JA (2008) Design and Implementation of a generic modeling framework- a platform for integrated land use modeling. Center for Environmental Systems Research, Kassel University Press, University of Kassel, Germany.
32. Ministry of New and Renewable Energy (2010) National Policy on Biofuels, , Government of India, 2009, Available at http://www.mnre.gov.in/policy/biofuel-policy.pdf, [Accessed on April 20, 2010].
33. Ministry of Railways (2008) Technical Specification for Jatropha Plantation along Railway Track, Government of India, Available from www.indianrailways.gov.in/tenders/IROAF/bd-pl-08.pdf. [Accessed 19 April, 2010]
34. Mitchell T D and Jones P D (2005) An improved method of constructing a database of monthly climate observations and associated high resoultion grids, International Journal of Climatology. 25 (2005) 693-712.
35. NRSA (National Remote Sensing Agency) (2005) Wasteland Map of Karnataka, Government of India, Hyderabad, India.
36. NRSA (National Remote Sensing Agency) and DOLR (Department of Land Resources) (2005) Wastelands Atlas of India, Government of India, New Delhi.
37. Parikh J (2008) Diesel Substitute from Oilseeds in Roundtable on Sustainable Biofuels-Summary Report of South Asian Stakeholder Meeting, New Delhi.
38. Parthiban KT, Kumar RS, Thiyagarajan P, Subbulakshmi V, Vennila S, Govinda RM (2009) Hybrid progenies in Jatropha – a new development, Current Science. 96- 6.

39. Parton WJ, Hartman M, Ojima D, Schimel D (1998) DAYCENT and its land surface submodel: description and testing. Global and Planetary Change 19 1-4 35-48.
40. Planning and Statistics Department (2005) Karnataka Human Development Report, Government of Karnataka, Bangalore.
41. Planning Commission (2006) Integrated Energy Policy, Report of the Expert Committee, Government of India, New Delhi.
42. Priess JA, Mimler M, Klein AM, Schwarze S, Tscharntke T, Stefan- Dewenter I (2007) Linking deforestation scenarios to pollination services and economic returns in coffee agroforestry systems, Ecological Applications 17-2 407-417.
43. Priess JA, Schweitzer C, Wimmer F, Batkhishig O, Mimler M (2010) The consequences of land-use change and water demands in Central Mongolia- an assessment based on regional land-use policies, Land Use Policy 28, 4-10
44. Punia MS (Ed.) (2009) 4th R &D Report on Tree Borne Oilseeds, National Oilseeds and Vegetable Oils Development Board, Ministry of Agriculture, Government of India, Gurgaon.
45. Ramakrishnaiah D (2006) Land Availability for Biofuel Plantation in Biodiesel Conference towards Energy Independence- Focus on Jatropha, Hyderabad, India.
46. Saikia SP, Bhau BS, Rabha A, Dutta SP, Choudhari RK, Chetia M, Mishra BP, Kanjilal BP (2009) Study of accession source variation in morpho - physiological parameters and growth performances of Jatropha curcas Linn., Current Science. 96-12.
47. Schweitzer C, Priess JA, Das S (2011) A generic framework for land-use modeling, Environmental Modelling and Software, *accepted February 2011*
48. Stehfest E, Heistermann M, Priess JA, Ojima DS, Alcamo J (2007) Simulation of global crop production with the Ecosystem model DayCent. Ecological Modelling, 209 2-4, 203-219.
49. Zomer RJ, Trabucco A, Bossio DA, Verchot LV (2008) Climate change mitigation: A spatial analyis of global land suitability for clean development mechanism afforestation and reforestation, Agriculture, Ecosystems & Environment 126, 67-80.

Supplementary Material

Below in Table 1 we present the parameters of the DAYCENT "tree.100" file, in which the tree-type plants are characterised. Carbon and Nitrogen allocation, maximum leave area index (LAI) and the efficiency of photosynthesis (conversion of energy to biomass) were adjusted in accordance to available literature. The wasteland allocation (= nutrient & water limitation) required increasing the belowground carbon allocation. Maximum leaf area index (LAI) was reduced, reflecting the open forest type structure of a mature Jatropha plantation. Note that the MAXLAI parameter is a 'semi-conceptual' parameter and does not correspond directly to values observable in forests or plantations. DayCent does not provide a 'fruit' or 'seed' compartment for tree-type plants and thus we followed the recommendation of one of the DayCent developers (Dennis Ojima 2004; personal communication) to parameterise the compartment 'fine branch' as fruits and adjust Carbon allocation accordingly (see Table 1 below) and N (C/N ~ 25 instead of ~50 for normal 'non fruit' fine branches).

Table 1 Jatropha parametrisation in DayCent

DayCent parameter	Parameter Value	Explanation
DECID	2	system is parameterized as drought deciduous
prdx (2)	0.5	coefficient, to calculate potential production as a function of solar radiation
ppdf (1)	25	Optimum temperature for production for parameterization of a Poisson Density Function curve to simulate temperature effect on growth
ppdf (2)	45	Maximum temperature for production for parameterization of a Poisson Density Function curve to simulate temperature effect on growth
FCFRAC (1, 1)	0.15	C allocation fraction of new leaves
FCFRAC (2, 1)	0.15	C allocation fraction of new fine roots
FCFRAC (3,1)	0.3	C allocation fraction of new fine branches
FCFRAC (4,1)	0.35	C allocation fraction of new large wood
FCFRAC (5,l)	0.05	C allocation fraction of new coarse roots
MAXLAI	5	Theoretical maximum LAI achieved in mature forest

Table 2 presents a list of reported yields with details of corresponding management practices (wherever mentioned). Simulated plant biomass (not shown) and yields from this study (0.6 – 1.2 Mg ha $^{-1}$) are within the range of reported yields from India (0.1 to 1.6 Mg ha $^{-1}$) (Brittaine and Lutaladio 2010).

Table 2 Yields from different Jatropha cropping systems reported from India and other tropical countries

Region / State	**Conditions**	**Seed yield reported (Mg ha $^{-1}$)**	**Reference**
Reported studies from Indian trials			
Bawal,Haryana (North India)	Intercropping with Cowpea Interrcropping with WaterMelon	0.2 0.2	(Punia 2009)
Kanpur ,Uttar Pradesh Allahabad, Uttar Pradesh (North India)	Intercropping with Wheat Intercropping with Onions	0.1 1.6	(Punia 2009)
Hyderabad, Andhra Pradesh (South India)	Intercropping with Red Gram	0.6	(Punia 2009)
Ludhiana, Punjab (North India)	Intercropping with Wheat/ Oats	0.6	(Punia 2009)
Nashik, Maharashtra (Western India)	Seven years age	< 1.25	(Gokhale 2008)
RangaReddy (AndhraPradesh) (South India)	Watering+ intercropping + Fertilizing + Pruning, at five years age	0.1	(Wani 2008)
Coimbatore, Thiruvannamalai (Tamil Nadu) (South India)	At three years of age: Rainfed conditions Irrigated conditions	 0.45 0.75	(Ariza-Montobio 2010)
Tiptur,Karnataka (South India)	Fifth year, average fertility soils + protective irrigation	0.3-0.5	(Daniel, undated)
New Delhi	Pruning+ irrigation+ intercropping	0.18	(Singh 2006)
Reported studies from International trials			
South Africa	Modelling estimates on marginal lands (rainfall > 300mm)	< 1.5	(Holl 2007)
China	Barren land Normal soils	1.7-2.2 3.9-7.5	(Weyerhaeuser 2007)

Guatemala	800 mm rainfall	1.25	(Ouwens 2007)
Brazil	1st year, late planting	0.25	(Ouwens 2007)
Indonesia	Good soil + high organic matter content	4-5	(Ouwens 2007)
India	2nd year ,high nutrient level	1.27	(Ouwens 2007)
Nicaragua	4th year	4.5	(Ouwens 2007)
Mali	-	3.5- 5	(Ouwens 2007)

From this study, simulated yields present a strong correlation (0.81) with the age of the plant as shown in Fgure1. As can be seen from the figure, Jatropha yields increase from the first year of plantation up to the 8th year of growth. From the 8th year onwards up to the 15th year, yields stabilise in a range of 0.8 - 1 Mg ha $^{-1}$.Our simulations are in good agreement with recent FAO reports (Brittaine and Lutaladio 2010) that Jatropha yields stabilise after the 7th year of growth to less than 1.25 Mg ha $^{-1}$.

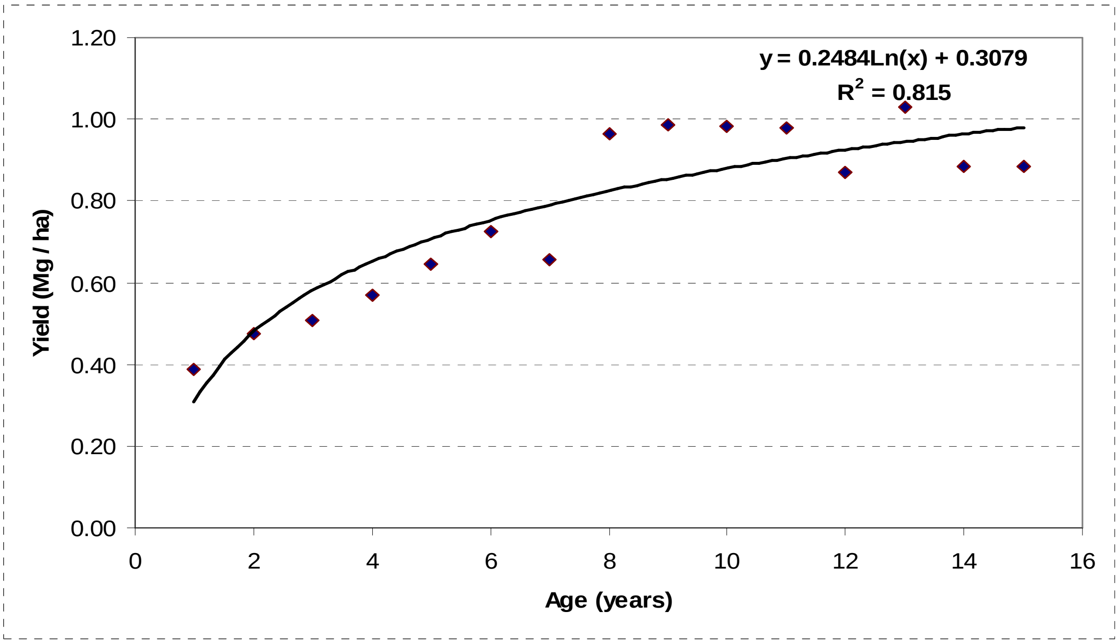

Fig. 1 Jatropha growth curve for plants aged 1 - 15 years

Furthermore, we analysed the growth of simulated Jatropha for a selected year (year 8) against mean annual rainfall [annual precipitation is obtained as DayCent output (PRCANN)].Fig 2 shows the correlation ($R^2 = 0.61$) between rainfall and yields for a set of 40 simulated locations (=pixels).

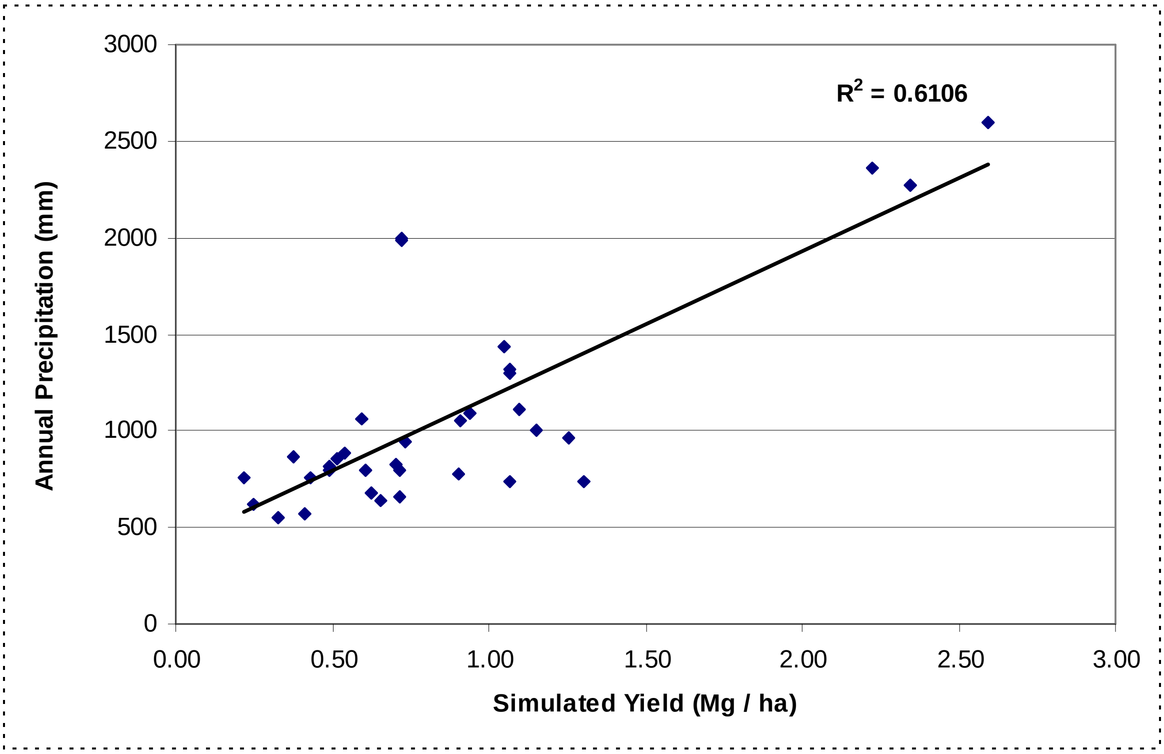

Fig. 2 Correlation between annual precipitation and simulated yields of Jatropha at the 8th year of growth

Fig. 3 District map of Karnataka

References (Supplementary)

1. Brittaine R and Lutaladio N (2010) Jatropha: A Smallholder Bioenergy Crop- The Potential for Pro Poor Development, Integrated Crop Management, Vol. 8. FAO, Rome.
2. Punia MS (Ed.) (2009) 4th R &D Report on Tree Borne Oilseeds, National Oilseeds and Vegetable Oils Development Board, Ministry of Agriculture, Government of India, Gurgaon.
3. Gokhale D (2008) Jatropha: Experience of Agro- Forestry and Wasteland Development Foundation, Nashik, India. In: International Consultation on Pro-poor Jatropha Development. 10-11 April, 2008, Rome, IFAD (Available at http://www.ifad.org/events/jatropha/),[Accessed on April 19, 2010].
4. Wani S, Sreedevi TK, Marimuthu S (2008) Pro-poor biodiesel initiative for rehabilitating degraded drylands. In: International Consultation on Pro-poor Jatropha Development. 10-11 April, 2008, Rome, IFAD (Available at http://www.ifad.org/events/jatropha/),[Accessed on April 19, 2010].
5. Ariza-Montobbio P, Lele S, Kallis G, Martinèz-Alier J (2010) The Political Ecology of Jatropha plantations for biodiesel in Tamil Nadu , India, The Journal of Peasant Studies 37, 875-897
6. Daniel J.N (undated) Jatropha production options under varied resource conditions, BAIF Karnataka, Undated. (Available at www.baif.org.in/aspx_pages/pdf/Agroforesty/SouthernRailway.pdf), [Accessed on April 19, 2010].
7. Singh B, Joshi PN (2006) Biofuel Park at Rashtrapati Bhavan, New Delhi, in Biodiesel Conference Towards Energy Independence – Focus on Jatropha, Hyderabad.
8. Holl MA, Gush MB, Hallowes J, Versfeld DB (2007) Jatropha curcas in South Africa : An Assessment of its Water Use and Bio-Physical Potential, Report to the Water Research Commission on the project ‘Investigation into the Impacts of Large-scale Planting of Jatropha curcas on Water Resources, through Process- Based Research and Modelling, 2007, WRC Report No 1497 /1 / 07, ISBN 978-1-77005-593-3.

9. Weyerhaeuser H, Tennigkeit T, Yufang S, Kahrl F (2007) Biofuels in China: An Analyis of the Opportunities and Challenges of Jatropha curcas in Southwest China, World Agroforestry Center, ICRAF Working Paper number 53, China.
10. Ouwens KD, Francis G, Franken YJ (2007) Position Paper on Jatropha curcas- State of the Art Small and Large Scale Project Development FACT Foundation, (URL: www.fact-foundation.com)

6 Modelling regional scale biofuel scenarios- a case study for India[5]

Abstract

Biofuel initiatives in India have gained momentum with the national biofuel policy targeting 20% blending of both petrol and diesel by 2017. Most of India's biofuel plans revolve around using sugarcane for bioethanol and Jatropha for biodiesel production. This study, taking the southern Indian state of Karnataka as an example, aims at estimating the potential to achieve policy targets. The study spatially analyses land use change due to biofuel expansion and its effects on food production. We used an integrated modelling framework to simulate land use change and bioenergy production under two scenarios- Industrial Economy (IE) and Agricultural Economy (AE). Results indicate that meeting the 20% blending target is a challenging goal to achieve under both scenarios. Bioethanol requirements can be nearly fulfilled (88% under IE and 93% under AE) due to sugarcane expansion. However, biodiesel demands cannot be fulfilled using only degraded lands as currently planned in India, but additional agricultural land (3-4%) will be required for Jatropha based biodiesel production. Food production will not be directly impacted until 2025, because the largest source of additional land could be short and long-term fallows.

We conclude that conservation oriented initiatives such as water harvesting and energy conservation measures can increase productivities of biofuel crops and reduce fuel demands respectively. State support and CDM opportunities can enhance economic incentives for energy cropping. Therefore a simultaneous and multi-pronged approach is needed to accomodate food and fuel demands in India.

Keywords- Bioethanol, Biodiesel, Sugarcane, Jatropha, Integrated assessment, Karnataka

1. Introduction

Biofuels have gained much ground as an important component of the renewable energy matrices at national scales. With many countries developing targets for biofuel production, an increased focus has been generated on investigating direct and indirect long-term impacts of biofuel production on natural resources such as land and water (Hoogwijk *et al.* 2005; Fargione *et al.* 2008; Bryan *et al.* 2010; Delucchi *et al.* 2010). Quantitative scenarios are used as a tool to investigate potential environmental changes and provide numerical results

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[5] Das S, Priess JA and Schweitzer C, Modelling regional scale biofuel scenarios-a case study for India, *Global Change Biology Bioenergy, submitted March 2011*

based on simulation models (Alcamo, 2008). Several authors have developed biofuel scenarios at the global scale to address land use change as an impact of biofuel production. Hoogwijk *et al.* 2005 , have studied the potential of biomass energy under different levels of land productivity using IPCC scenarios as boundary conditions. The IMAGE model was used to study biofuel production capacities at global scale and to assess feedbacks between different ecosystems in the context of biofuel production up to 2050 (Fallot *et al*. 2006). In another study, food-fuel tradeoffs have been analysed under three scenarios using the IMPACT model (Msangi *et al.* 2007). Gurgel *et al.* 2008, used a multi-regional general equilibrium model of the world economy to analyse biofuel scenarios, while the GLUE-11 model was employed to evaluate global bioenergy potential (Yanamoto *et al*. 2001). In recent years, analysis of indirect impacts of land use change has been the focus of several studies which aimed at looking beyond direct displacement of other land-uses and analysed carbon debts and payback times (Tilman *et al.* 2006*;* Fargione *et al*. 2008; Havlik *et al.* 2010; Lapola *et al.* 2010). These studies ranging from national to global scales used different approaches to analyse the complex issues of direct and indirect land-use changes (dLUC and iLUC). Dale (2009) has critically summarised the ongoing debate in an editorial stating that “current ILUC analysis does not meet scientific standards”.

National or sub-national perspectives are difficult to address in the continental to global scale studies introduced above, e.g. addressing questions like regional levels of productivity or impacts on soil fertility, which are indicators requiring the processing and application of more detailed data sources and a more process-oriented approach. Comparably, the role of regional scenarios also differs from global scenario studies in terms of the foci, research questions addressed and level of detail (Alcamo *et al.* 2008). A review of the recent regional studies shows that they considerably differ with respect to energy crops used, land use change drivers and productivity of the type of land evaluated. Commonly used methods include spatially explicit modelling, literature based approaches or a combination of both. Secchi *et al.*2010, have underlined the importance of spatially explicit approaches that allow the identification of sub-regions of particular interest that are missed by global models. The explicit identification of marginal lands is essential for biofuel potential estimation (Zhang *et al*. 2010). This is especially relevant for India, since the national biofuel plans are highly dependent on wastelands and their availability for biofuel production. Land suitability assessment is a key factor in the overall bioenergy potential estimation, which can be strengthened by including more factors than geographical constraints as demonstrated in a regional study for Italy (Ragaglini *et al*. 2010).

Although the importance of developing countries in the context of land use change and biofuels is higher than developed / OECD countries , the estimation of bioenergy potentials in these regions is frequently challenged by unclear political targets and constraints in data availability (Thrän *et al.* 2010). India, as a rapidly growing economy, is faced with the challenge of simultaneous fulfilment of strongly increasing food and fuel demands (Ugarte *et al.*2007; Das *et al.* 2010). Land - under intense pressure of supporting several requirements of the growing population ranging from housing, food, feed to energy plays a decisive role as a critical limiting factor. Efforts to take care of rising GHG emissions aggravate the challenge of developing more sustainable future (bio-) energy pathways. Consequently, the interaction of the energy and agricultural sectors need to be addressed in biofuel studies (Kløverpris *et al.* 2008). Although in India several aspects of biofuel policies and production have been studied, a review of published literature reveals that only few studies have addressed the linkage of biofuels and food production at national or sub-national scales (Das and Priess, 2011). Based upon different sets of assumptions these studies largely differ in their conclusions with respect to impacts on food production. Schaldach *et al.* 2010 have analysed the impacts of sugarcane based bioethanol development on land use change in India, using a spatially explicit simulation model. The study revealed that if food and bioethanol demands (up to 20% blending) are to be fulfilled; cropping areas would expand into areas covered by non-forest natural vegetation and degraded or wastelands. In another study, land requirements for bioethanol (from sugarcane) and biodiesel (from Jatropha) for India were simulated using a spatially explicit approach (Lapola *et al.* 2010). Results indicated that total land requirement for biodiesel would be 212,000 km² which is equal to 13% of cultivated land considering a mean yield of 3.77 Mgha^{-1}of Jatropha. However, the study did not consider the opportunities of wasteland cultivation in India which provide 556,000 km² of land (NRSA and DOLR, 2005), half of which would be sufficient to fulfil land demands for biodiesel if simulated mean yields are achieved thereby dismissing the need to divert arable land. For bioethanol estimations, the study accounted for two important pathways of ethanol production– the existing molasses and future bagasse routes, but assumed 100% ethanol use for the transport sector. However, in India ethanol has multiple end-users such as chemical, beverage and dye industries which leave only surplus ethanol for the transport sector. Contrastingly, Ravindranath *et al*. (2010) who have studied biofuel potentials of four crops (Jatropha, Palm Oil, Sugarcane and Sweet Sorghum), mainly based on existing literature, conclude that competition for land between food and fuel production is highly unlikely, mainly because biofuel production is restricted only to degraded land by policy. Further, without additional land, Jatropha based biodiesel demands are projected to be fulfilled by 21%- 57% on degraded lands under “low” and “high” scenarios of demand. The study assumes “low” (0.5 Mgha^{-1}), “realistic” (1.5 Mgha^{-1}) and “optimistic” (3 Mgha^{-1}) Jatropha biodiesel yields, which translate into 1.5 Mgha^{-1}, 4.7 Mgha^{-1} and 11.5 Mgha^{-1} of Jatropha seed yield respectively (assuming 40% oil content+80% extraction efficiency+ 99% trans-esterification efficiency). If seed yields of Jatropha are lower than those assumed in the study, the proportion of biodiesel demand that can be fulfilled would be reduced further. Thus, large variations in the results of the existing studies indicate the importance of underlying assumptions of pathways of bioenergy production, land classification systems and expected yields from different feedstocks.

This study aims to complement existing studies by covering additional aspects and improving details such as making a clear distinction between bioenergy potential on degraded lands vis-à-vis productive agricultural land, and accounting for critical losses in the production chains of ethanol and biodiesel. Additionally, we include an assessment of the sectoral use of ethanol to improve estimations for the transport sector and also improve land suitability assessment by using biophysical and economic factors and constraints. We examine total biofuel and food production as well as impacts on food security through land use change in two policy scenarios. The role of institutionalised markets and potential economic returns from energy crop cultivation are also addressed.

We applied a spatially explicit land-use model to simulate the land use dynamics of two policy scenarios, using the state of Karnataka in southern India as a case study. The main aims of this study are (i) application of cellular automata based land-use model to address food vs. fuel competition (ii) quantification of biofuel scenarios to assess potential pathways of change with a focus on land demands to meet food and energy requirements, and, (iii) analysis of current biofuel policy targets. The approximately 200,000 km^2 in this case study, are indicative of the entire South Indian region given the socio-economic and environmental similarities. Therefore the methods and concepts used in this study are well suited to address similar research questions in other states or regions in India or elsewhere. Analyses presented in this article cover total biofuel production potential, impacts on land use and food commodities and biofuel related co-benefits such as revenue generation. We conclude with future options for the Indian biofuel strategy.

2. Study Area

The study was conducted in the densely populated state of Karnataka in southern India (192,000 km^2; population 53 million (2001). The major physiographic regions of the state are the Deccan plateau which forms part of the peninsular plateau of India extending southwards and the coastal plain region on the western boundary of the state, popularly known as the Western Ghats. The region receives rainfall in two seasons - during June – September an October - December. The average annual rainfall is 1189mm with large variations ranging from 300 mm $year^{-1}$ to 2500 mm $year^{-1}$ across the state. The soils of the area can be broadly classified into red and black soils with loamy and sandy textures. Karnataka is predominantly an agricultural economy with almost 60% of the working population employed in this sector. Agriculture is characterised by a diverse cropping system that is highly dependent on rainfall.

Over recent decades the economy of the state has seen high growth rates under the influence of a favourable services sector, mainly in Information technology. With rising population and economic capacity, transport sector in the state has grown, especially in the bigger cities like the state capital, Bangalore. Escalating fuel demand has evolved into a search for alternative transport fuels such as biofuels. The state has taken several initiatives towards biofuel production. A state biofuel policy has been drafted under which a biofuel board has been established to perform advisory capacities for enhancing biofuel production (Karnataka Biofuel Policy, 2007). Examples of end users of biofuel include the Karnataka State Road Transport Corporation (KSRTC) and the Southern Railways section of the Indian Railways that run a fraction of their fleet of buses and trains on biofuels respectively (KSRTC 2010; Whitaker and Heath (2008)). “Biofuel Parks” have been set up that support the institutionalisation of biofuel markets and production technologies. State universities such as the University of Agricultural Sciences, Bangalore, have enhanced their research focus on agricultural extension for biofuels and developing business models to help farmers market non-edible oilseed produce. State NGOs (eg., BAIF) have undertaken projects involving biofuel plantation through participatory mechanisms (BAIF, 2006) . The need to pursue “aggressive scientific assessments” in several aspects of biofuel production ranging from production, agronomy, wasteland reclamation, industrial processing and second generation biofuels has been expressed by several scientists. Special emphasis has been laid on finding optimal pathways of production of biofuels without compromising food security (Biofuel Task Force, 2010).

3. Methods

The study employed the integrated modelling framework- SITE (Simulation of Terrestrial Environments), which is specifically designed for regional scale land use modelling (Mimler and Priess, 2008; Schweitzer *et al*. 2011). The SITE framework provides a platform to develop regional land-use models. SITE-Karnataka applies generic functions of the SITE framework, namely, multi-criteria suitability analysis of land use classes, cellular automata based land use allocation driven by commodity specific production/ demands (food and energy), simulation of crop growth (commodity production) by the DayCent model (Parton *et al.*1998) and inclusion of annual feedbacks into consecutive time steps. Rule sets were developed for SITE Karnataka that govern the processes of land use change in the area and simulate the effects of the introduction of energy crops on food crop production. The spatial resolution of the study was 2 x 2 km.

3.1 Land use classification

Simulation with SITE-Karnataka required an initial land use map corresponding to a historical period in time. Since such a map was not readily available at the level of detailed classification required for achieving the objective of simulating food-fuel issues, there was a need to construct the same. This was achieved by a sequence of steps given below-

(i) development of a suitable land use classification system

(ii) allocation of area to each land use class

(iii) allocation of crops to agricultural areas

The development of the land classification system was based on a combination of land classes traditionally used in the context of land use modelling, availability of time series of statistical data for these classes and regionally significant classes w.r.t the research question of food-fuel which adequately represented major sources of pressure on land. After studying all these aspects, three hierarchical tiers of land use classes were employed to arrive at the final classification (Tier III) (Table 1).

Table 1 Evolution of land use classification for Karnataka

Tier I (5 classes) (Basic classes)	Tier II classification (8 classes) (Regional details)	Tier III (14 classes) (Details for food - fuel research question)
Cropland	Cropland	Rice, Maize, Millets, Pulses, Oilseeds, Cotton, Sugarcane
Fallow	Fallow	Fallow
Population	Urban	Urban
	Rural	Rural
Forest	Forest	Forest
	Plantation	Plantation
Water	Water	Water
Other	Other	Wasteland

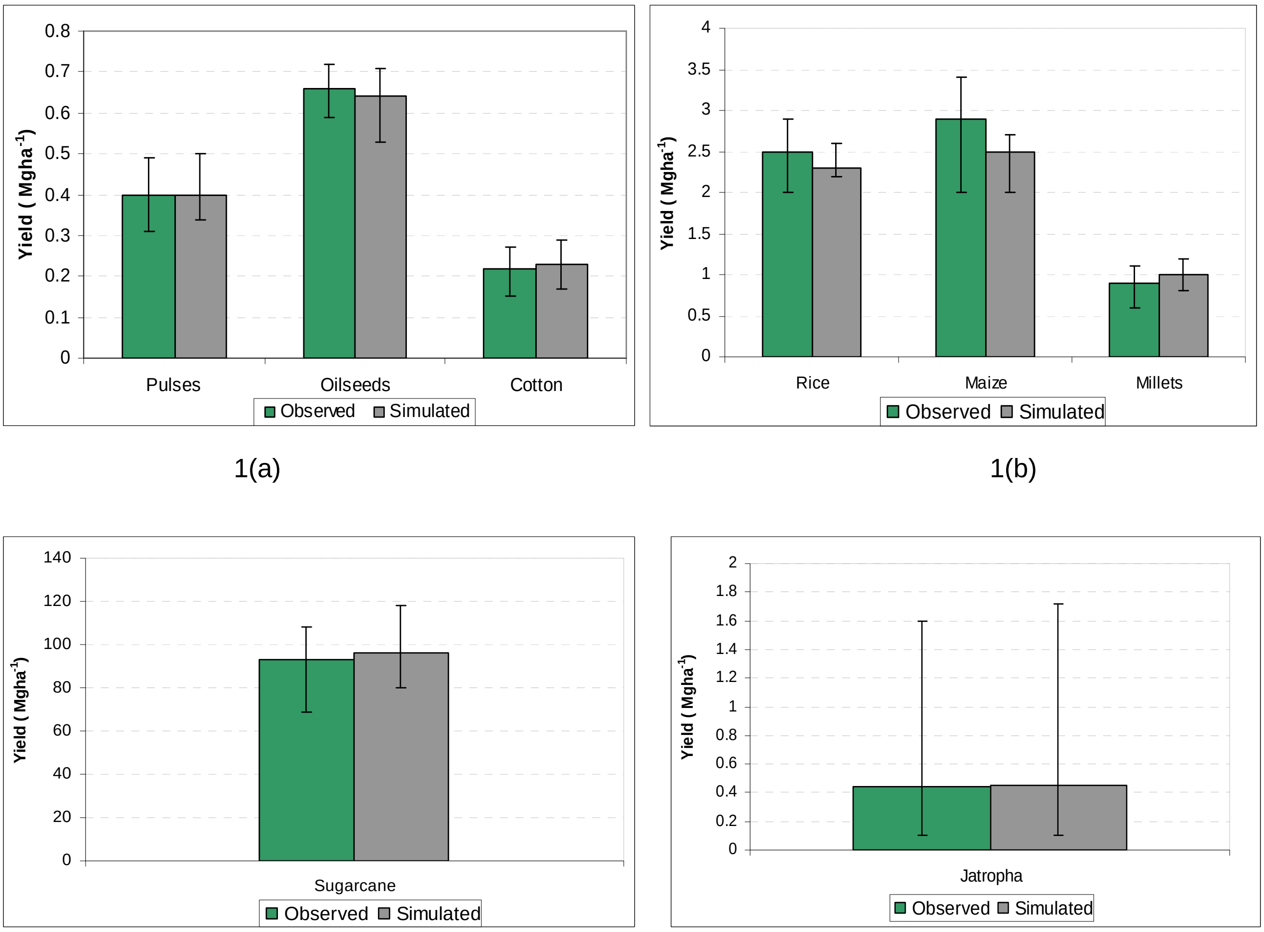
Note: Millets = Finger millet + Pearl millet + Sorghum + Minor millets

Pulses = Pigeon pea + Green gram + Lentils + Horse gram + Black gram

Oilseeds = Sunflower + Groundnut + Safflower + Castor + Niger + Linseed + Sesamum + Rapeseed

* Crops were selected and grouped based on contribution to overall food production and agricultural area covered from a total of 56 crops growing in the state; Jatropha was used as a land use class in the study but did not cover any area in the initial map

IGBP (1992) (Loveland *et al.* 2000) was used as a base map for the Tier I classification. Spatial database on land use land cover from Indian sources (NRSA 2004a) was used to improve Tier I classification by incorporating “Plantation” and refining other classes. For the distribution of urban and rural areas, administrative boundaries (up to village level) were used in combination with available demographic statistics. In the third stage, Tier III classification involved incorporation of wastelands and crop distribution. Wastelands were allocated by using the wasteland map (NRSA 2004b), since available statistics (NRSA and DOLR 2005; NRSA and DOLR 2010) indicated no significant change (less than 1 %) in the area under wastelands for the period 1986 to 2004, the wasteland area of 2004 (10,452 km^2) was also used for subsequent years. Spatial distribution of crops was the last step in arriving at the 14 class system. This was achieved in two steps- (a) simulating potential productivities for all croplands and all seven crops/crop types in the region and (b) distribution of the crops at the district level by using district area statistics and assignment of crops based on productivity ranking. The seven crops of Tier III were parameterized for Karnataka by using an adapted version of DayCent (Stehfest *et al.*2007) implemented in SITE for crop growth simulation. Figure 1(a) and 1(b) show the comparison between observed and simulated yields of food crops; 1 (c) for sugarcane and 1(d) for Jatropha. Detailed information of the parameterization of all crops is presented in the Supplement (Section I).



1(a) 1(b)

1(c) 1(d)

Note: Y Error bars denote the range of maximum and minimum observed and simulated values; R^2 (Coefficient of correlation) - Rice = 0.56; Maize =0.54; Millets = 0.57;Pulses = 0.55; Oilseeds=0.52; Cotton = 0.44; Sugarcane = 0.56; Jatropha = 0.72; data used for observed yields are based on 1992-2004 datasets; sample pixels from jatropha simulation on wastelands are compared against available data for Jatropha

Figure 1(a-d) Comparison between observed and simulated yields of major crops in Karnataka

3.2 Land use model - SITE Karnataka

The SITE Karnataka model has been developed as a tool to simulate biofuel and other crops competing for land resources using the SITE platform (Mimler and Priess 2008; Schweitzer *et al.* 2011) at a spatial resolution of 2 x 2 km. The model simulates land-use decisions in annual time-steps, using three main sub-modules for the allocation of the major land-use classes – settlements, crops and forests. Separate sub-modules handle model initialization, configuration and suitability assessment (see Mimler and Priess 2008 and Schweitzer *et al.* 2011 for further details). The DayCent model is used to calculate crop yields (Section 3.1) and the growth of natural vegetation. Simulations address important feedbacks between land use decisions and environmental changes such as crop-yields and soil properties that are taken into account in subsequent decisions. Figure 2 shows the structure of the model components and their interactions. In the following sub-sections the major components are described.

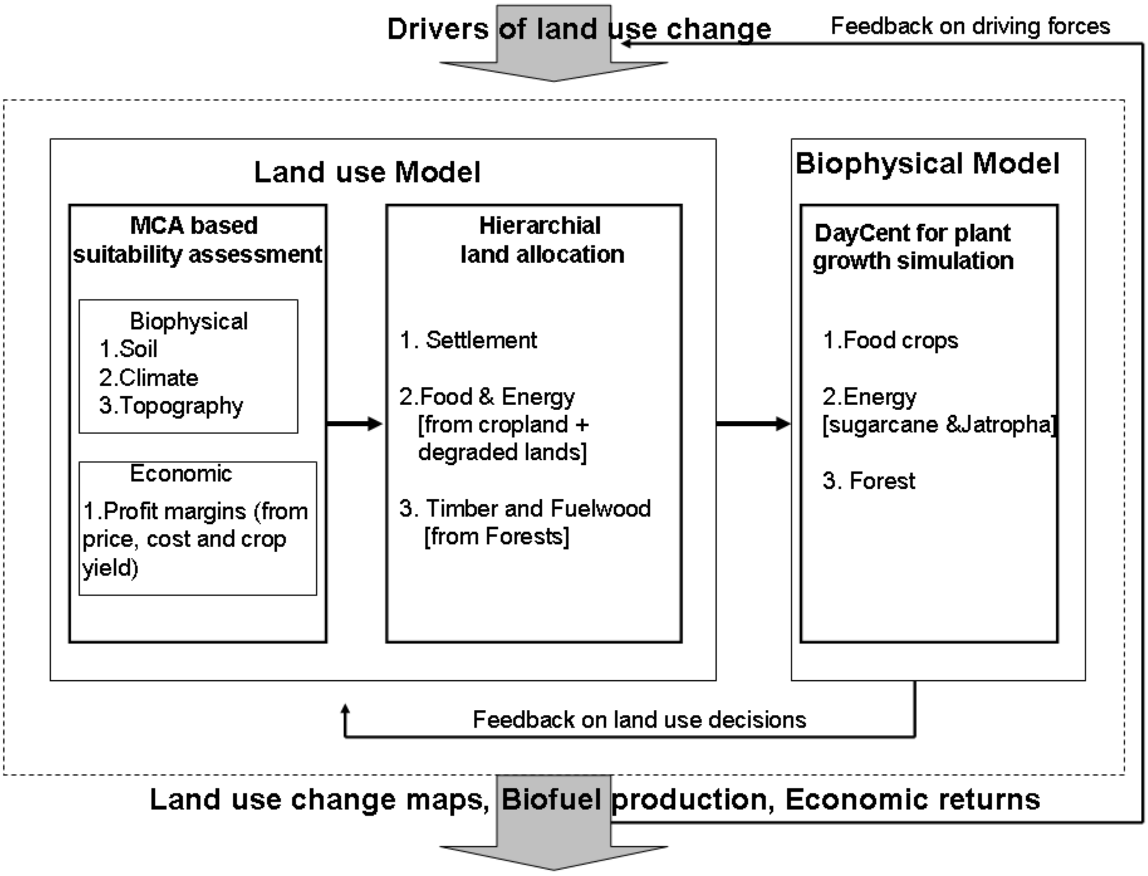


Figure 2 Structural components of the SITE-Karnataka model

Suitability assessment sub-module in SITE-Karnataka - A multi criteria assessment algorithm (Equation 1) calculates suitability maps for all land use classes represented in the model. Suitability is based on (a) biophysical and (b) economic criteria and constraints. Crop suitability is characterised by crop-specific ranges of biophysical parameters (Supplement Section II).

$$s_{kl} = \underbrace{\left(w_B \sum_{i=1}^{m} \beta_i s_{Bikl} + w_E \sum_{i=1}^{n} \varepsilon_i s_{Eikl} \right)}_{\text{suitability}} \cdot \underbrace{\prod_{j=1}^{o} c_{Bjkl} \prod_{j=1}^{p} c_{Ejkl}}_{\text{constraints}}$$

with $w_B + w_E = 1$; $\sum_{i=1}^{m} \beta_i = 1;\ \sum_{i=1}^{n} \varepsilon_i = 1;\ s_{Bikl}, s_{Eikl}, c_{Bjkl}, c_{Ejkl} \in [0,1]$

Equation 1 MCA based suitability assessement (The calculation of the overall suitability value s_{kl} for each grid cell k and land-use type l consists of two terms. In first part (suitability) the mean value of the partial suitabilities s_{Bikl} for biophysical and s_{Eikl} for socio-economic criteria are weighted using the partial weights β_i / ε_i, where *m/n* represent the total number of criteria included (Schweitzer *et al.* 2011).

The SITE framework enables the calculation of distances between grid cells, a function which is used in SITE Karnataka to incorporate distance based suitabilities, eg., suitability for growing paddy rice as a function of distance to water bodies, assuming the availability of irrigation water. Economic suitability for growing crop X is addressed by simulating the representation of agricultural markets (locations), crop prices and cost of cultivation. As in the rest of India, South India also has a strong government supported network of agricultural markets that facilitate farmers to sell their produce directly without the involvement of middle men (CSO 2010; Prasad and Prasad 1995). Most markets buy more than one type of produce. The existence, access and prices offered by these markets are parameters strongly influencing crop allocation both in reality and in the simulations. In this study, 204 agricultural markets were used (see Supplement Section II). Accessibility of markets was simulated using distance functions available in SITE. Net profit margins for each crop were calculated from time series data of cost of cultivation (Ministry of Agriculture 2007) and farm harvest prices (FHP) (DACNET 2010).Transport costs to the markets were included by representing a cost surface that determines the total cost of travel per grid cell (to a certain marketplace). Similarly, suitability for the new biodiesel crop Jatropha is based on biophysical parameters and economic criteria, additionally implementing criteria for growth on wastelands. Protected areas, such as parts of the forests of the Western Ghats were excluded from land use (e.g. timber extraction). The different sources of spatial data used and additional details are listed in the Supplement, Section II.

Land allocation – Settlement sub-module- As in most other parts of the world, in South India the allocation of land for settlements has the highest priority and hence is allocated first in the model. Census records (Census of India 1991, 2001) are used to allocate rural and urban population at the district level. Urban / rural growth in the model is simulated by distributing additional people to grid cells based on the suitability of the locations, based on typical population densities (rural = 275 persons/km^2 ; urban =2985 persons/km^2; megacity of Bangalore = 19435 persons/km^2) (Planning and Statistics Department 2005; Ministry of Water Resources 2008). If additional urban or rural space is needed, croplands and forests can convert to urban or rural pixels.

Land allocation – Crop sub-module- Crops are second in priority in the model with no additional priorities assigned to food or energy crops. Change in cropping patterns and therefore, the allocation of land for each crop is driven by commodity demands. District level production statistics (DES 2007) for each crop represent the demands fulfilled by local producers during the historical period from 1992-2004 while projected food requirements represent the demand in the scenario period (2005-2025). Demand fulfilment is achieved, starting with the crop type that has the largest difference between current production and demand. Allocation is based on crop-specific suitability results from suitability maps (suitability >0) using “candidate cells”. If productions for crop X in a year is lower than the demand, additional suitable cells (from all land use classes that are allowed to change to X) are used whereas if production is higher than the demand, cells are removed from class X and used for other crops or changed to fallow. The transition of a cell depends on several decision criteria that are evaluated consecutively for crop allocation. Allocation of fallow land is done by bringing back a fallow cell into production after one year of no cropping. Double cropping is considered upto the period 2004 after which it remains constant.

Land allocation-Forest sub-module- The main focus of the forest sub-module of the SITE Karnataka is similar to that of the other two sub-modules, i.e. to adequately represent forest growth, and analyse if demands for forest products can be met. These demands include roundwood, plywood, timber and fuelwood. Keeping in view the basic principles of forest management in Karnataka (and India) - meeting the needs of local population through sustainable management and development of forests, discontinuation of “clear felling and planting” and restricting fuelwood production to dead/fallen timbers and industrial hardwood to forest plantations (Karnataka Forest Department 2008), the demand is fulfilled in the model by using 10% of the above ground biomass simulated by DayCent. Suitable forest cells (from suitability assessment) which fulfil wood demand are “flagged” in the model, rendering it unsuitable for extraction in the following year. Demands for forest products are fulfilled in non-protected forests assuming perfect law enforcement in the protected areas of the Western Ghats. Such non-protected forest pixels may also convert to urban or rural settlements to accommodate population growth.

The entire suite of plausible land conversions are listed in the form of a two-dimensional conversion matrix (see Supplement, Table 5) that allows or prohibits changes from one land use class to another. In total, SITE-Karnataka represents three static land use classes that do not change in extent or type (water, plantation and wastelands), and twelve dynamic classes that are allowed to change to at least one other class.

3.3 Model calibration and validation

The time period 1992–2004 was used for model calibration. No biofuel crops were grown during this time period. The model run was started in 1992 based on the initial land-use map and other spatial datasets needed to drive the model (soil, elevation, weather, population etc.) (Section 3.1). Land-use change was simulated until 2004 and calibrated against a reference map of 2004. Calibration of important variables was performed based on model assumptions formulated via empirical evidence (see Supplement Section II for details of assumptions and values used in the model). The SITE framework offers several map comparison methods to test model performance. The two map comparison methods employed in this study were the Kappa statistics (to evaluate overall general agreement of land-use types between paired observations of simulated and reference pixels) and the Moving window approach (to assess the spatial location and land use structure). Table 2 shows the contingency matrix of the standard Kappa for land use class “urban” as an example (Kappa = 75%, “very good”). The overall Kappa was 0.43 or 43% which indicates “fair” agreement (Monserud and Leemans, 1992). Table 3 shows the results of the calibration based on the Moving Window (Costanza, 1989) approach for three window sizes 5, 15 and 20 pixels that correspond to areas of 100 km^2, 900 km^2, 1600 km^2. The overall value indicates 60% agreement with the reference map (with non-aggregated land use classes), based on a window size of 5 pixels (Table 3).

Table 2 Kappa contingency matrix for the land use class “Urban”

		Map 1		
		Urban	All others	Sum
Map 2	Urban	0.0210	0.0068	0.0278
	All others	0.0064	0.9658	0.9722
	Sum	0.0274	0.9726	0.9868
		Urban 0.7539		

Overall Kappa value = 0.42

Kappa = $(\sum f_o - \sum f_e) / N - \sum f_e$

where f_o = sum of observed frequencies in the diagonal (shown in the table)

f_e = sum of expected frequencies in the diagonal

N = Number of cells

Table 3 Map comparison based on the moving window approach

Moving Window	Window size = 5	Window size = 15	Window size = 20
Overall	0.60	0.67	0.69
Cropland	0.97	0.98	0.98
Fallow	0.98	0.99	0.99
Urban	0.99	0.99	0.99
Rural	0.97	0.97	0.97
Forests	1.0	1.0	1.0

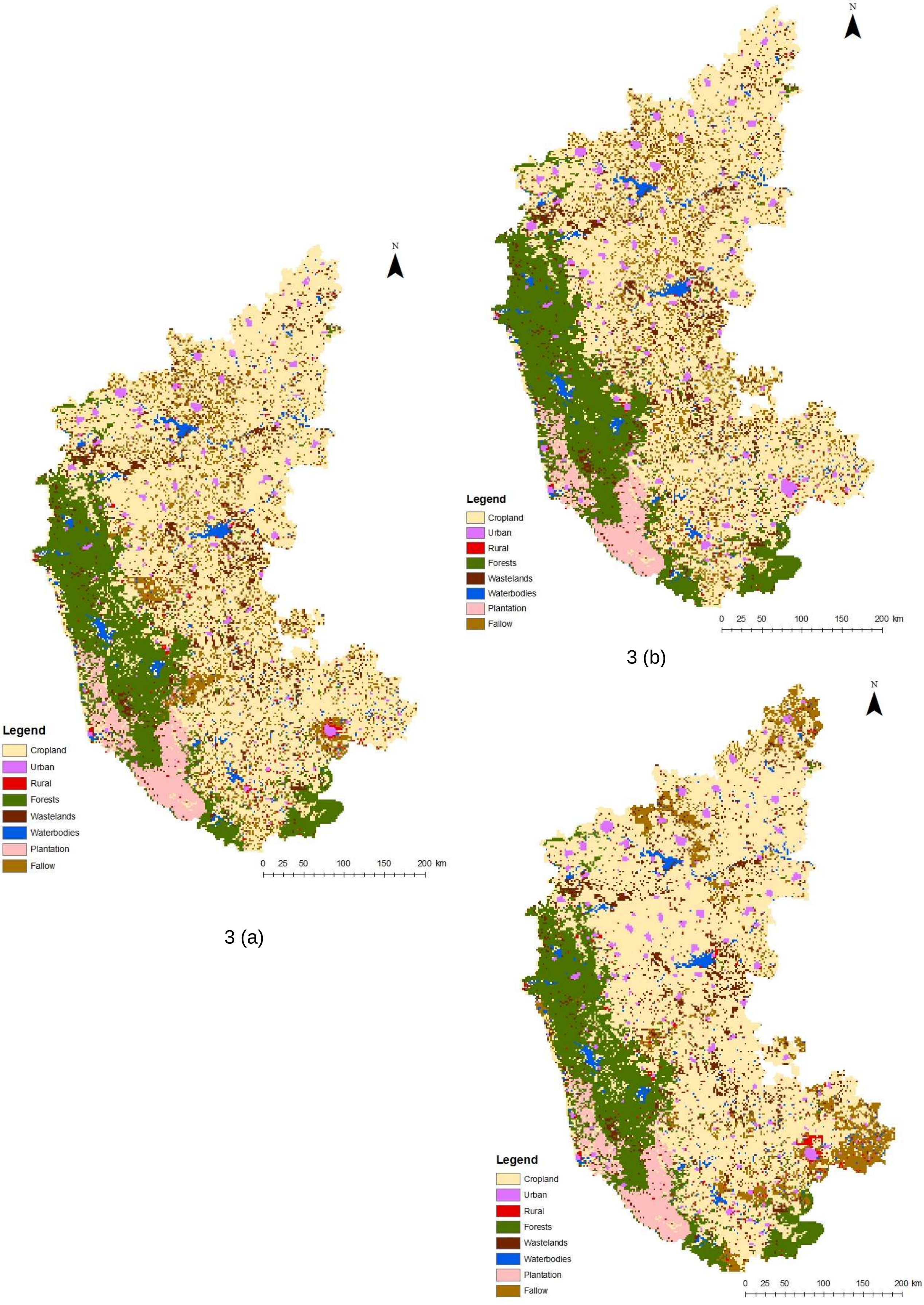
Note: “Overall” refers to map comparison result using disaggregated classes

Figure 3 and Table 4 show the spatial and statistical comparison between simulated and reference maps of land use classes in Karnataka.

Table 4 Comparison of simulated and reference land use areas for the year 2004

Land use class	Reference (km^2)	Simulated (km^2)	Difference from Reference (%)
Total cropland	114,992	114,088	-0.8
Fallow land	16,160	14,680	-9.2
Urban settlement	5,256	5,324	1.3
Rural settlement	2,572	2,936	+14.2
Forest	31,108	31,232	+0.4

Note: Static land use classes “Water”, Wasteland” and “Plantation” are not shown here



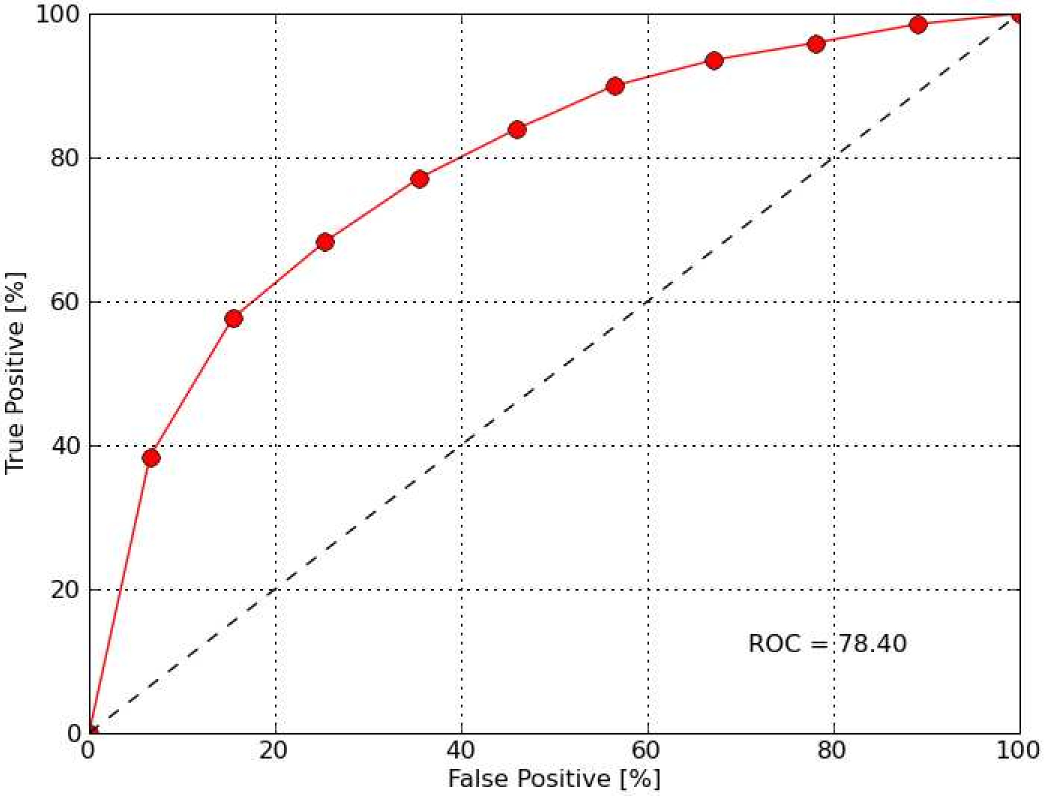
3 (a)

3 (b)

3 (c)

Figure 3 (a-c) Land use maps of Karnataka: 3 (a) 1992 land use; 3(b) 2004 reference land use; 3 (c) 2004 simulated land use

We partly validated the model by the Relative Operating Characteristic (ROC) method (Pontius *et al.* 2001) which aimed at estimating the extent of agreement between suitability assessment and actual allocation of land use classes. ROC is a useful model validation method for assessment of multi-criteria based suitability driven land use modeling. At each time step in the simulation, suitability maps for all classes are used that drive the land use allocation (Section 3.2). Therefore simulation of land use change is highly dependent on the accuracy of suitability maps. ROC is illustrated in the form of a graph, with the rate of percentage of true positives (grid cell changed both in reality and simulation) on Y axis and false positives (grid cell changed in the model but not in reality) on X axis, and the area under the curve indicating the agreement between simulated suitabilities and actual land allocation. The resultant ROC value for the class millets which that covers maximum area was 78.4% (Figure 4). ROC values for other classes are 75.05% (Rice), 84.84% (Maize), 96.3% (Pulses), 92.2% (Oilseeds), 95.2% (Cotton), 88.5% (Sugarcane) and 94.4% (Urban).



Note: Y axis indicates true positives, X axis indicates false positives and area under the curve indicates percentage of agreement (for details please refer to Section 3.3)

Figure 4 ROC analysis for the land-use type”millets”

3.4 Policy Scenarios

Two sets of scenarios were quantified for the time period 2005-2025 using 2004 as the base year (year after which scenario assumptions diverge). We explored future pathways of land use change in the form of - “Industrial Economy (IE)” encompassing higher economic and technological growth rates with higher population due to improvements in the health-sector and “Agricultural Economy (AE)” assuming the strengthening of the agricultural sector and less emphasis on technological progress up to 2025. Scenario storylines cover parameters of economic and population growth, food demands, bioethanol and biodiesel demands, costs of production and producer prices of agricultural commodities. In both scenarios it is assumed that the political targets of 20% mix of bioethanol and 20% biodiesel are met from 2017 onwards. The scenarios were based on existing scenarios of per capita food demand (Mittal et al., 2008), population (Census of India, 2006) and fuel demand (Ministry of Petroleum and Natural Gas, 2006).

Storyline Scenario Industrial Economy (IE) - This scenario assumes that the GSDP (Gross State Domestic Product) would grow at a rate of 9% p.a. Growth would be dominated by industrial output, mainly from the manufacturing and services sectors. Agriculture would play a relatively smaller role in the GSDP with its growth rate being 3.5% p.a. Karnataka has already achieved the national population growth rate target of 2.1% TFR (Total Fertility Rate). Hence it is assumed that under this scenario population would continue to grow at the same TFR. Control of fatal diseases such as AIDS which contribute substantially to total mortality would be more successful than currently. We therefore apply a “Without AIDS” concept to IE. Food commodities will see an increase in demands. Due to higher income levels and increased urbanisation, demands for some commodities would grow faster than others (e.g. maize demands would grow by 6 % p.a. due to higher demand for poultry production, which mainly depends on maize as feed). IE assumes a 10% annual growth rate of the poultry industry. Similarly, in an industrialized and high economic growth future, export of the main cash crop of the state, cotton, would rise significantly by 20% from 2004 levels. In the transport sector, gasoline (petrol) and HSD (High Speed Diesel) demand would rise to 1.55 million tons and 5.43 million tons respectively. Bioethanol and biodiesel demands were calculated accordingly to achieve the 20% blending target of the Indian biofuel policy by 2017. Technological improvements would be faster in the IE scenario than the AE scenario. Hence it is assumed that technical improvements in various stages of alternative energy production would be achieved. In the case of biodiesel, oil content of 40% and an extraction efficiency of 81% would be achieved by 2025. Transesterification losses would be reduced to 1% by 2025. Cost of production of agricultural commodities, as well as that of Jatropha based biodiesel would increase due to higher economic growth coupled with higher inflation rates. Prices earned by growers would also see a rise in the future (details are provided in the Supplement Section III).

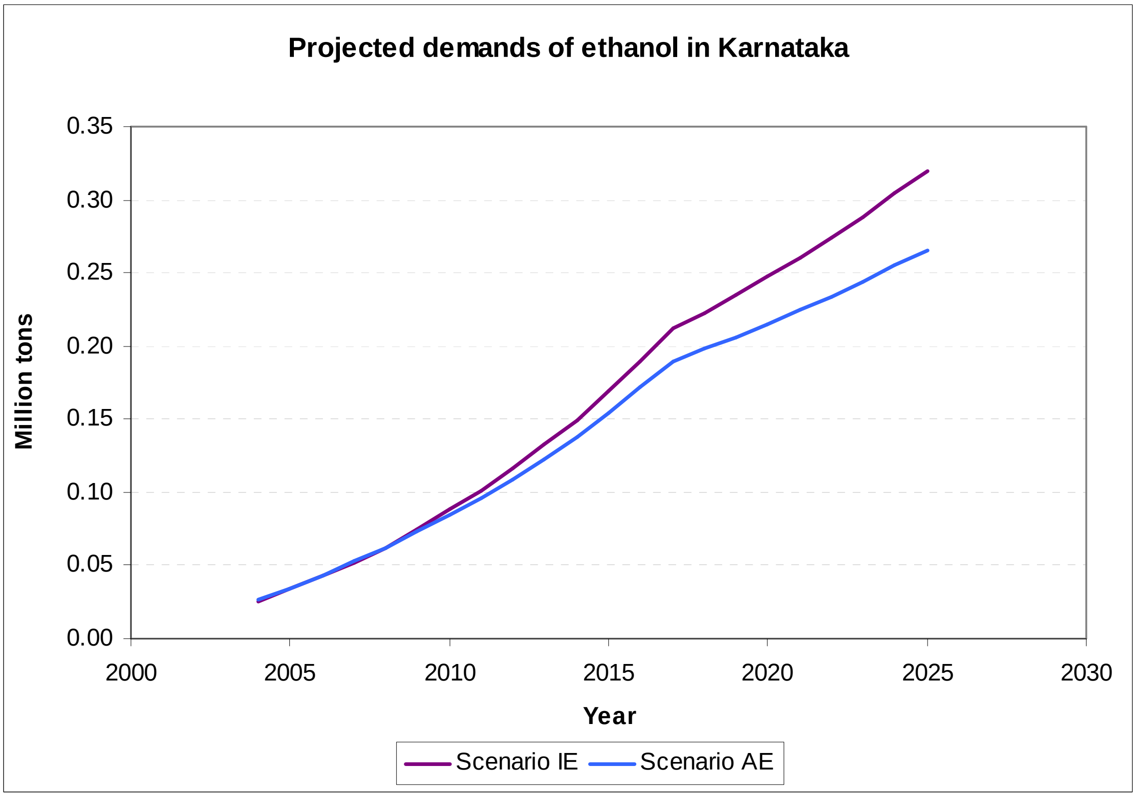
Storyline Scenario Agricultural Economy (AE) - It is assumed that the GSDP grows by 8% p.a. until 2025 in the AE scenario with a greater emphasis on the agricultural sector, growing 4% annually. Population grows with the same TFR as in IE but the awareness level of fatal diseases (including AIDS) is low and hence total population is less than in the IE scenario. Agricultural production is enhanced and per capita staple food demand (eg., millets, pulses, oilseeds) is lower than in IE due to lower purchasing power. Due to lower rates of inflation, total cost of production and revenues earned are assumed to be lower than IE. The scenario assumes increased dependence on the agricultural sector and fulfilment of commodity demands through regional production. Export levels are lower than the IE scenario (e.g. 10% growth for cotton exports is assumed until 2025 from 2004 figures). The transport sector shall expand at a lower rate than the IE scenario, hence the requirements for alternative fuels will be lower. Gasoline and HSD use are expected to grow to 1.29 million tons and 4.88 million tons respectively in 2025. However, due to slower technical improvements, interim processes of biodiesel manufacturing and biotechnological improvements are expected to be less successful than the IE scenario. Hence 35% oil content of Jatropha would be reached by 2025, and extraction efficiency would be able to grow up to 68% by 2025.

Five “market places” for Jatropha based biodiesel (at the locations- Doddabati, Tiptur, Bangalore, Mangalore and Mysore) were used in both scenarios; these locations are sites of biodiesel plants currently in operation or established purchase centers (K1 Jatropha Oils, Government Purchase centers and Labland Biodiesel Pvt Ltd.). Both scenarios assume equal demands for forest products, continuing the trend of steadily declining demands on the forest sector and reflecting that forest conversion is prevented by legislation. Thus, in this study no conversion of forests to agricultural land (or for energy production) is possible.

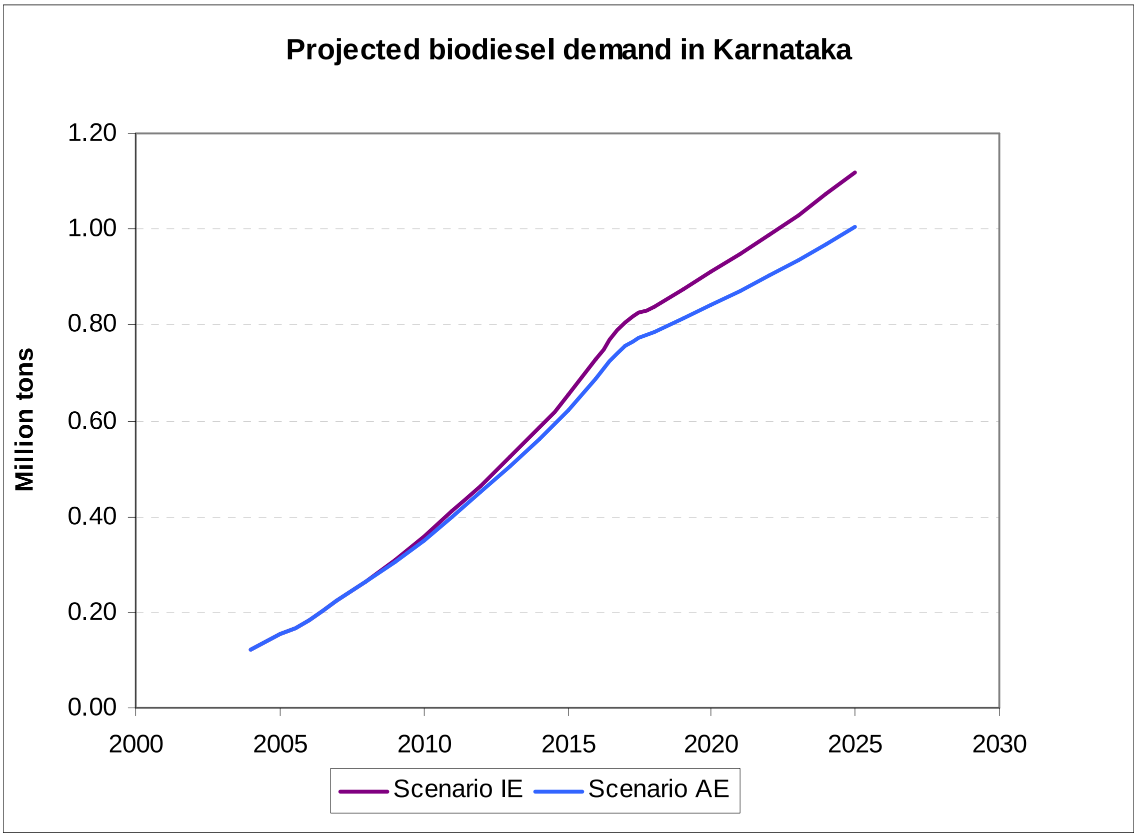
Table 5 provides a summary of the key assumptions used in the two scenarios. Figure 5(a) and 5(b) depict the bioethanol and biodiesel demand up to 2025 in both scenarios based on the 20% blending target to be achieved in 2017. Details of the methods of quantification of the various components for both scenarios used in the model are given in the Supplement (Section III).

Table 5 Quantification of commodity demands in scenarios IE and AE in 2025

Commodity	Total demand Scenario IE	Total demand Scenario AE	% Difference (IE and AE)	Unit
Foodgrain demand	17,450,377	16,669,709	5%	Million tons
Oilseeds demand	4,331,154	3,865,708	11%	Million tons
Maize	4,801,691	4,335,009	10%	Million tons
Sugarcane demand	32,631,706	26,830,793	18%	Million tons
Bioethanol demand	0.32	0.27	16%	Million tons
Biodiesel demand	1.12	1.0	11%	Million tons
Population	66,541,000	65,742,508	2%	Million



5(a)



Note: Petrol and diesel demands are assumed to increase after 2017 but ethanol and biodiesel blending is constant at 20% after 2017

5(b)

Figure 5 Scenario demand of bioethanol 5(a) and biodiesel 5(b) in Karnataka

4. Results

Simulations for the two scenarios IE and AE were run until 2025. Figures 6 (a-c) show the results of the simulations and Table 6 shows the area under different land use classes for Scenario IE and Scenario AE.

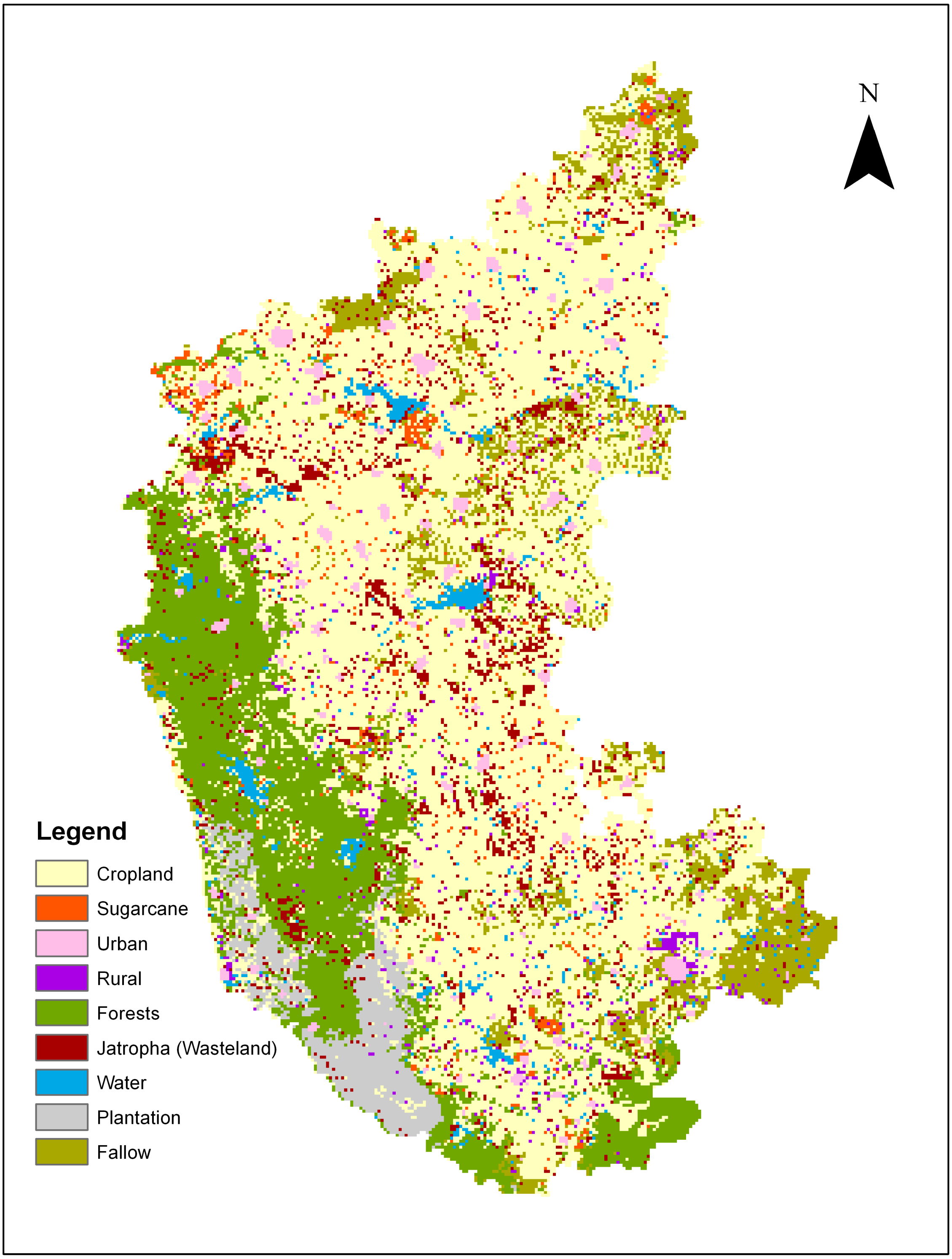


Figure 6(a) 2004 Reference map

Figure 6 Land use in Karnataka in 2004 6(a) and 2025. Scenarios IE 6(b) and AE 6(c) showing bioethanol production (sugarcane) and biodiesel production (jatropha) on wastelands and agricultural land

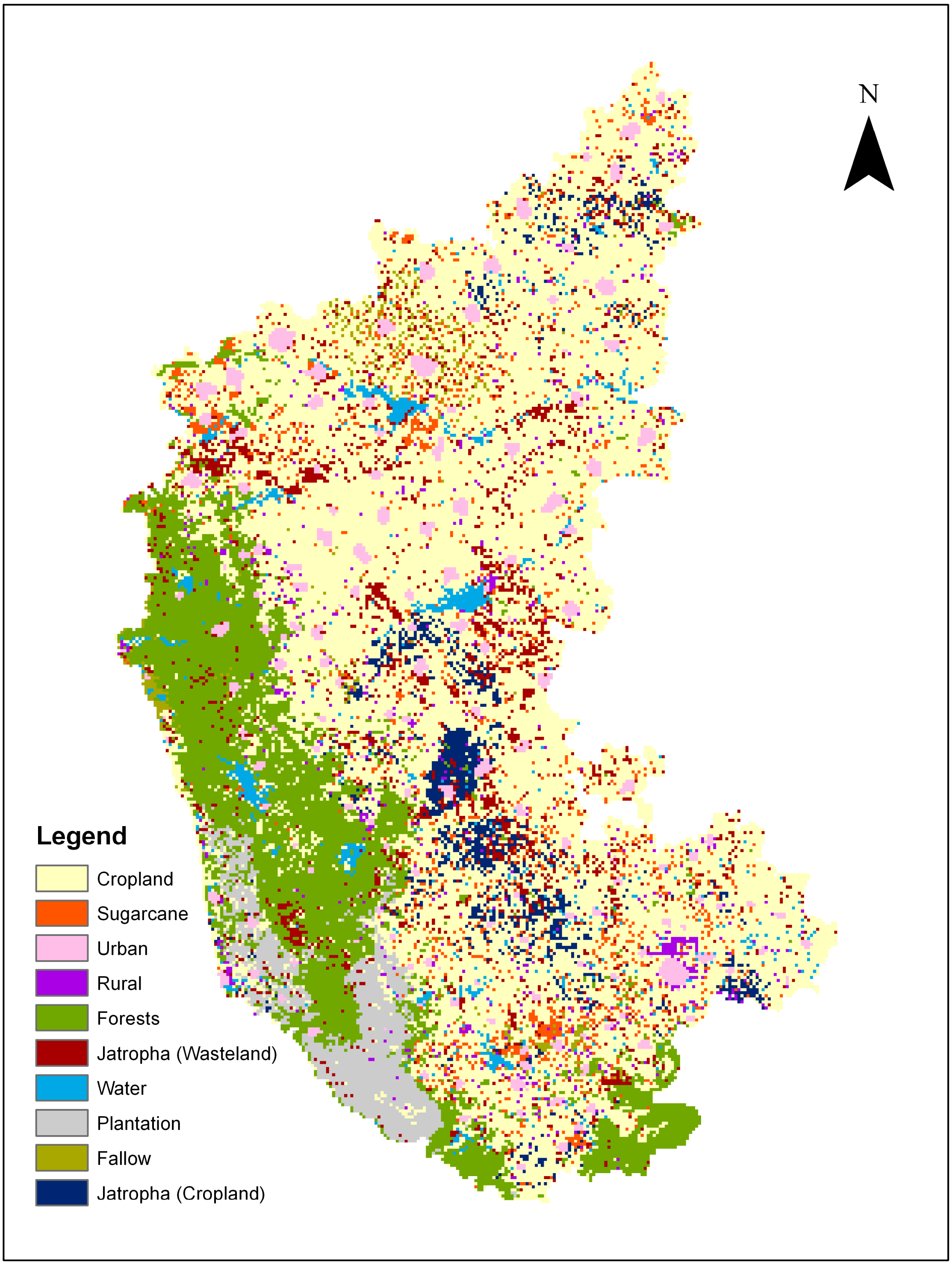


Figure 6(b) IE Scenario 2025

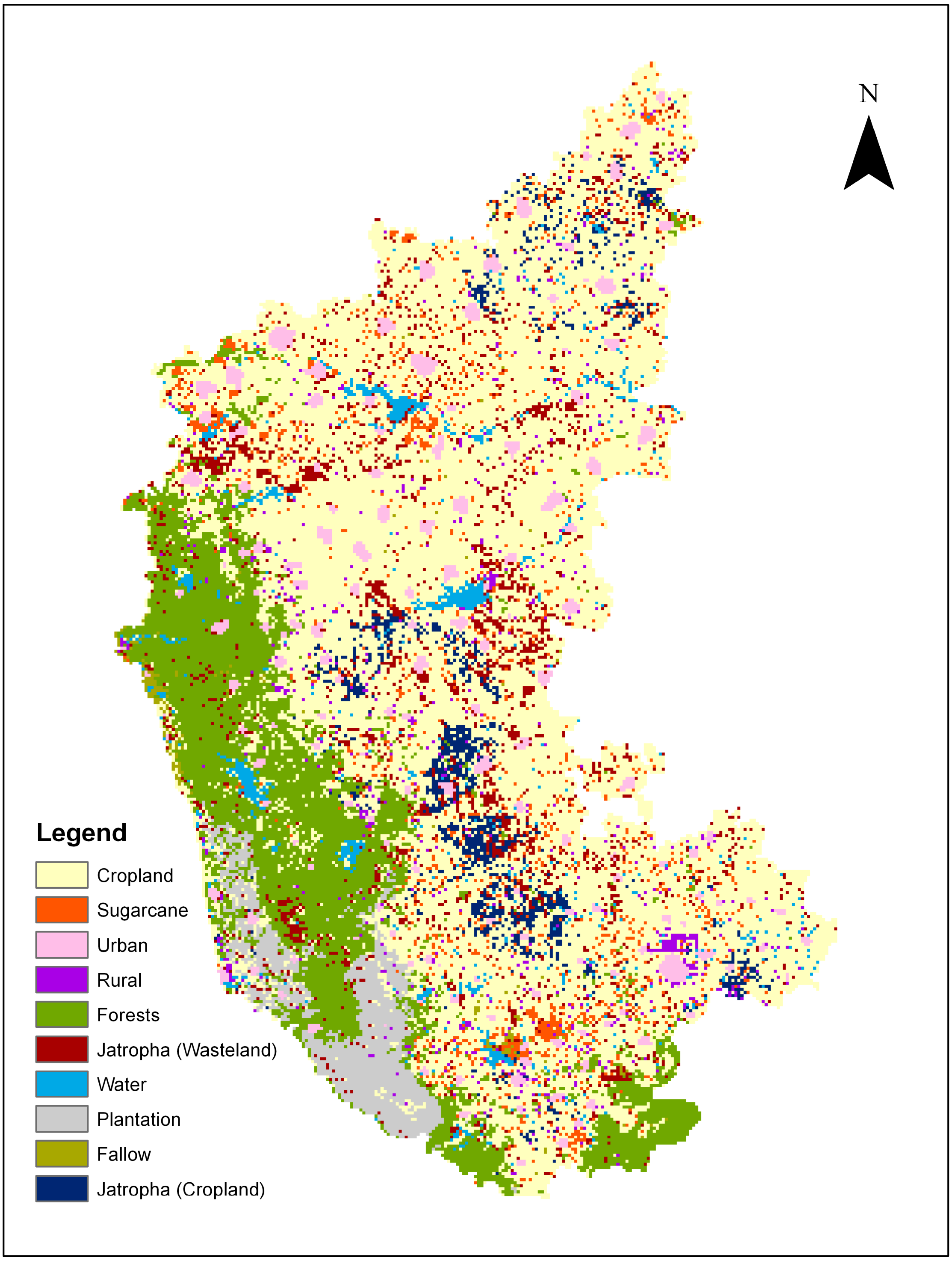


Figure 6(c) Scenario AE 2025

Table 6 Land use areas in scenarios IE and AE

Land use class	**2004 (km^2)**	**2025 IE Scenario (km^2)**	**2025 AE Scenario (km^2)**	**Difference between IE and AE (%)**
Net Area Sown	114,088	118,678 (+4%)	119,700 (+5%)	-0.9%
Area sown more than once	25,170	25,170	25,170	0
Gross cropped area	139,258	143,848(+3.3%)	144,870 (+ 4%)	-0.71%
Fallow	14,680	1,976 (-87%)	952 (-94%)	+52%
Urban	5,324	7,556 (+42%)	7,528 (+41%)	+1%
Rural	2,936	3,128 (+7%)	3,080 (+5%)	+2%
Jatropha	0	5,920	5,992	+1
Sugarcane	3,964	7,652(+93%)	7,324 (+84%)	+4.2%
Maize	10,744	18,112 (+69%)	16,012(+50%)	+12%
Total reported area	191,612	191,612	191,612	

Note- Figures in parentheses show the percentage difference from 2004

Table 7 Land use change between 2004 and 2025 in scenarios IE and AE

To From	Cropland		Fallow		Urban		Rural		Jatropha	
	IE	AE	IE	AE	IE	AE	IE	AE	IE	AE
Cropland	0	0	0.92 (1280)	0.44 (616)	1.2 (1668)	1.17 (1636)	0.16 (220)	0.13 (184)	3.6 (5012)	3.72 (5180)
Fallow	87 (12768)	90 (13228)	0	0	2 (296)	2.04 (300)	0.05 (2)	0.03 (4)	6.21 (912)	5.53 (812)
Rural	0	0	0	0	2.3 (68)	2.59 (76)	0	0	0	0
Forests	0	0	0	0	0.64 (200)	0.63 (196)	0.08 (24)	0.08 (24)	0	0

Note: Numbers indicate % change between 2004 and 2025; numbers in parentheses represent area in km^2

IE - Scenario Industrial Economy and AE- Scenario Agricultural Economy

It can be observed from Figure 6 that fallow land decreases considerably under both scenario assumptions, converting to cultivated area and Jatropha. However, in AE scenario, the decrease in fallow is more pronounced (95%) by 2025 as against in the IE scenario (93%). Net sown area increases in both scenarios to cover additional food demands. Area under urban occupation increases by 42% in Scenario IE and 41% in Scenario AE. Growth in rural areas however is slower compared to urban areas with a net growth of 6.5% (Scenario IE) and 4% (Scenario AE). Forest area in Karnataka decreases slightly by less than 1% in both scenarios. Table 7 shows the important conversions between various land use classes. The most notable changes occur in the area of fallow land available. Food demands are covered but some differences amongst crop types are visible, most prominent being that of maize. Under Scenario IE assumptions, maize expands by almost 70% (from 2004) as against 50% expansion under Scenario AE. Due to increased demand of food and fuel, fallow land is converted to cropland including the bioenergy crop Jatropha. When demands for Jatropha seeds grow beyond the amounts which can be produced on wastelands, the energy crop spreads like other crops to available fallow land and agricultural land. A sharp reduction in fallow areas is observed under both scenarios, with up to 90% of former fallows being used to produce food crops and up to 6% to produce Jatropha. The fractions of cropland diverted to Jatropha under scenarios IE and AE are 3.6% and 3.7% and that of fallow land is 6.2% and 5.5 %. If fallow land is treated as “cropland”, the net conversion to Jatropha is 3.8% and 4 % under Scenarios IE and AE respectively. Jatropha cultivation is concentrated in the central districts (Davangere, Chitradurga) whereas limited parts of the southern (Tumkur, Chamrajnagar and Kolar) and northern districts (Gulbarga) are diverted to energy production.

Biofuel targets of the state are 20% blending for both bioethanol and biodiesel. Our simulations indicate that bioethanol targets cannot be fulfilled completely under either scenario. Ethanol production in India is from the molasses route. During distillation, 4% molasses per ton of sugarcane is produced, 25% of which equals ethanol after fermentation (Ghosh and Ghose 2003; Kumar and Maithel 2006). In India, the primary consumers of ethanol are the chemical and beverage industries. The average fraction of ethanol available for the transport sector is about 40%. Area under sugarcane increased by 42% and 37% by 2017 in Scenario IE and Scenario AE respectively. Continuing existing trends, the largest sugarcane expansion is observed in the north-western districts of Belgaum and Bagalkote. Total ethanol production for the transport sector is 0.18 million tons (Scenario IE) and 0.17 (Scenario AE) million tons respectively, fulfilling 88% and 93% of the demands by 2017.

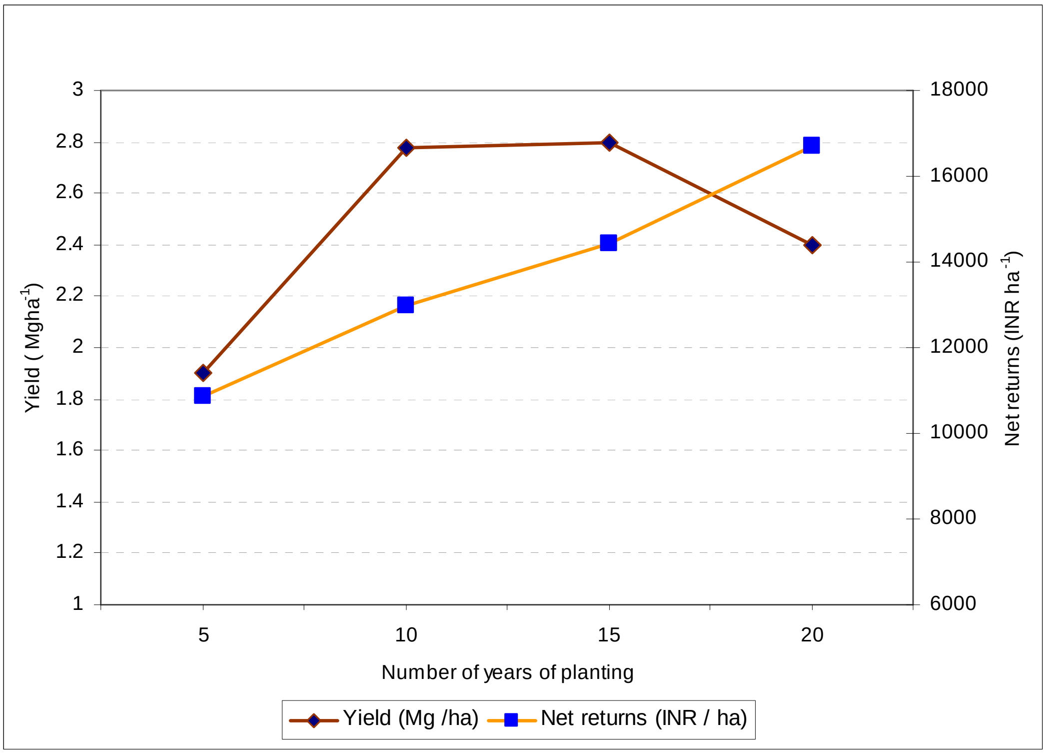
The total biodiesel production calculated in this study is based on Jatropha production on wastelands and additional Jatropha production on agricultural land which occurred if biodiesel demand could not be fulfilled by growing it on wastelands alone. In both scenarios, land conversion from agricultural land (including fallow) to Jatropha seems to be inevitable under the plausible conditions assumed therein. In Scenario IE, the total production of biodiesel is 0.79 million tons in 2017. This is almost equal to the demand of 0.8 million tons. The total production from wastelands was 0.21 million tons (26%) while production on agricultural land was 0.58 million tons (74%). Under Scenario AE conditions, the total demand of 0.76 million tons is met by 2017, with wasteland production contributing 29% (0.21 million tons) and agricultural land contributing 71% (0.5 million tons). Land conversion due to Jatropha based energy production is only marginally higher under Scenario AE (4%) than Scenario IE (3.89%).

An economic analysis of bioenergy crops showed large differences in sugarcane and Jatropha production systems. While sugarcane consistently remains the most profitable crop in Karnataka with net margins of reaching 122,500 INR ha^{-1} by 2025, Jatropha perfoms poorly with respect to economic benefits to farmers. Figure 7 and Table 8 show the average estimates of profits and yields until 2025 on agricultural land. Our results indicate that when Jatropha is planted in 2005, the first positive net returns are achieved in 2010, i.e. the first four years of cultivation incur losses due to the very high establishment costs and low yields during the initial years. We used a simple approach of cash-flow analysis by calculating the Internal Rate of Return (since there is a large initial investment involved) for different time periods for jatropha cultivation to assess the economic feasibility of the crop. Results suggest that although, after the fifth year, net returns are positive, IRR even after ten years is -1% in Scenario IE and -3% in Scenario AE. By the end of the 20th year of the plantation IRR rises up to 9% (Scenario IE) and 14% (Scenario AE). Hence, Jatropha cultivation under the assumed cost and price structures is limited in its capacity to provide adequate returns to farmers on initial investment and subsequent re-investment of interests earned from profits.

Table 8 Net returns from sugarcane and Jatropha in Scenario IE and Scenario AE

	Scenario IE		Scenario AE	
Year (years of plantation of Jatropha)	Net returns Sugarcane (INR/ha)	Net returns Jatropha (INR/ha)	Net returns Sugarcane (INR/ha)	Net returns Jatropha (INR/ha)
2010 (5)	24,082	1,289	24,814	1,232
2015 (10)	49,029	12,431	38,014	7,092
2020 (15)	76,102	12,980	57,862	12,083
2025 (20)	122,711	16,696	75,712	13,922

Price of Jatropha seed: 8.25 INR / kg; IRR at 10 years of plantation: 9%; Inflation rate: 14% per yearIE - Scenario Industrial Economy and AE- Scenario Agricultural Economy



Note: Jatropha yields are calculated from production on agricultural land; this figure corresponds Scenario IE ;Internal Rate of Return (IRR) for Scenario AE were too low to be calculated for the first 15 years

Figure 7 Economic evaluation of net returns from Jatropha cultivation

5. Discussion

This study reveals that the two most important drivers of future land use change in south India are increasing population and fuel demand of the transport sector. Moreover, despite changes in cropping pattern, current targets of 20% blending of gasoline (with ethanol) cannot be met whereas that of diesel (with non-edible oil) can be almost be achieved by 2017. Questions have been frequently raised about the viability of accomplishing the current political biofuel targets which have been often termed “over-ambitious” (Biswas *et al*. 2010; Das and Priess 2011). It is interesting to note that current policies aim at fulfilling demands of biodiesel by using production (mainly from Jatropha) on degraded land under rainfed and unfertilized conditions (Ministry of New and Renewable Energy 2009). However, our study is a strong indication that the 20% blending mandate is based on an overestimated potential productivity of Jatropha, especially on wastelands.

Assuming 100% availability, degraded lands or wastelands can contribute around one quarter to fulfil demands, whereas the rest has to be cultivated on agricultural land. Simulated results of Jatropha production indicate low yields on wastelands (0.85 Mgha^{-1}) and comparatively higher yields on agricultural land (2.2 Mgha^{-1}after six years of planting). Our results, which take nutrient and water limitations into account, confirm studies based on field measurements and farmers’ perceptions (Ariza-Montobbio and Lele 2010; Shinoj *et al.* 2010; Brittaine and Lutadalio 2010; NOVODB 2010) that the productivity of degraded lands is low and has been overestimated previously by a number of mostly large scale assessments, not specifically aimed at wasteland productivity (Lapola *et al.* 2009; Zhengguo *et al.* 2010; Trabucco *et al.* 2010). Low productivity of Jatropha has also been reported from experimental outputs of four years research developed and conducted by the NOVOD board collaborating with more than 30 national research institutes in India (NOVODB 2010).

Furthermore, our results imply that sugarcane based bioethanol will fail to meet the required demands under both scenario conditions, either of rapid industrialization with higher technical inputs or an agricultural based economy. The results show that despite 42% (Scenario IE) and 37% (Scenario AE) increase in sugarcane area by 2017, ethanol demands would not be fulfilled. Sugarcane being a food-fuel crop serves multiple demands of sugar, sweeteners, chemical industries, beverage industries and bioethanol production. The shortfall in ethanol production for the transport sector is attributable to several sections of the production chain and no singular limiting factor is identifiable. In this study, we considered the molasses based ethanol production route in both scenarios, which is one of the major limitations for the production of bioethanol. Net yields from molasses based production are seven times lower than bagasse based production (Bharadwaj *et al.* 2007). The bagasse route could therefore be more profitable than the molasses route. However, most distilleries in India have traditionally used the molasses route, based on the traditional and current focus on sugar production. Secondly, sugarcane expansion is highly dependent on the expansion of irrigation systems and availability of water. Bharadwaj *et al.* (2007), have shown the role of drip irrigation in sugarcane production and yield increment. In Karnataka, the second largest sugarcane producer in India, a marginal increase in sugarcane production may be sufficient to fulfil bioethanol requirements, although this assumption cannot be transferred to the entire country. Therefore, dependence on the productivity of sugarcane and expansion of irrigation are critical for future ethanol availability. One important area of intervention that is yet to be explored is the introduction of Fuel Economy norms in the country. Several countries, e.g. the USA, the European Union, China and Canada have already successfully implemented fuel economy norms to reduce vehicular emissions (Clean air initiative for Asian cities 2010). Presently, India does not have mandatory norms/regulations in this direction although efforts are already underway (Sethi N 2007). Increasing the fraction of diesel vehicles that currently constitutes 30 % of passenger vehicles and introducing several short, medium and long-term technical improvements in vehicular efficiency for both gasoline and diesel automotives can contribute substantially to energy conservation and reduction of current and future fuel use, demands for biofuels, as well as GHG emission. Encouraging the cultivation of other dual use food-fuel crops such as sweet sorghum, cassava or sugar beet in combination with decentralized processing of ethanol, would increase ethanol production and hence would contribute to fulfil the 20% blending goal.

With respect to land use change, our results clearly indicate that if, as mandated by the Indian biofuel policy, no agricultural land is diverted to energy crop production, a 74% deficit of biodiesel under IE Scenario conditions or a 71% deficit under AE Scenario conditions can be expected. Both sugarcane and Jatropha expansion occurred in the simulations to fulfil biofuel targets. Due to rising demands of food and fuel, a large decrease in fallow areas was simulated. The strong decrease of fallow areas (95% and 93% in Scenario IE and AE) may prove to be an unsustainable process of land use intensification, as fallows under current management and climate conditions are needed for livestock and to restore soil fertility levels.

In the study, we assumed no increase in double cropping areas beyond 2004. The cropping intensity (ratio of net area sown to gross cropped area) of the state rises to 82% by 2025 which is detrimental for soil productivity. Moreover the average life time of Jatropha plantations is more than food crops. Consequently, fallow land once converted cannot easily be re-converted back to croplands without incurring huge losses in case of crop failure. Across much of India, the conversion of cropland may be detrimental, especially to poor farmers with small land parcels, who mainly use their produce for subsistence and not as commercial crops. Therefore, small/ marginal farmers may be exposed to high risks in

Jatropha cultivation as they may be simultaneously faced with financial and food deficits. The findings of our study are in agreement with Shinoj *et al*. (2010) and Ariza-Montobbio and Lele (2010) who have reported the conversion of fallow land in other Indian states for Jatropha production and substitution of edible oilseeds with Jatropha in south India respectively. Several studies have observed yield increases in irrigated Jatropha systems (Gupta *et al.* 2010; Behera *et al.* 2010; Lapola *et al.* 2009). With merely 30% of cropland under irrigation, water availability for irrigation of Jatropha is limited. However, Jatropha yields can be enhanced through conservation oriented approaches for example water harvesting and lift irrigation. Water harvesting structures such as check dams coupled with lift irrigation in the dryland areas of India, such as parts of Karnataka (which usually have a rugged terrain where entrapment of water is not naturally possible) is a viable option for irrigating Jatropha plantations (Agoramoorthy 2009).

Scenarios IE and AE differ significantly in technological improvements assumed in the biofuel sector. It is evident from our results that under Scenario AE, although total biodiesel demand is 11%lower than in Scenario IE, more land is needed to meet the target. This result clearly indicates the importance of simultaneously analysing the roles of land management and technical pathways when assessing potential land use changes and/or environmental impacts. The main parameters considered in this study were that of oil content, extraction efficiency and yields after transesterification. Considering the key factors discussed above, an improvement in extraction technologies would make the largest contribution to raising biodiesel production (>40%). Secondly, while most studies, including this study, concentrate on estimating biofuel potential through the gasoline-ethanol pathway, Karnataka State Road Transport Corporation has patented the technology of using a diesel-ethanol mix which is successfully being used by Karnataka roadways (KSRTC 2010). Such technical innovations are highly consequential, since high speed diesel demand in India is five times the gasoline demand, with an increasing number of automobiles converting to diesel engines.

An important aspect that emerges from this study is that the absence or insufficient number of markets for direct selling of Jatropha seeds is a major factor of the limited success of biofuel planning. This study has used “semi-hypothetical” markets by including current Jatropha biodiesel plants as a proxy for the locations of wholesale markets. This assumption was made, since an established marketing mechanism for Jatropha comparable to the markets for food crops does not exist yet. Our study shows that the presence / absence of markets is directly linked to Jatropha expansion since such expansion took place in close proximity of the markets used in the model, indirectly validating the assumptions we made (Figure 6(b) and (c) and Figure 6 in Supplement). The presence of established markets can also ensure fixed level of prices for Jatropha seeds which may encourage farmers. The preliminary economic analysis of our study shows that net returns from Jatropha production to farmers are sub-optimal. Income generation from Jatropha cultivation has been included in most discussions on the choice of Jatropha for sustainable energy production. Given the present situation and current interest rates and rates of inflation, Jatropha cultivation does not seem profitable, at least in the short-term (Ariza-Montobbio and Lele 2010). Most farmers in Karnataka or India, have little scope to incur financial losses, hence Jatropha cultivation may prove to be a risky venture- both financially and environmentally. The situation is only exacerbated by the absence of markets, fixed minimum support prices or crop insurance in case of crop failures. Overall, the extent of financial and environmental risk (in terms of decreased productivity of fertile land) is not a viable option for poor/ marginal farmers, at least in the short term of five years as is evident from the calculations presented above. For more detailed economic assessments of Jatropha cultivation it would be necessary to quantify and account for other possible services or byproducts such as the use of pressed cake as biofertilizer, Jatropha oil as a source of light in rural households, medicinal value etc. Increasing government support in the form of subsidies and loans with attractive repayment mechanisms can help in reducing the financial risk involved, as has been predicted by several authors (Srinivasan 2009; Pohit *et al*. 2010; Ariza-Montobbio and Lele 2010). But, since financial support from the government is not applicable when farmers produce Jatropha (or any other crop) for large multinational companies (such as contract farming business models), it is very important that farmers are well protected against non-payment by companies in case of crop failure through adequate enforcement of agreements. Opportunities for financial gains from carbon credits (from the Clean Development Mechanism (CDM)) should be made a part of energy plantation programmes after clarifying whether the producer or the consumer would be the net beneficiary of the credits. CDM has been successful in India and small scale plantation projects from India have been approved for credits by the UNFCCC (Chakraborty 2010). Successful schemes could be applied in energy plantations such as Jatropha or similar systems, which would not only contribute to covering initial expenses but also ensure adequate protection/care of the plantation system by farming households (e.g. on wastelands). In the long-term, monetary transfers to farmers for the environmental services they provide, could encourage biofuel production and cushion losses of the initial years.

To summarise, several components of the biodiesel matrix need to be revisited if India wants to achieve long-term energy sustainability. A multi pronged approach can help a long way in reducing the current uncertainty of future biofuel availability in the country. Cross-sectoral improvements are necessary in agricultural, land, energy, technical, water and financial management. Most of the success in ensuring food and energy security in India seems to be based on two pivots- conservation of available resources and implementing and expanding existing technological improvements, both on the demand and supply side of the biofuel chain. Currently, the most dangerous aspect of biodiesel optimization is the complete dependence on sugarcane and Jatropha. Although efforts are ongoing towards evaluating other crops, it is necessary to include them in the policy framework in the immediate future, as large spatial differences in outputs across the country are to be expected. Overall, dual use food-fuel crops are candidates that are easier to integrate in India than dedicated energy crops. Besides crop diversification, conservation of water resources, improving irrigation methods such as drip and lift irrigation practices, increase in agricultural extension and reducing losses of food/fuel (post harvesting and transportation losses) can sharply increase the total capacity of biofuel production. Technological interventions such as increasing fuel efficiency in the automotive sector, contributions of biotechnology to increase oil content and yields of Jatropha and improvement in oil extraction processes especially in rural areas are necessary. Thus, a multi-faceted approach if implemented without further delays would support the overall goal of food-fuel security in India more than the current approach, which is mainly focused on two key biofuel-feedstocks.

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7. References

1. Agoramoorthy G, Hsu MJ, Chaudhary S, Shieh PC (2009) Can biofuel crops alleviate tribal poverty in India’s drylands? *Applied Energy* **86,** S118-S124
2. Alcamo J (2008) The SAS approach: combining qualitative and quantitative knowledge in environmental scenarios In: *Environmental Futures: The Practice of Environmental Scenario Analysis* (Ed., Alcamo J) Elsevier, The Netherlands
3. Alcamo J, Kasper K, Bush G, Priess JA (2008) Searching for the future of land: scenarios from local to global scale In: *Environmental Futures: The Practice of Environmental Scenario Analysis* (Ed., Alcamo J) Elsevier, The Netherlands
4. An economic assessment along the Jatropha-based biodiesel value chain in India, *Agricultural Economics Research Review* **23** (Conference Number) 393-404
5. Ariza-Montobbio P and Lele S (2010) Jatropha plantations for biodiesel in Tamil Nadu, India: viability, livelihood trade-offs and latent conflict, *Ecological Economics* **70,** 189-195

6. BAIF Institute of Rural Development (2006) The biofuel hype- Chance or challenge for sustainable agriculture in Sustainable Agriculture in A Pathway out of Poverty for India's Rural Poor, In: *SUSTAINET- Sustainable Agriculture Information Network*
7. Behera SK, Srivastava P, Tripathi R, Singh JP, Singh N (2010) Evaluation of plant performace of Jatropha curcas L. under different agro-practives for optimizing biomass- a case study, *Biomass and Bioenergy* **34,** 30-41
8. Bharadwaj A, Tongia R and Arunachalam VS (2007) Scoping technology options for India's oil security : Part I – ethanol for petrol, *Current Science* **92,** 1071-1077
9. Biofuel Task Force, Government of Karnataka (2010) In: Proceedings of Workshop on Research Opportunities in Bio-Fuels, University of Agricultural Sciences, Bangalore
10. Biswas PK, Pohit S, Kumar R (2010) Can India meet the 20% blending target? *Energy Policy* **38,** 1477-1484
11. Brittaine R and Lutadalio N (2010) Jatropha: a smallholder bioenergy crop- the potential of pro-poor development, FAO, Rome
12. Bryan BA, King D, Wang E (2010) Biofuels agriculture: landscape-scale trade-offs between fuel, economics, carbon, energy, food and fiber, *GCB Bioenergy* **2 (6)**, 330-345
13. Census of India (2006) Population Projections for India and States 2001-2026, Report of the Technical Group on Population Projections Constituted by the National Commission on Population, Government of India
14. Census of India (1991) Primary Census Abstract, Office of the Registrar General of India, New Delhi, Available at http://www.censusindia.net/
15. Census of India (2001) Primary Census Abstract, Office of the Registrar General of India, New Delhi Available at http://www.censusindia.net/
16. CSO (Central Statistics Office) (2010) Manual on Agricultural Prices and Marketing, Ministry of Statistics and Programme Implementation, Government of India, New Delhi, India
17. Chakraborty D (2010) Small holder's carbon forestry project in Haryana India: issues and challenges,*Mitigation Adaptation Strategies and Global Change* **15**:899–915
18. Clean air initiative for Asian cities (2010) *Improving vehicle fuel economy in the ASEAN region*, FIA Foundation, International Energy Agency, International Transport Forum, UNEP, Working Paper 1/ 10

19. Constanza R (1989) Model goodness of fit: A multiple resolution procedure, *Ecological Modelling* **47**, 199-215

20. DACNET web portal (2010) Agricultural Informatics Division, Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India Available at http://www.dacnet.nic.in/ Accessed 2007-2010

21. Dale B E (2009) Biofuels: good science must precede good policy, Editorial*, Biofuels, Bioproducts and Biorefinery*, **3**,1-2

22. Das S and Priess J A (2011) Zig-zagging into the future: the role of biofuels in India, *Biofuels, Bioproducts & Biorefining* **5**,18-27

23. Das S, Priess J, Schweitzer C (2010) Biofuel options for india - perspectives on land availability, land management and land-use change. *Journal of Biobased Materials and and Bioenergy* **4**, 243–255.

24. Delucchi MA (2010) Impacts of biofuels on climate change, water use, and land use, *Annals of the New York Academy of Sciences* **1195**, 28-45

25. DES (Department of Economics and Statistics) (2007) Statistical Abstract of Karnataka, 2001-02 to 2004-05, Government of Karnataka, Bangalore

26. Fallot A , Girard P, Dameron V, Griffon M (2006) The assessment of biofuel potentials on global and regional scales in the tropical world *Energy for Sustainable Development*,**10(2),** 80-91

27. Fargione J, Hill J, Tilman D, Polasky S, Hawthorne (2008) Land Clearing and the Biofuel Carbon debt *Science* **319(5867)**1235-1238

28. Ghosh P and Ghose T K (2003) Bioethanol in India: recent past and emerging future, In Series : Advances in Biochemical Enginnering/ Biotechnolgoy (Ser Ed. Scheper T) 85, Vol: Biotechnology in India II (Eds: Ghose T K and Ghosh P), Chapter 1,1-28, Springer-Verlag, Germany

29. Gupta A, Bharadwaj KV, Lama S, Mathur J (2010) Energy analysis of irrigated Jatropha cultivation for producing biodiesel, *Low Carbon Economy* **1**, 54-60

30. Gurgel A, Reilly JM , Paltsev S (2008), Potential land use implications of a global biofuels industry, In: *MIT Joint Program on science and policy of global chang report No. 155,* Cambridge, USA

31. Havlík P Schneider UA, Schmid E, *et al.* (2010) Global land-use implications of first and second generation biofuel targets, *Energy Policy, In Press*

32. Hoogwijk M, Faaij A, Eickhout B, de Vries B, Turkenburg W (2005) Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios *Biomass and Bioenergy,* **29(4)** 225-257
33. Karnataka forest department (2008) Annual Report, Government of Karnataka, Bangalore
34. Karnataka state draft Biofuel Policy (2007) Bangalore, Government of Karnataka
35. Kløverpris J, Wenzel H, Banse M, Milà i Canals L, Reenberg A (2008): Conference and Workshop on Modelling Global Land Use Implications in the Environmental Assessment of Biofuels. *Int J LCA* **13 (3)** 178–183
36. KSRTC (Karnataka State Road Transportation Corporation) (2010) Golden Peacock Eco- Innovation Award for Ethanol Blending of Diesel, available at http://ksrtc.in/ECO-INNOVATION%20AWARD.html Accessed on February 3, 2011
37. Kumar L and Maithel S (2006) Alternative feedstock for bio-ethanol production in India, In: *Biofuels towards a greener and secure energy future* (Ed: Bhojvaid P P) Section 2, 89-103, TERI Press, New Delhi
38. Lapola DM, Priess JA, Bondeau A, (2009) Modeling the land requirements and potential productivity of sugarcane and jatropha in Brazil and India using the LPJmL dynamic global vegetation model, *Biomass and Bioenergy* **33(8),** 1087-0195
39. Lapola DM, Schaldach R, Alcamo J, Bondeau A, Koch J, Koelking C, Priess JA (2010) Indirect land-use changes can overcome carbon savings from biofuels in Brazil, *Proceedings of the National Academy of Sciences* **107(8)**, 3388-3393
40. Loveland TR, Reed BC, Brown JF, Ohlen DO, Zhu Z, Yang L, Merchant JW (2000) Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data, *International Journal of Remote Sensing,* **21**(6, 7), 1303-1330, (2000)
41. Mimler M and Priess JA (2008) Design and Implementation of a generic modeling framework- a platform for integrated land use modeling, Center for Environmental Systems Research, Kassel University Press, University of Kassel, Germany
42. Ministry of Agriculture (2007) Cost of cultivation of principal crops in India, Government of India, New Delhi
43. Ministry of New and Renewable Energy (2009) National Policy on Biofuels, Government of India, New Delhi

44. Ministry of Petroleum & Natural Gas (2006) Report of the Working Group on Petroleum & Natural Gas Sector for the XI Plan(2007-2012), Government of India
45. Ministry of Water Resources (2008) Ground Water Information Booklet, Bangalore Urban District, Karnataka, Government of India
46. Mittal S (2008) Demand- supply trends and projections of food in India, Working Paper No. 209 Indian Council for Research on International Economic Relations
47. Monserud RA and Leemans R (1992) Comparing global vegetation maps with the Kappa statistic *Ecological Modelling* **62**, 275-293
48. Msangi S, Sulser T, Rosegrant M, Valmonte- Santos R (2007) Global Scenarios for Biofuels : impacts and implications *Farm Policy Journal* **4(2),** 1-9
49. NRSA (National Remote Sensing Agency) (2004a) Land-use land-cover map Karnataka, Hyderabad, India
50. NRSA (National Remote Sensing Agency) (2004a) Wasteland map of Karnataka, Hyderabad, India
51. NRSA (National Remote Sensing Agency),Department of Space and DOLR (Department of Land Resources), Ministry of Rural Development (2005), Wastelands Atlas of India, Government of India, New Delhi
52. NRSA (National Remote Sensing Agency),Department of Space and DOLR (Department of Land Resources), Ministry of Rural Development (2010), Wastelands Atlas of India, Government of India, New Delhi
53. NOVODB (National Oilseeds and Vegetable Oil Development Board) (2010) 5th R & D report on tree borne oilseeds, Eds: Punia MS, Kureel R S, Kumar V, Pandey A, Ministry of Agriculture, Government of India, Gurgaon
54. Parton WJ, Hartman M, Ojima D, Schimel D (1998) DAYCENT and ist land surfact submodel: description and testing, *Global and Planetary Change* **19(1-4)**,35-48
55. Planning and Statistics Department (2005) Karnataka Human Development Report, Government of Karnataka, Bangalore
56. Pohit S, Biswas PK, Kumar R, Goswami A (2010) Pricing model for biodiesel feedstock: a case study of Chattisgarh in India, *Energy Policy* **38** 7484-7496
57. Pontius GR and Schneider LC (2001) Land-cover change model validation by an ROC method for the Ipswich watershed, Massachusetts, USA, *Agriculture, Ecosystems and Environments* **85,** 239-248

58. Prasad J and Prasad A (Eds.) (1995) Indian agricultural marketing: emerging trends and perspectives, Mittal Publications, New Delhi, India

59. Ragaglini G, Triana F, Villani R, Bonari E (2010) Can sunflower provide biofuel for inland demand? An integrated assessment of sustainability at regional scale, *Energy Article in press*

60. Ravindranath NH, Lakshmi CS, Manuvie R, Balachandra P (2010) Biofuel production and implications for land use, food production and environment in India, *Energy Policy, In Press, Corrected Proof, Available online*

61. Secchi S, Kurkalova L, Gassman PW, Hard C (2010) Land use change in biofuels hotspot: the case of IOWA, USA, *Biomass and Bioenergy Article in press*

62. Schaldach R, Priess JA, Alcamo J (2010) Simulating the impact of biofuel development on country-wide land-use change in India, *Biomass and Bioenergy, In Press, Corrected Proof*

63. Schweitzer C, Priess JA, Das S (2011) SITE- a generic land-use modelling framework, *Environmental Modelling and Software*, *accepted February 2011*

64. Sethi N (2007) Soon, your car will come with a mileage tag, Times of India Oct 5, 2007,Available at http://timesofindia.indiatimes.com/Govt_to_set_fuel_efficiency_norms/articleshow/2430700.cms, last accessed February 28, 2011

65. Shinoj P, Raju SS, Kumar P, Msangi S, Yadav P, Thorat V S, Chaudhary KR (2010) An economic assessment along the Jatropha based biodiesel value chain in India, *Agricultural Economics and Research Review* Vol 23 (Conference Number) 393-404

66. Srinivasan S (2009) The food v. fuel debate: a nuanced view of incentive structures, *Renewable Energy* **34,** 950-954

67. Stehfest E, Heistermann M, Priess JA, Ojima D, Alcamo J (2007) Simulation of global crop production with the ecosystem model DayCent, *Ecological Modelling* **209,**203-219

68. Thrän D, Seidenberger T, Zeddies J, Offermann R (2010) Global biomass potentials — Resources, drivers and scenario results, *Energy for Sustainable Development*, **14(3),** 200-205

69. Tilman D, Hill J, Lehman C (2006) Carbon-negative biofuels from low-input high-biodiversity grassland and biomass *Science,* **314,**1598- 1600

70. Trabucco A, Achten W M J, Bowe C, Aerts R, Orshoven J V, Norgroves L, Muys B (2010) Global mapping of Jatropha curucas yield based on response of fitness to present and future climate *Global Change Biology Bioenergy* **2** 139-151
71. Ugarte DDLT and He L (2007) Is the expansion of biofuels at odds with the food security of developing countries? *Biofuels, Bioproducts and Biorefining*, **1,** 92-102
72. Whitaker M and Heath G (2008) Life Cycle Assessment of the use of Jatropha biodiesel in Indian Locomotives, *Technical Report NREL/ TP- 6A2-44428*, National Renewable Energy Laboratory, Colorado, USA.
73. Yanamoto H, Fujino J, Yamaji K (2001) Evaluation of bioenergy potential with a multi-regional global-land-use-and-energy model, *Biomass and Bioenergy* **21**,185-203
74. Zhang X, Izaurralde RC, Manowitz D, West T O, Post W M, Thomson A M, Bandaru V P, Nichols J, Williams J R (2010) An integrative modeling frameowork to evaluate the productivity and sustainability of biofuel crop production systems *Global Change Biology Bioenergy*, **2,** 258-277

Supplementary Material

Section I

DayCent parameterization of crops and trees

FAO soil data (FAO 2009) was downscaled for the study area, main parameters used were carbon and nitrogen (in top soil and sub-soil), bulk density, texture (sand, silt and clay fractions in top soil and sub-soil), pH (in top soil and sub-soil). CRU weather data (daily) (Mitchell and Jones, 2005) was used with the parameters -temperature (minimum and maximum), rainfall. Daycent spin up run for 500 years was performed to stabilise carbon pools in the soil using native vegetation (grass, forests) and sorghum for agricultural areas.

Seven crop types (rice, maize, millets, pulses, oilseeds, cotton and sugarcane) and two tree types (Forests and Jatropha) were parameterised. The parameters used are provided in Table 1. Details on parameter definitions can be found in technical documentation (Metherell *et al.* 2011).

Table 1. Parameter values for crops and trees used in the Karnataka study

Crop	**Rice**	**Maize**	**Millets**	**Pulses**	**Oilseeds**	**Cotton**	**Sugarcane**
prdx	0.5	0.6	0.2	0.2	0.05	0.2	0.4
ppdf(1)	15	15	15	15	15	20	20
ppdf(2)	55	55	55	55	55	55	50
frtc(1)	0.5	0.5	0.5	0.5	0.5	0.5	0.4
frtc(2)	0.1	0.1	0.1	0.1	0.1	0.1	0.3
cfrtcn(1)	0.25	0.25	0.25	0.25	0.25	0.40	0.25
crftcn(2)	0.25	0.25	0.25	0.25	0.25	0.25	0.25
himax	0.5	0.4	0.5	0.2	0.3	0.1	0.7
Tree	**Forest**	**Jatropha**					
DECID	2	2					
Prdx (2)	1.5	0.5					
PPDF (1)	15	25					
PPDF (2)	40	45					
CERFOR(1,1,1)	35	20					
CERFOR(1,1,2)	697	700					
CERFOR(1,1,3)	100	40					
CERFOR(1,2,2)	50	35					
MAXLAI	5.7	5					

Table 2 Spatial data used in the study

Data	Source	Reference
Soil	Digital Soil map of the world	FAO 2009
Slope and Elevation	USGS HydroSHEDS	Lehner *et al*. 2008
Land use data (1992)	IGBP-DIS	Loveland *et al*. 2000
Land use data	NRSA	NRSA 2004a
Wastelands	NRSA	NRSA 2004b
Irrigated areas	GIAM	Thenkabail *et al.* 2008
Rainfed areas	GMRCA	Biradar *et al.* 2009
Protected Area network	World Database on Protected Areas	UNEP-WCMC, IUCN, 2009
Urban areas	MODIS Global Urban Extent	Schneider *et al*. 2009; Schneider *et al*. 2010
Roads	Digital Chart of the World	ESRI, 2000

Table 3 Main assumptions used in SITE-Karnataka

	General assumptions	**Reference**
1	Wasteland area remains constant during the entire period of simulation (1992-2025)	NRSA and DOLR, 2005, 2010
2	5 % Bioethanol is assumed to have been achieved in 2004 while biodiesel blending was assumed to be zero in 2004	Ministry of Petroluem and Natural Gas 2008
3	Ethanol production pathway –All bioethanol is produced using sugarcane to molasses route. 4% molasses production per ton of sugarcane is obtained, of which 25% ethanol recovery is possible. Out of total ethanol produced, 40% is used for bioethanol production.	Ghosh P and Ghose T K 2003; Kumar L and Maithel S 2006

4	Biodiesel pathway- All biodiesel is produced by Jatropha with varying levels of oil content, extraction efficiency and yields after transesterfication used in the scenarios (see Section V in this supplement)	Ministry of New and Renewable Energy 2009
	Settlement sub-module	
5	Total number of towns in Karnataka is 170 and villages is 28,849	Karnataka State Remote Sensing Agency 2007
6	Total population is divided between rural (66%) and urban (34%)	Planning and Statistics Department ,Government of Karnataka 2005
7	All settlements expand spatially starting at the center, assuming declining population densities towards the periphery	Brush 1968, Taubenböck *et al.* 2008
	Crop sub- module	
8	Irrigated area is 14,472 km^2	DES 2007
9	Area under double cropping increases from 13,780 to 25,170 km^2 from 1992-2004 and remains constant thereafter	DES 2007
10	Wasteland cells cannot grow food crops; however crop cells can be cultivated with Jatropha in the scenario period	Ministry of New and Renewable Energy 2009
11	Fallow pixels are brought back into production after one year	Ministry of Agriculture 2010
12	We used all 206 registered agricultural markets for the simulations. Note that markets a trading different commodities, a fact that is influencing crop allocation – both in reality and in the simulations.	Directory of Agricultural Markets, Department of Agriculture, Government of Karnataka 2004
13	Jatropha biodiesel markets are simulated by using current processing units/ industries in Karnataka	WWF and GEXSI LLP 2008
	Forest sub-module	
14	A grid cell is not used for biomass extraction in consecutive years	Karnataka forest department, 2008
15	Forest use increases with increasing proximity to villages and roads	Karanth *et al*. 2006

Table 4 Important parameters used in multi-criteria suitability analysis

	maxElev(m)	maxPPT (mm)	Reference
Rice	1000	1500	IKISAN web portal 2010; DBT-MOEF 2009
Maize	700	800	
Millets	850	1000	
Pulses	1000	650	
Oilseeds	1050	500	
Cotton	900	1000	
Sugarcane	1000	2500	
Jatropha	1000	1200	Kureel *et al.* 2007

Table 5 Land use change conversion matrix employed in the model

FROM													**TO**
Rice	Maize	Millet	Pulses	Oil.	Cot.	Sug.	Jatro.	Urban	Rural	For.	Fal.		
✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	✓	Rice	
✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	✓	Maize	
✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	✓	Millet	
✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	✓	Pulses	
✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	✓	Oil	
✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	✓	Cot	
✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	✓	Sug	
✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	✓	Jatro	
✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Urban	
✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	Rural	
-	-	-	-	-	-	-	-	-	-	✓		For.	
✓	✓	✓	✓	✓	✓	✓	-	-	-	-	✓	Fal.	

Oil. = Oilseeds; Cot. = Cotton; Sug. = Sugarcane; Jatro. = Jatropha; For.= Forests; Fal.= Fallow

✓ indicates change allowed ; **-** indicates change not allowed

Section II

Details of scenario quantification for Scenario IE and Scenario AE

Population

We used the population projections from (Census India 2006) and policy documents of Karnataka (Karnataka State Planning Board 2008). Projected TFR (Total Fertility Rate) of the national goal of 2.1 is achieved in 2005 in Karnataka. Thus, population can be expected to grow at a constant TFR of 2.1. We adopt the Census India underlying assumptions of “With AIDS” and “Without AIDS” scenarios applying the percentage difference as indicated by Census India (Figure 1).

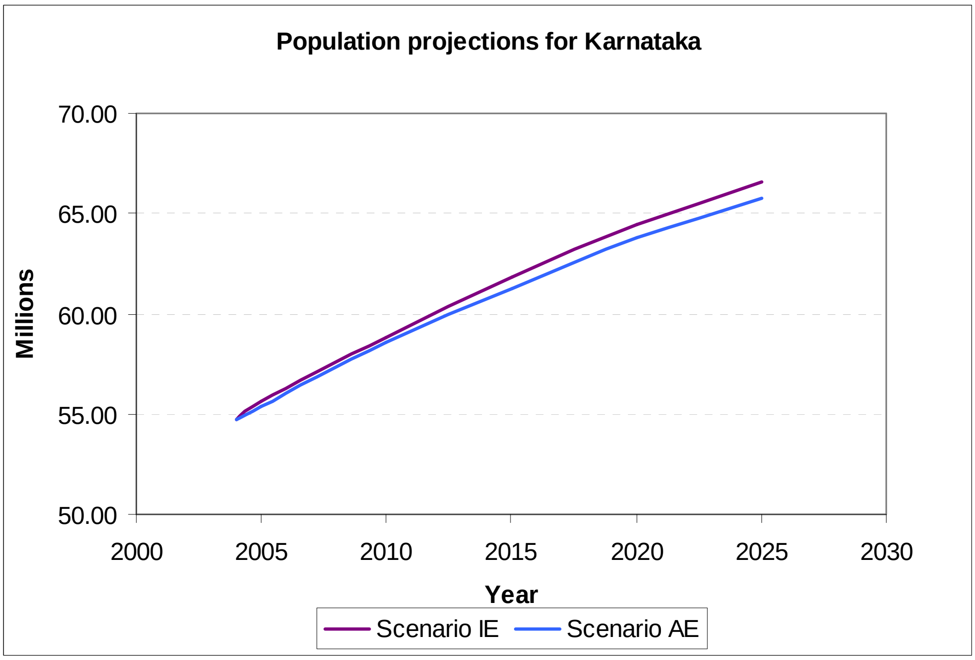

Figure 1 Projected population of Karnataka until 2025

Economy

The state equivalent of the national GDP is the Gross State Domestic Product (GSDP). The state accounts statistics are an extension of the national accounts at the regional level and is a measure of the total output of the state economy (Central Statistical Organization 2008).Unlike GDP forecasts, GSDP forecasts or projections are not commonly available. This study has broadly utilized the projections available in the “Karnataka- A Vision for Development” document prepared by the state government (Karnataka State Planning Board 2008). Two levels of GSDP growth rates have been adopted in this study to reflect the rate of change of economic growth until 2025. Scenario IE assumes a higher growth rate (9% p.a by 2025) while Scenario AE assumes slightly lower growth rates (8% p.a until 2025) with 2004-

05 as the base year (Figure 2). While Scenario IE assumes higher rates of economic growth based on manufacturing and services sector, Scenario AE assumes strengthening of the agriculture sector and hence an enhanced contribution to the GSDP.

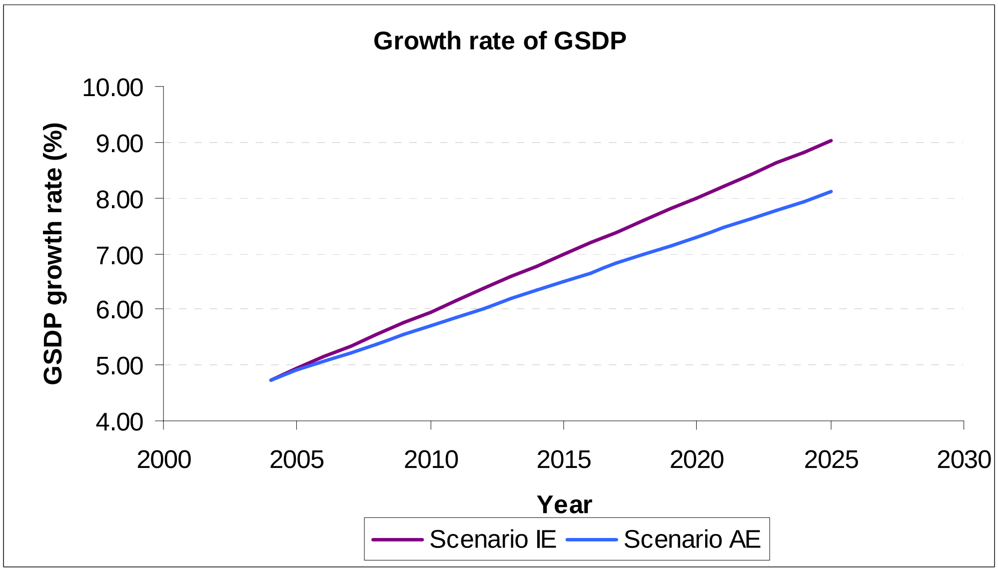

Figure 2 Projected growth rate of GSDP for Karnataka

Food demand

Sectoral demands for Rice, Maize, Millets, Pulses, Oilseeds, Cotton and Sugarcane are quantified for both scenarios. Various authors have projected food demands at the national level whereas only one study could be located that has developed foodgrain demands for Karnataka (Rosegrant 1995; Mittal 2008; Mohanty *et al*. 1998; Bhalla 1999; Savadatti 2007; Chand 2007).The general methodology applied in this study to calculate future commodity demands was based on per capita consumption patterns and projected population.

For all commodities apart from cotton and maize this study has used and adapted per capita demand projections from Mittal (2008). The per capita demands used in this study for Scenario IE and Scenario AE with base year 2004-2005 are given in Table 6. Table 7 shows the total demand for commodities for both Scenarios. Figures 3(a) to Figure 3(g) show the demands for each commodity.

Realistic projections of per capita maize requirements could not be located, as most studies account for maize as food whereas the larger demand stems from the use of maize as feed. Maize is the major feed for the poultry sector in India and also in Karnataka. In Karnataka particularly, which is a non-traditional maize growing zone in India, there has been a tremendous increase in maize production over the last two decades. Egg and maize production have followed the same trends in Karnataka (Joshi *et al*. 2005). The per capita maize consumption in the state was 8.4 kg per annum Karnataka (Pavithra *et al.* 2009). 55% of the total maize cultivated goes to the feed industry, other prominent users being the starch industry, breweries, pharmaceuticals and wet mills (Mehta and Dias 1999). Annual growth rate of poultry between 1997 and 2003 was almost 6%. The government target is to achieve an annual growth rate of 10% during 2007-2012 (Dept. of Animal Husbandry 2008). This study has assumed an average growth rate of 10% in Scenario IE and 7% in Scenario AE throughout the entire period.

Cotton demands were generated assuming 20% export and 10% export capacity of India for Scenario I and Scenario II respectively. The baseline cotton demand in Karnataka is 1.95kg / capita / annum. Data from Chaudhary (2005) has been used for annual increments in cotton demand in both scenarios.

Table 6 Per capita demand for agricultural commodities in Karnataka

Commodity	**Per capita demand (kg/annum) (Scenario IE)**			**Per capita demand (kg/annum) (Scenario AE)**		
	2015	**2020**	**2025**	**2015**	**2020**	**2025**
Rice	77.7	76.20	74.7	76.6	74.6	72.6
Millets	81	86	91	80.45	85.2	89.95
Pulses	26.05	28.8	31.55	23.83	26.48	29.13
Oilseeds	52.19	58.64	65.09	49.11	54.16	59.21
Sugarcane	366	428	490	324	367	410
Cotton	2.53	2.82	3.15	2.24	2.37	2.51

Table 7 Summed up demands for agricultural commodities in Karnataka

Commodity	**Demand in million tons (Scenario IE)**			**Demand in million tons (Scenario AE)**		
	2015	**2020**	**2025**	**2015**	**2020**	**2025**
Rice	4.80	4.91	4.97	4.69	4.76	4.77
Maize	3.91	4.36	4.80	3.64	4.00	4.34
Millets	5.01	5.54	5.99	4.89	5.40	5.88
Pulses	1.57	1.85	2.10	1.45	1.68	1.90
Oilseeds	3.22	3.77	4.33	2.98	3.43	3.87
Cotton	0.16	0.18	0.21	0.14	0.15	0.16
Sugarcane	22.63	27.57	32.60	19.72	23.27	26.8

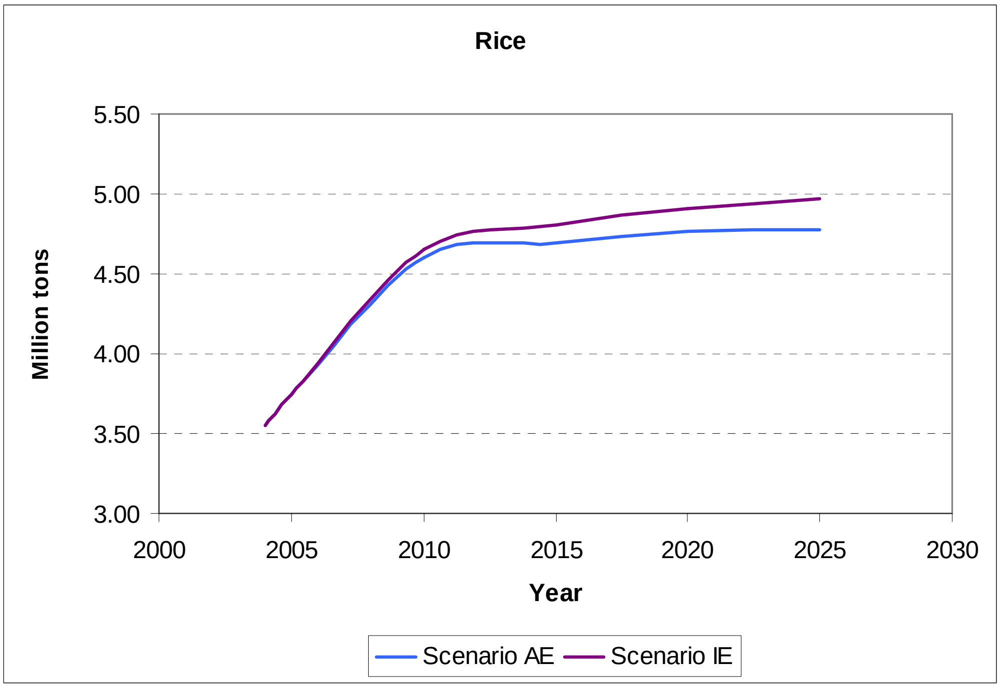

Figure3 (a) Projected rice demand in Karnataka

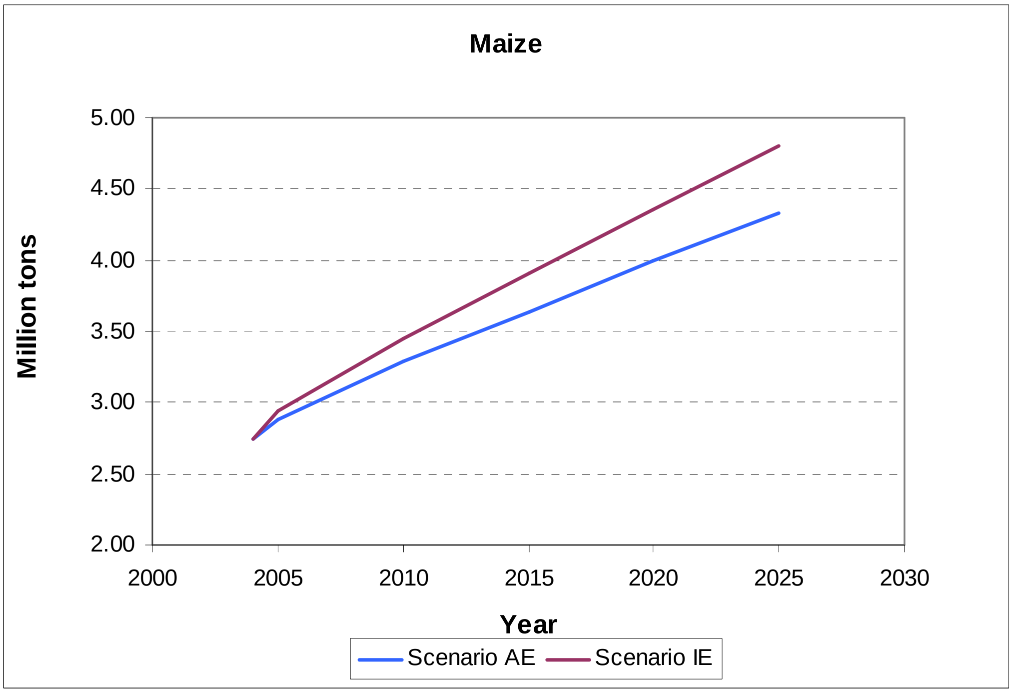

Figure 3 (b) Projected maize demand in Karnataka

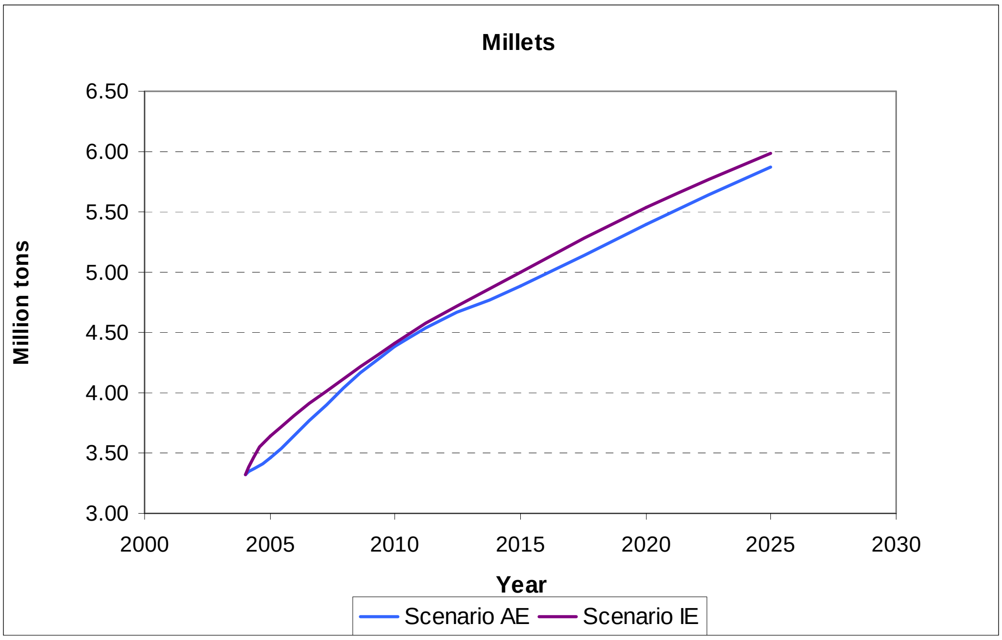

Figure 3 (c) Projected millets demand in Karnataka

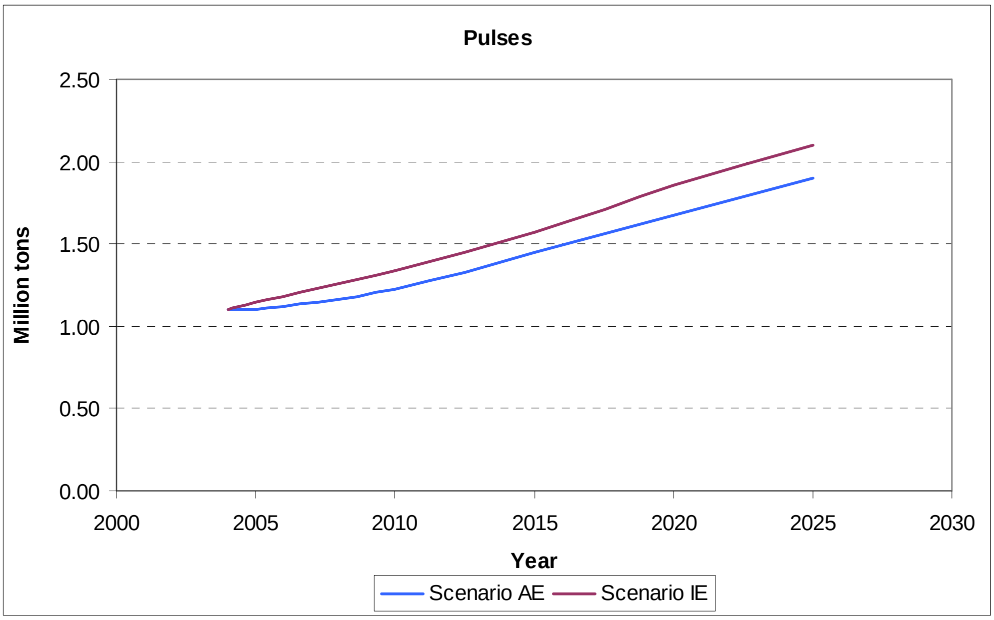

Figure 3 (d) Projected pulses demand in Karnataka

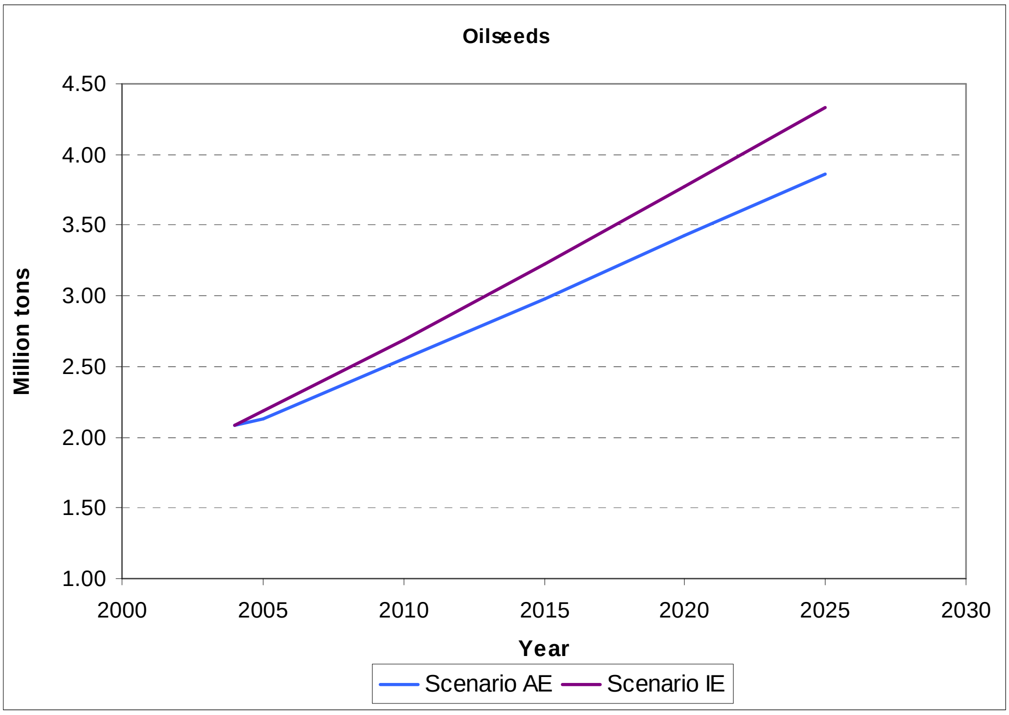

Figure 3 (e) Projected oilseeds demand in Karnataka

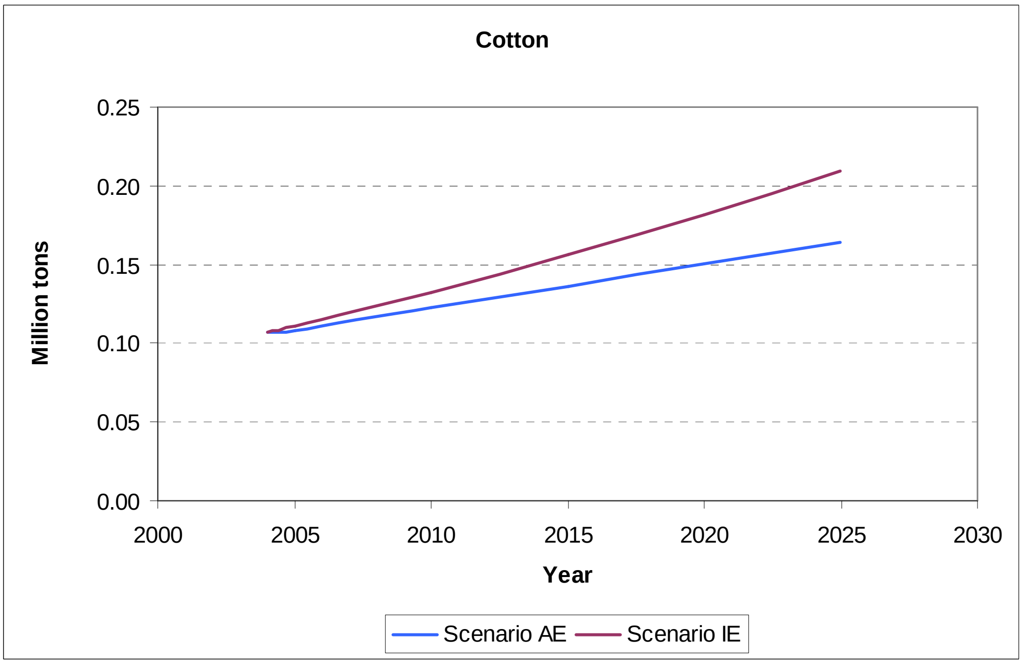

Figure 3 (f) Projected cotton demand in Karnataka

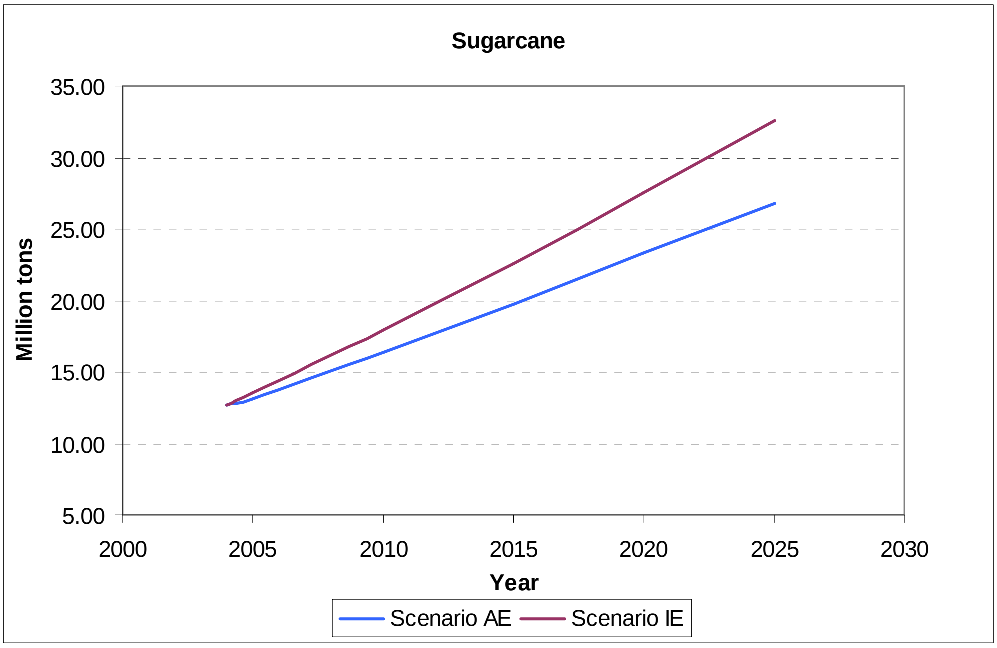

Figure 3 (g) Projected sugarcane demand in Karnataka

Biofuel demand

Several international bodies have developed scenarios for India e.g. (International Energy Agency) IEA and EIA (Energy Information Administration). In India scenarios for demands for petroleum products have been developed by the Ministry of Petroleum and Natural Gas, Government of India (Ministry of Petroleum and Natural Gas 2006). The scenarios have been developed on indicators pertaining to GDP, energy demand elasticity and impacts related to infrastructure development (e.g. underground railway systems in metro cities), Compressed Natural Gas (CNG) expansion, and conservation and efficiency improvement measures amongst others. For this study the scenarios have been adapted to fit regional demands for Karnataka. The generic term “petrol” has been used as the equivalent of “Motor Gasoline” that is defined by the United Nations and used in India as “a mixture of relatively volatile hydrocarbons with or without small quantities of additives, which have been blended to form a fuel suitable for use in spark-ignition internal combustion engines. Natural gasoline, aviation gasoline and naphtha's are excluded” (CSO 2010). Similarly, High Speed Diesel (HSD) would be used for “High Speed Diesel Oil (HSDO)” or “Gas oil” for petroleum derived diesel used to fuel diesel engines.

Due to the lack of time-series statistics on consumption of petrol and HSD in Karnataka, the fraction of consumption in the state was calculated from national level statistics as 6.5% and 6.1% respectively. The “Upper case” and “Base case” in the scenarios by the Ministry are adapted to Scenario IE and Scenario AE for Karnataka. Under Scenario IE the annual compound growth rates of petrol and HSD demand are 5.3% and 4.2%, while under

Scenario AE they are 4.3% and 3.6% respectively. Under Scenario IE petrol demands in the state increase to 1.6 million tons while under Scenario AE they reach 1.3 million tons (Table 8).

The biofuel policy of India has set a target for 20% blending of petrol with ethanol and HSD with non-ebible oil until 2017 (MNRE 2009). 5% blending of petrol is currently practiced in 20 states of India while no information is available for blending of HSD. On the basis of previous plans and targets set by the government it is assumed that 5% blending for HSD has been undertaken in Karnataka since 2004. Future blending rates were calculated to reach the 20% blending target by 2017 assuming a linear growth rate (Table 9). Table 10 and Table 11 show the requirements for ethanol and non-edible oil for blending in petrol and diesel.

Table 8 Projected petrol demands in Karnataka

	Scenario IE (CAGR 5.3%)		**Scenario AE (CAGR 4.3%)**	
Year	Petrol demand in Karnataka (Million tons)	Ethanol Demand in Karnataka (million tons)	Petrol demand in Karnataka (Million tons)	Ethanol Demand in Karnataka (Million tons)
2004	0.51	0.03	0.53	0.03
2005	0.55	0.03	0.55	0.03
2006	0.58	0.04	0.58	0.04
2007	0.60	0.05	0.61	0.05
2008	0.63	0.06	0.64	0.06
2009	0.68	0.07	0.66	0.07
2010	0.73	0.09	0.69	0.08
2011	0.75	0.10	0.72	0.10
2012	0.79	0.12	0.75	0.11
2013	0.84	0.13	0.78	0.12
2014	0.88	0.15	0.81	0.14
2015	0.93	0.17	0.85	0.15
2016	0.98	0.19	0.88	0.17
2017	1.03	0.21	0.92	0.19
2018	1.08	0.24	0.96	0.21
2019	1.14	0.26	1.00	0.23
2020	1.20	0.29	1.04	0.25
2021	1.26	0.32	1.09	0.28
2022	1.33	0.35	1.14	0.30
2023	1.40	0.39	1.18	0.33
2024	1.48	0.43	1.24	0.36
2025	1.55	0.47	1.29	0.39

Table 9 Projected HSD demands in Karnataka

	Scenario IE (CAGR 4.2%)		**Scenario AE (CAGR 3.6%)**	
Year	HSD demand in Karnataka (Million tons)	Oil Demand in Karnataka (million tons)	HSD demand in Karnataka (Million tons)	Oil Demand in Karnataka (Million tons)
2004	2.43	0.12	2.43	0.53
2005	2.46	0.15	2.46	0.55
2006	2.49	0.18	2.49	0.58
2007	2.60	0.22	2.59	0.61
2008	2.69	0.26	2.68	0.64
2009	2.81	0.31	2.78	0.66
2010	2.94	0.36	2.87	0.69
2011	3.05	0.41	2.97	0.72
2012	3.18	0.46	3.08	0.75
2013	3.31	0.52	3.19	0.78
2014	3.45	0.59	3.30	0.81
2015	3.60	0.65	3.42	0.85
2016	3.75	0.73	3.55	0.88
2017	3.91	0.80	3.67	0.92
2018	4.07	0.89	3.81	0.96
2019	4.24	0.98	3.94	1.00
2020	4.42	1.07	4.09	1.04
2021	4.60	1.17	4.23	1.09
2022	4.80	1.28	4.39	1.14
2023	5.00	1.39	4.54	1.18
2024	5.21	1.51	4.71	1.24
2025	5.43	1.64	4.88	1.29

Table 10 Projected ethanol demands in Karnataka

	Scenario IE		**Scenario AE**	
Year	Petrol demand (Million tons)	Ethanol demand (Million tons)	Petrol Demand (Million tons)	Petrol Demand (Million tons)
2010	0.73	0.09	0.69	0.08
2015	0.93	0.17	0.85	0.15
2020	1.20	0.29	1.04	0.25
2025	1.55	0.47	1.29	0.39

Table 11 Projected non-edible oil demands in Karnataka

	Scenario IE		Scenario AE	
Year	HSD demand (Million tons)	Blending oil demand (Million tons)	HSD Demand (Million tons)	Blending oil Demand (Million tons)
2010	2.94	0.36	2.87	0.35
2015	3.6	0.65	3.42	0.62
2020	4.42	1.07	4.09	0.99
2025	5.43	1.64	4.88	1.47

Technology developments assumed for biodiesel

Three key-factors contributing to total biodiesel production from Jatropha:

(i) Oil content of seeds

(ii) Oil extraction efficiency

(iii) Yields of biodiesel after processing of non-edible oil

Oil contents and oil extraction efficiencies vary widely depending upon the species or varieties used and the scale of production. The average oil content varies between 30 and 40%, while the micro-mission plan for improved varieties aims at achieving a maximum of 40% oil content (Diwakar *et al.* 2010). Under higher rates of technology growth assumption of Scenario IE that include major advances in biotechnological and genetic improvements towards high yielding varieties it is assumed that oil content of Jatropha can reach as high as 40% while in Scenario AE it is assumed oil content shall be limited to 35% from the base year oil content of 30% (Figure 4(a)). Depending on the scale of production (local to industrial) oil extraction efficiency may vary between 57% and 100%. We assume extraction technologies to achieve 81% and 68% by 2025 under Scenario I and II respectively (Figure 4(b)). Although Jatropha oil can be directly used in engines as Straight Vegetable Oil there are drawbacks on engine efficiency and therefore several modification methods exist to produce biodiesel such as micro-emulsion, pyrolyis, cracking and transesterfication. Transesterification is the most commonly used process in India which yields biodiesel and the important by-product glycerine (Jain and Sharma 2010). The yields may vary between 95% to 99% depending on the types of catalysts used as well as other modifications in the processing chain (Whitaker and Heath 2009; Kumar *et al.*2010). Scenario IE assumes constant 99% ester yield while Scenario AE assumes a constant ester yield of 95% (Figure 4(c)).

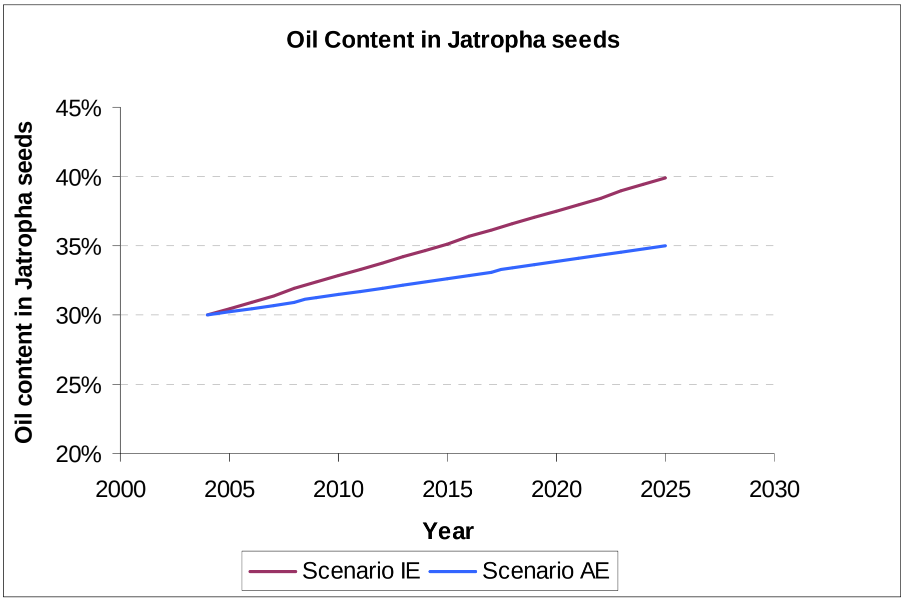

Figure 4(a) Projected oil content for Jatropha seeds

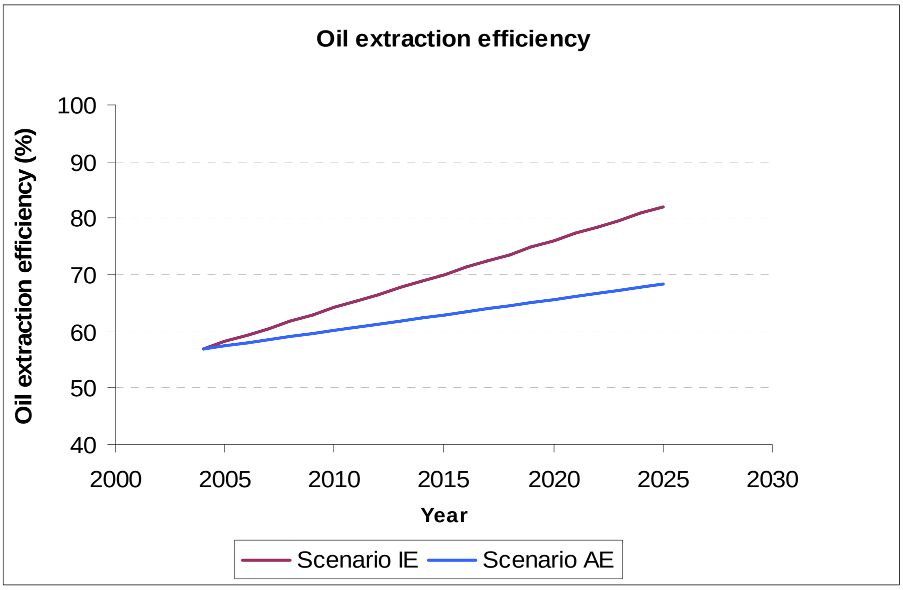

Figure 4(b) Projected oil extraction efficiency for Jatropha

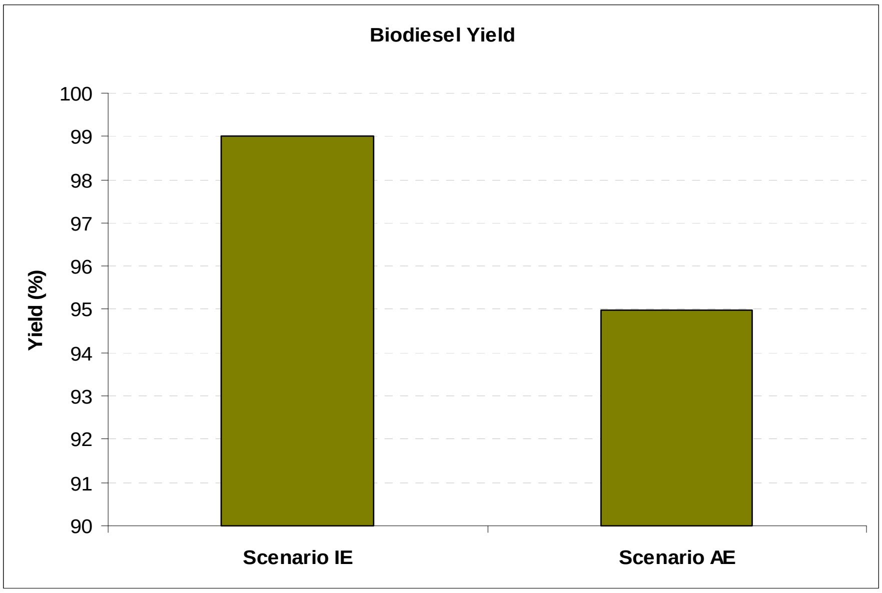

Figure 4(c) Projected transesterification yields for Jatropha

Agricultural Prices and Cost of Cultivation

Farm Harvest Prices (FHP) or Farm gate prices are defined as the average wholesale price at which the commodity is disposed of by the producer at the village site during the specified harvesting period (Ministry of Statistics 2008). Continuous time series data for all crops in all districts of Karnataka was not available. Data gaps were filled by taking mean values wherever necessary. Decadal growth rates of FHP for different crops have been used by Deshpande *et al*. 2002 based on which we calculate annual rates of increase in FHP.

A comprehensive scheme for studying the cost of cultivation was initiated in India in 1970-71. The items of cost of cultivation (COS) cover both paid out costs (out of the pocket expenses) and imputed costs. Details of computation of cost of cultivation are found in the cost compilation publication (Ministry of Agriculture 2006). For this study we computed annual increase in cost of cultivation over a time period of 5 years (1991-2003) to maintain consistency across all crops (decadal time series data for all crops was not available). Figure 5 shows the annual increases in FHP and COC for all crops applied to Scenario AE. Scenario IE calculations added 14% annually (2009-2010 inflation in food prices) to the growth rate.

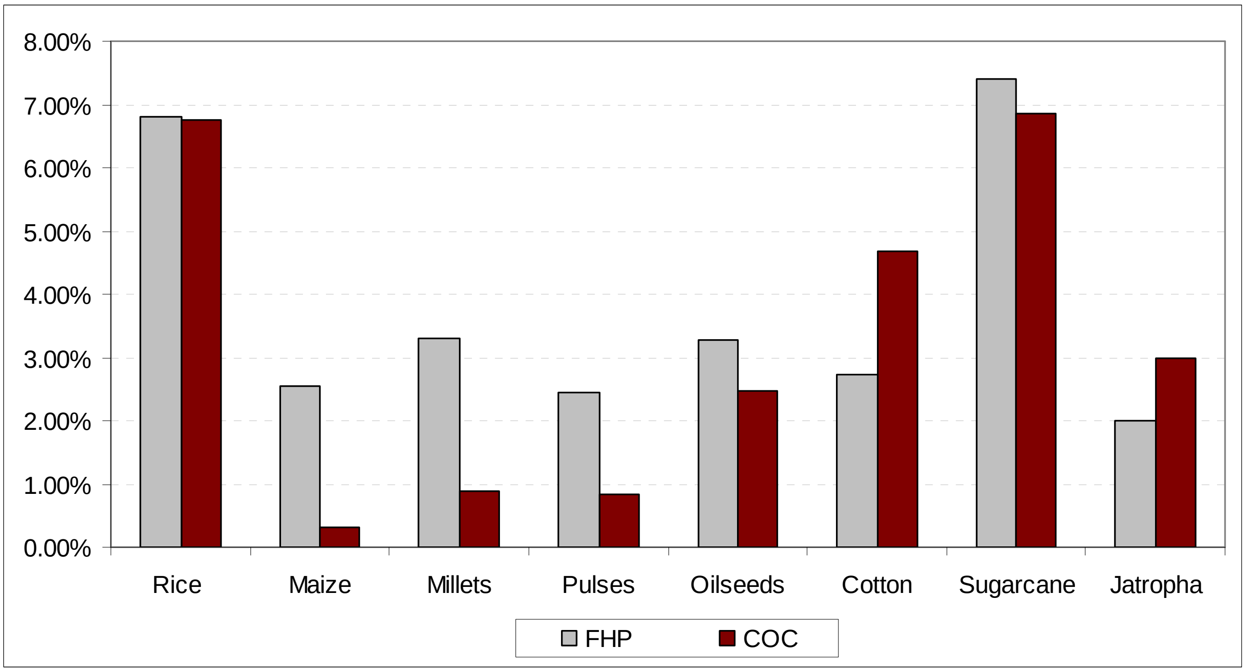

Figure 5 Annual increase in FHP and COC for Scenario AE

To depict the agricultural marketing system a spatial database of markets (APMCs) was developed with details of 204 APMCs across Karnataka (available at the online MIS portal- (http://www.ksamb.gov.in/). As shown in Figure 6, a careful analysis of available qualitative information was transformed into detailed spatial information to be used as an input to the model. No information on established markets for jatropha biodiesel could be located as the development of the marketing network for biodiesel is still at a nascent stage in the area. Therefore, the location of existing commercial biodiesel processing units (K1 Oils and Labland Biodiesel Pvt. Ltd.) and government owned oil refineries (at Bangalore and Mangalore) were used as “Jatropha markets”. Detailed information on commodities traded at each of these 204 APMCs was incorporated into the database using the Directory of Markets (Ministry of Agriculture, 2004).

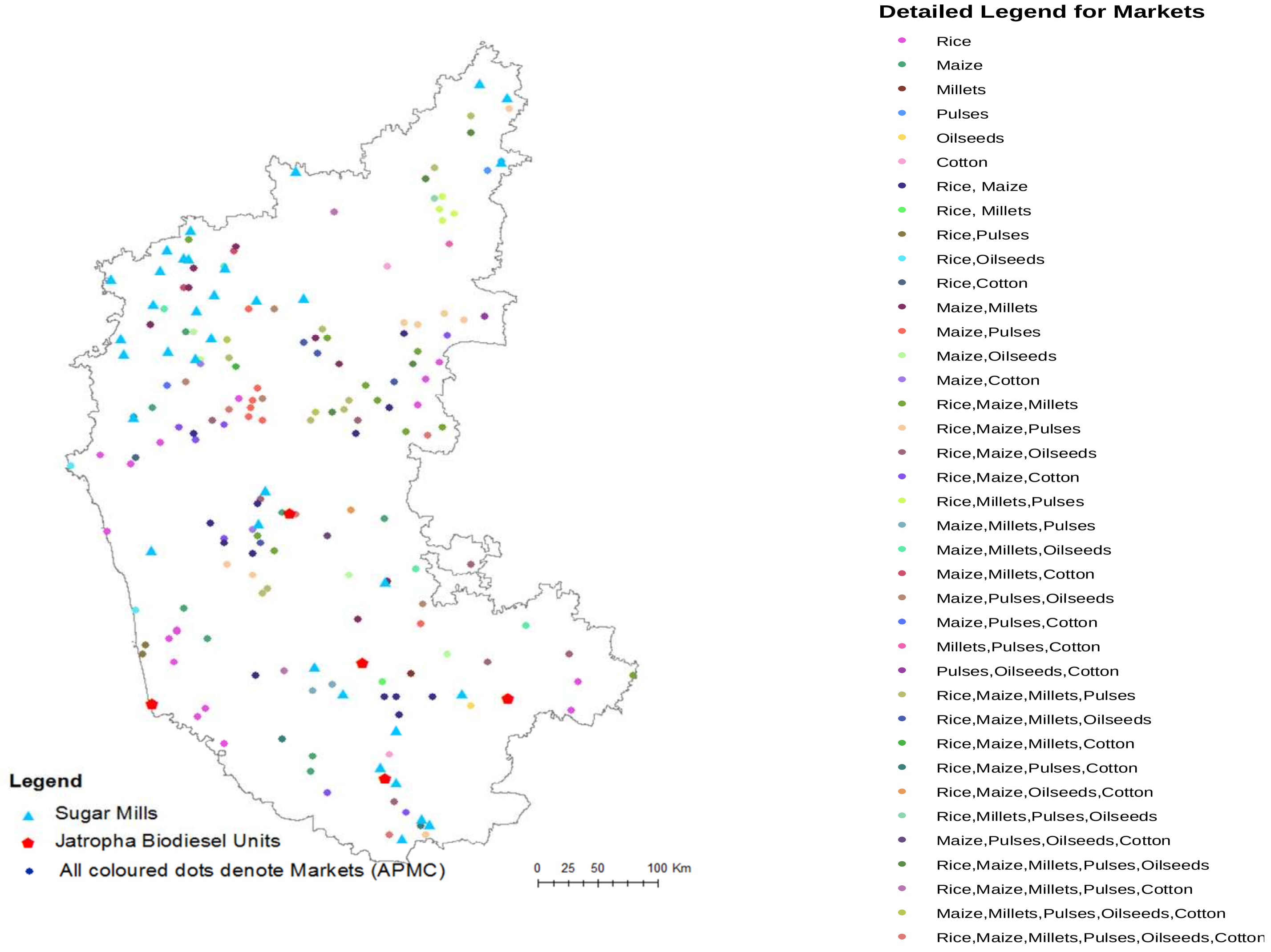

Figure 6 Agricultural Markets in Karnataka with details of commodities traded

Demand on Forests in Karnataka

Available data for wood demand in the state is very limited. Forestry statistics in India is compiled by the Indian Council for Forestry Research and Education (ICFRE) in the form of a bi-annual publication titled "Forestry Statistics in India". For the period of our study, two the issues published in the years 2001 and 2005 (ICFRE 2002; ICFRE 2009) were useful. The Statistical Abstract of Karnataka (DES 2007) was also used for other years. The calculations presented below are also supported by personal communication with the Forest Department and unpublished literature cross referenced from published books.

There is a high degree of uncertainty presented by the data studied. A wide range of estimates for total annual wood production from Karnataka's forests were found to exist in literature ranging from 29 million tons (Ranganathan *et al.* 1993) to 0.17 million tons (Table 12). The following table summarises the trends in wood production in Karnataka as derived from statistical reports.

Table 12 Annual wood production in forests of Karnataka

Year	Timber (tons)	Pulpwood+ Matchwood (tons)	Fuelwood (tons)	Poles (tons)	Total (million tons)	Reference
1998	48,777	181,596	1,248,863	859	1.48	1
1999	44,029	146,011	1,288,322	1544	1.48	1
2001	66,013	87,225	313,453	40542	0.51	3
2002	58,049	9,797	166,821	28601	0.26	2,3
2003	48,806	30,235	186,820	22283	0.29	2,3
2004	19,495	6,442	104,248	35099	0.17	3

Source: recalculated for this study from references

Notes: Conversion ratios: Roundwood (timber / poles) - 750kg per m^3, pulpwood – 675 kg per m^3, fuelwood – 725 kg per m^3 as per volume-weight conversions in Forest Statistics of India, pg 118, 2005

Demand projections for 2025

According to Table 12 the annual wood availability / removal from forests has decreased by 88% over six years from 1998 to 2004. Due to lack of data on demand – supply gaps, imports from other states/countries and unrecorded forest removals, it was not possible to establish consistent trends in wood production. Ranganathan *et al.*1993, have projected demands 2021 to be 1.76 million tons that has been accepted by Forest Department, Karnataka (Ranganathan *et al.* 2009). Projections for 2025 have been derived by extrapolating data with base year as 1998. Demands for projections were kept constant for both scenarios (Table 13).

Table 13 Future wood demand in Karnataka

Year	Demand(million tons)
2015	1.68
2020	1.74
2025	1.8

References (Supplementary)

1. Bhalla GS, Hazell P, Kerr J (1999) Prospects for India’s cereal supply and demand 2020- 2020 Vision, IFPRI, Washington DC
2. Biradar CM, Thenkabail PS, Noojipady P, Li Y, *et al.* (2009) A global map of rainfed cropland areas (GMRCA) at the end of the last millenium using remote sensing, *International Journal of Applied Earth Observation and Geoinformation* **11**, 114-129
3. Brush JE (1968) Spatial patterns of populations in Indian cities, *Geographical Review*, **58(3)** 362-391, American Geographical Society,
4. Census of India (2006) Population Projections for India and States 2001-2026, Report of the Technical Group on Population Projections Constituted by the National Commission on Population, Government of India
5. Central Statistical Organization (2008), National accounts statistics: manual on estimation of state and district income, New Delhi
6. Chand R (2007) Demand for Foodgrains, *Economic and Political Weekly* **42** (52)
7. Chaudhary J (2005) The future of Indian cotton suppy and demand: implications for the US cotton industry, PhD Dissertation, Texas Tech University, USA
8. CSO (Central Statistics Office) (2010), Energy Statistics of India, Ministry of Statistics and Programme Implementation, Government of India
9. DBT (Department of Biotechnology) and MOEF (Ministry of Environment and Forests) (2009), Series of Crop Specific Biology Documents, Government of India
10. Department of Animal Husbandry (2008) Annual Report 2007-2008, Ministry of Agriculture, Government of India, New Delh
11. DES (Department of Economics and Statistics) (2007) Statistical Abstract of Karnataka, 2001-02 to 2004-05, Government of Karnataka, Bangalore
12. Deshpande RS, Naika TR (2002), Impact of Minimum Support Price in Agricultural economy: a study in Karnataka, Institute for Social and Economic Change, Bangalore

13. Divakar BN, Upadhaya HD, Wani SP, Gowda CLL (2010) Biology and genetic improvement of Jatropha curcas L.: a review, *Applied Energy* 87732-742
14. ESRI (2000) Digital Chart of the World dataset, Pennsylvania state university library, available at http://www.maproom.psu.edu/dcw/ Last accessed February 2011
15. FAO (2009) Digital Soil Map of the World and Derived Soil Properties, Available at www.fao.org [last accessed April 19, 2010]
16. Ghosh P and Ghose T K (2003) Bioethanol in India: recent past and emerging future, In Series : Advances in Biochemical Enginnering/ Biotechnolgoy (Ser Ed. Scheper T) 85, Vol: Biotechnology in India II (Eds: Ghose T K and Ghosh P), Chapter 1,1-28, Springer-Verlag, Germany
17. ICFRE (2002) Forestry Statistics India- 2001,Dehradun, India
18. ICFRE (2009) Forestry Statistics India- 2005, Dehradun, India
19. Ikisan Limited, Information technology enabled services on agriculture (ITES), available at http://www.ikisan.com/ Last accessed February 2011
20. Jain S and Sharma MP (2010) Prospects of biodiesel from Jatropha in India: a review, *Renewable and Sustainable Energy Reviews* 14763-771
21. Joshi PK, Singh NK, Singh NN, Gerpacio RV, Pingali PL (2005) Maize in India: Production systems, constraints and research priorities. Mexico D.F: CIMMYT
22. Karanth KK, Curran LM, Reuning-Scherer JD (2006) Village size and forest disturbance in Bhadra Wildlife Sanctuary, Western Ghats, India, *Biological Conservation* 128, 147-157
23. Karnataka forest department (2008) Annual Report, Government of Karnataka, Bangalore
24. Karnataka State Planning Board (2008) Karnataka – A vision for development, Government of Karnataka, Bangalore
25. Karnataka State Remote Sensing Agency (2007) Spatial data on administrative boundaries, *personal communication*
26. Kumar G, Kumar D, Johar R, Singh CP (2010) A continuous tranesterification process of Jatropha curcas oil in the presence of biodiesel as a green solvent, *Bioresource Technology,* Article in press
27. Kumar L and Maithel S (2006) Alternative feedstock for bio-ethanol production in India, In: *Biofuels towards a greener and secure energy future* (Ed: Bhojvaid P P) Section 2, 89-103, TERI Press, New Delhi

28. Kureel RS, Singh CB, Gupta AK, Pandey A (2007) Jatropha an alternate source for biodiesel, NOVODB, Ministry of Agriculture, Government of India, Gurgaon
29. Lehner B, Verdin K , Jarvis A (2008) New global hydrography derived from spaceborne elevation data, EoS Transactions AGU **89**, 93-94
30. Loveland TR, Reed BC, Brown JF, Ohlen DO, Zhu Z, Yang L, Merchant JW (2000) Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data, *International Journal of Remote Sensing,* **21**(6, 7), 1303-1330, (2000)
31. Mehta DC and Dias FF (1999) Maize: Perspectives and applications in India, Starch/Stärke 51 (2-3) S.52-57
32. Metherell AK, Harding LA, Cole CV, Parton WJ (2011) CENTURY Soil Organic Matter Model Environment ,Technical Documentation, USDA-ARS Fort-Collins Colorado, USA available at http://www.nrel.colostate.edu/projects/century/MANUAL/html_manual/man96.html
33. Ministry of Agriculture (2004) Directory of wholesale agricultural produce assembling markets in India, Government of India, Nagpur
34. Ministry of Agriculture (2007) Cost of cultivation of principal crops in India,Government of India, New Delhi
35. Ministry of Agriculture (2008) Annual Report, 2007-2008, Department of Animal Husbandry, Dairying and Fisheries, Government of India, New Delhi
36. Ministry of Agriculture (2010) Web based land use statistics information system, Concepts and Definitions, DACNET, Government of India, Available at
37. Ministry of New and Renewable Energy (2009) National Policy on Biofuels, Government of India, New Delhi
38. Ministry of Petroleum & Natural Gas (2006) Report of the Working Group on Petroleum & Natural Gas Sector for the XI Plan(2007-2012), Government of India
39. Ministry of Petroleum and Natural Gas (2008) Annual Report, Government of India
40. Ministry of Statistics and Programme Implementation (2008) Manual on Agricultural Prices and Marketing,Government of India
41. Mitchell TD, Jones PD (2005) An improved method of constructing a database of monthly climate observations and associated high resolution grids, *International Journal of Climatology* **25,** 693-712

42. Mittal S (2008) Demand- supply trends and projections of food in India, Working Paper No. 209 Indian Council for Research on International Economic Relations

43. MNRE, Ministry of New and Renewable Energy (2009) National Policy on Biofuels, Government of India, New Delhi

44. Mohanty S, Alexandratos N, Bruinsma J (1998) The long-term food outlook for India, Technical Report, Center for Agricultural and Rural Development, Iowa State University

45. NRSA (National Remote Sensing Agency) (2004a) Land-use land-cover map Karnataka, Hyderabad, India

46. NRSA (National Remote Sensing Agency) (2004b), Wasteland map of Karnataka, Hyderabad, India

47. NRSA (National Remote Sensing Agency),Department of Space and DOLR (Department of Land Resources), Ministry of Rural Development (2005) Wastelands Atlas of India, Government of India, New Delhi

48. NRSA (National Remote Sensing Agency),Department of Space and DOLR (Department of Land Resources), Ministry of Rural Development (2010) Wastelands Atlas of India, Government of India, New Delhi

49. Pavithra BS, Basvaraja H, Kiresur VR, Mahajanshetty SB, Mageri SN (2009) An economic analysis of food consumption patter in Karnataka, *Karnataka Journal of Agricultural Sciences* **22** (4) 840: 845

50. Planning and Statistics Department (2005) Karnataka Human Development Report, Government of Karnataka, Bangalore

51. Ranganathan V, Subba Rao S, Prabhu GS (1993) Demand and supply of fuelwood in Karnataka (unpublished) for the Forest Department, Government of Karnataka, Indian Institute of Management, Bangalore, In: *Pandey D, Fuelwood studies in India – Myth and Reality*, Center for International Forestry Research, Jakarta, Indonesia, 2002

52. Ranganathan V, Subba Rao S, Prabhu GS (2009) Demand and supply of fuelwood in Karnataka (unpublished) for the Forest Department, Government of Karnataka, Indian Institute of Management, Bangalore, in Chavan SG, Extract of State Forestry Action Programme (1997-2007), Karnataka Forest Department, personal communication

53. Rosegrant MW (1995) Global Food Projections to 2020: Implications for investment, IFPRI, Washington DC

54. Savadatti PM (2007) An econometric analysis of demand and supply response of pulses in India, *Karnataka Journal of Agricultural Sciences* **203,** 545-550
55. Schneider A, Friedl MA, Potere D (2009) A new map of global urban extent from MODIS data *Environmental Research Letters,* **4**- 044003.
56. Schneider A, Friedl MA and Potere D (2010) Mapping global urban areas using MODIS 500 m data: new methods and datasets based on ‘urban ecoregions’, *Remote Sensing of the Environment* **114 (8),** 1733-1746
57. Statistical Abstract (2007) Karnataka, Government of Karnataka
58. Taubenböck H, Wegmann M, Berger C, Breunig M, Roth A, Mehl H (2008), Spatiotemporal analysis of Indian megacities, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol XXXVII Part B2, Beijing
59. Thenkabail PS, Biradar CM, Noojipady P, Dheeravath V, Li Y J, *et al.*(2008) A Global Irrigated Area Map (GIAM) using remote sensing at the end of the last millennium, pp63 International Water Management Institute, Colombo,Sri Lanka
60. UNEP-WCMC, IUCN (2009) World Database on Protected Areas, available at http://www.wdpa.org/Default.aspx Last accessed February 2011
61. Whitaker M and Heath G (2009), Life cycle assessment of use of Jatropha biodiesel in Indian locomotives, NREL/ TP-6A2-44428, 2009, USA
62. WWF and GEXSI LLP (2008) Global market study on Jatropha, Project inventory: Asia,London/Berlin available at http://www.jatropha-alliance.org/fileadmin/documents/GEXSI_Jatropha-Project-Inventory_ASIA.pdf Last accessed February 2011

7 Discussion and Conclusions

India aims to substitute 20% diesel and gasoline demand with biofuels by 2017 (Ministry of New and Renewable Energy 2009).The main feedstocks used in the Indian biofuel programme are Jatropha (for biodiesel) and sugarcane ethanol (for bioethanol). The first part of this dissertation aimed at assessing the dynamic nature of biofuel policies in India up to 2010. Detailed examination showed that the Indian biofuel policy has followed a zigzag pattern over the last decade with indecision presiding over key aspects of Jatropha including yield estimation on different types of land under different management options. The Biofuel policy does not encourage energy production on agricultural land, use of fertilizers or irrigation of bioenergy crops. The current status of blending of bioethanol is that 5% blending is being undertaken in almost half of the country (16 states+ 3 union territories). However, an estimation of the extent of implementation of the biodiesel programme was not possible. Other relevant research topics in the Indian context emerging from the study were (i) the estimation of land availability for first generation biofuels, (ii) the quantification of direct land use change and (iii) implications on food security in case of conversion of arable land.

The targeted areas for biodiesel production are the wastelands or degraded lands that are characterized by low fertility and are therefore unsuitable for food production. Taking the southern Indian state of Karnataka as an example, the main findings of this study suggest that average jatropha yield on wastelands (0.8 t/ ha) is lower than that on agricultural land (2.2 t/ha) with no fertilizer application in either case. Scenario analysis under the boundary conditions of IE (Industrial Economy) and AE (Agricultural Economy) suggests that 88 % and 93% of bioethanol demand can be fulfilled by 2017. Biodiesel targets are met under both scenario assumptions but at the expense of 3.8% and 4.2 % of agricultural land (including long and short-term fallows) being diverted to Jatropha cultivation. Although food production was not negatively impacted, land use intensification was observed in the form of a drastic decrease of fallow areas (93% in IE and 95% in AE). Moreover, results indicate that wastelands can contribute only up to ~30 % of the total biodiesel demand, whereas the 20% target for India was developed assuming 100% of biodiesel production on wastelands.

The results of this study are based on the paradigm of integrated assessments and achieved through the use of the spatially explicit modelling framework - SITE. The need to estimate biofuel production potential on marginal lands has been pointed out by earlier studies (Zhang *et al.* 2010). The approach used in this study included the use of spatial distribution of wasteland data, for which Jatropha production was calculated. The second key set of factors included here is based on the growth of the Indian biofuel industry being largely dependent on market forces, as is the case globally (Korobeinikov *et al.* 2010). This study has incorporated a spatial approach for estimating net profit margins (of food and fuel crops), taking into account all relevant costs and producer prices. The main observation emerging from the study that additional land will be required if the 20% target is to be met are consistent with previous studies that were conducted at the national scale (Lapola *et al.* 2009; Schaldach *et al.* 2010, Ravindranath *et al.* 2010). However, the previous studies were carried out at an aggregated national level and did not distinguish between biofuel production on wastelands and on agricultural lands. Thus, analysis of crop yields under more detailed biophysical and socio-economic conditions results in simulated Jatropha yields being lower than those simulated by Lapola et al. 2009. The difference in yields can be mainly attributed to the use of the DayCent model (in this study) that takes into account nitrogen limitations (Parton *et al.* 1998) whereas the LPJmL model (in Lapola et al. 2009) does not involve simulation of the nitrogen cycle (Lapola et al. 2009).

Most of the production of biodiesel is aimed at wastelands, making wastelands a critical aspect. Although 7% of the area in Karnataka (and 11% of the area of India) is categorized as wastelands, the availability of wastelands remains a major question (Balooni and Singh 2007). Most studies, including this study, assume that all wastelands are available, however, several authors have pointed out that wastelands in India may actually at least partially be in use by the poorest sections of the Indian society for dwelling, small scale agriculture or other purposes and afforestation on wastelands is challenged by encroachments and financing limitations (Balooni 2003). Therefore these wasteland areas may not be technically available for biofuel production, a fact raising serious doubts about the potential of biofuel programs solely dependent on the availability of wastelands.

Besides the need for spatial analysis as presented above, detailed representation of the pathways of biofuel production (although typically part of a Life Cycle Analysis (LCA) (Rejinders and Huibregts 2009)) is just as important in spatial studies, because they have clear impacts on land demands. Mulit-sectoral use of ethanol (industrial and potable alcohol consumption is 60% of the total ethanol production in India) in case of bioethanol and factors such as oil content, oil extraction efficiency and transesterfication losses in case of biodiesel were considered in this analyisis. Results clearly indicate that the largest gains may be derived from improved extraction efficiency increasing the total production by 40%. The magnitude of the effect of these parameters is visible in the scenario analysis section of the study where despite 11% higher biofuel demands in the IE scenario, land conversion was almost equal in the IE and AE scenarios as the AE scenario assumed lower oil content and oil extraction efficiencies than the IE scenario. Hence, technical improvements with respect to oil content of Jatropha seeds and oil extraction technologies play a decisive role in the success of the biofuel program.

Additionally, results from this study indicate the importance of integrating markets into spatial assessments as Jatropha production occurred in close proximity to markets. For biofuels to displace food crops, profit margins earned by cultivators need to be consistently higher than or at least equivalent to food crops, to act as an economic incentive for biofuel production. In order to capture the importance of economic viability, it is therefore essential that different marketing aspects such as distance to nearest market, cost of cultivation and prices earned by producers are taken into account. Results from this study agree with Ariza-Montobbio and Lele (2010) and Shinoj *et al*. (2010) that Jatropha cultivation incurs a net loss in the first three years of planting and can take up to ten years to earn profits. Often, aspects of marketing mechanisms are hard to implement in spatial studies due to the lack of data for example the location of biofuel markets, detailed management costs and producer prices offered under different business models. The economic approach used in this study could be strengthened by introducing the effects of minimum support prices (MSP) and financial incentives such as loans and subsidies, subject to the availability of detailed data.

The results emerging from this research have the potential to improve and widen the existing knowledge-base of biofuels in India. Firstly, yield estimation of Jatropha via the modelling approach presented here is not only complimentary to ongoing experimental approaches but can serve as a faster form of early indication of crop performance since generation of detailed experimental data requires at least 4-5 years of time. Secondly, spatially explicit estimates of productivity regimes can help in localised planning since most Indian states (including Karnataka) are large and comprise a high degree of spatial heterogeneity in terms of climate, soils and socio-economic conditions. Additionally, integrated assessments help identify and quantify the most influential parameters in biofuel production such as oil extraction efficiency and impacts on economic aspects of energy production such as income generation for producers. Lastly, the approach used in this study can be implemented for other regional or national level assessments. Given the availability of high quality spatial data from national/ state level remote sensing agencies and statistical data from online portals (developed by the National Informatics Center), data intensive assessments such as this study are definitely replicable for other parts of India and at national scale.

This research was mainly limited by difficulties in localised validation of Jatropha results. Since experimental research on Jatropha began in India in 2004-2005, only a small number of results on Jatropha yields and detailed physiological characteristics were published. This shortcoming was partially overcome by validating model results against the few published articles and government documents that reported Jatropha yields under similar climatic and edaphic conditions from other parts of India. As indicated above, availability of data was not a frequent impediment; however, the study was impacted by lack of detailed spatial and statistical information on urban and rural land use, which is a significant driver of land use change in India. Both of the aforementioned factors contributed to the uncertainty of model results. Lastly, the study had to be continuously adapted to the frequently changing paradigms of the Indian biofuel programme during the entire course of research which was a time consuming process.

In conclusion, first generation biofuels will continue to form a vital part of the renewable energy matrix in India and have a high potential to contribute to the substitution of fossil fuels in the transport sector. To strengthen the biofuel program a multi-pronged approach will be needed including (i) regional scale planning to identify suitable energy crops or a mix of crops, (ii) the adoption of farm-level conservation measures for water (iii) switching to a fuel economy especially in urban areas for energy conservation (iv) the implementation of technical improvements at decentralized biofuel processing units and (v) improving financial mechanisms to support producers. The small number of spatial assessments for India leaves much scope for further analyses of more feedstock options for biofuels in India. Although several alternative feedstocks such as Pongamia, Simarouba, Sugarbeet, Cassava etc. are available and have been proposed repeatedly, the basic questions of associated chances and risks (such as yields, losses / gains in production pathways and effective crop management practices) need to be analysed and tailored to regional circumstances in order to arrive at appropriate technological solutions and crop-mixes. Future research in this direction needs also to be linked to estimating the GHG balances of biofuel crops in India. As shown in previous studies (Searchinger *et al.* 2008; Tilman *et al.* 2006; Fargione *et al.* 2008; Lapola *et al.* 2010) long-term use of biofuels may not always be sustainable as they may eventually incur a carbon-debt. Estimation of direct and indirect land use change in India can be of vital importance to assessing the sustainability of biofuel in India.

References

1. Ajanovic A (2010) Biofuel versus food production: does biofuels production increase food prices? *Energy 1-7, in press*
2. Alcamo J, Kasper K, Bush G and Priess JA (2008) Searching for the future of land: scenarios from local to global scale In: *Environmental Futures: The Practice of Environmental Scenario Analysis* (Ed., Alcamo J) Elsevier, The Netherlands
3. Ariza-Montobbio P and Lele S (2010) Jatropha plantations for biodiesel in Tamil Nadu, India: viability, livelihood trade-offs and latent conflict, *Ecological Economics* **70** (2), 189-195
4. Beringer T, Lucht W and Schaphoff S (2011) Bioenergy production potential of global biomass plantations under environmental and agricultural constraints, *Global Change Biology Bioenergy* ,doi: 10.1111/j.1757-1707.2010.01088.x
5. Bhatt SC and Bhargava GK (2006) Ed., Land and people of Indian states and Union territories- Karnataka, Kalpaz Publications, New Delhi
6. Bogdanski A, Dubois O, Jamieson C, Krell R (2010) Making intergrated food-energy systems work for people and climate- an overview, FAO of the United Nations, Rome
7. Briassoulis H (2000) Analysis of land use change: theoretical and modelling approaches. The Web Book of Regional Science, Regional Research Institute, West Virginia University
8. Brindaban PS, Bulte EH and Conijn SG (2009) Can large-scale biofuels production be sustainable by 2020? *Agricultural Systems* **101**, 197-199
9. Brittaine R and Lutadalio N (2010) Jatropha: a smallholder bioenergy crop- the potential of pro-poor development, FAO, Rome
10. Buccholz T, Rasmetsteiner E, Volk TA, Luzadis VA (2009) Multi criteria analysis for bioenergy systems assessments, *Energy Policy* **37** 484-495
11. Census of India (2001) Primary Census Abstract, Office of the Registrar General, New Delhi, India, available on CD-ROM
12. Central Statistical Organisation (2008) Manual on Cost of Cultivation Surveys, Ministry of Statistics and Programme Implementation, Government of India, New Delhi
13. Clayton AMH and Radcliffe NJ (1996) Sustainability: A Systems Approach. Earthscan London

14. Dale HV, Kline KL, Wiens J, Fargione J (2010) Biofuels: implications for land use and biodiversity, Biofuels and Sustainability Reports, Ecological Society of America, Washington DC, Available at http://www.esa.org/biofuelsreports/ [last accessed February 10,2011]
15. DeFries R and Pandey D (2010) Urbanization, the energy ladder and forest transitions in India's emerging economy, *Land Use Policy* **27,** 130-138
16. Department of Economics and Statistics (2007) Statistical Abstract of Karnataka, 2001-02 to 2004-05, Government of Karnataka, Bangalore
17. Directorate of Economics and Statistics (2007) Cost of Cultivation of Principal Crops in India, Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India, New Delhi
18. Directorate of Economics and Statistics (2011) Web based land use statistics information system, Ministry of Agriculture, Government of India available at http://dacnet.nic.in/lus/ last accessed February 16, 2011
19. Eide Asbjorn (2008) The right to food and the impact of liquid biofuels (agrofuels), FAO, Rome
20. Elghali L, Clift R, Sinclair P, Panoutsou C, Bauen A (2007) Developing a sustainability framework for the assessement of bioenergy systems, *Energy Policy* **35** 6075-6083
21. Ewing M and Msangi S (2009) Biofuels production in developing countries: assessing tradeoffs in welfare and food security, *Environmental Science and Policy* **12** 520-528
22. FAO, The state of food and agriculture (2008) ISSN 0081-4539, Communication Division, FAO, Rome
23. Fargione J, Hill J, Tilman D, Polasky S, Hawthrone P (2008) Land clearing and the biofuel carbon debt, *Science* **319** (5867) 1235-1238
24. Gerber N, Eckert M, Breuer T (2009) Biofuels and food prices : a review of recent and projected impacts, RIO9- World climate and energy event, March 2009, Rio de Janeiro, Brazil
25. Haque T and Sirohi AS (Eds.) (1986) Agrarian reforms and institutional changes in India, Concept Publishing Company, New Delhi
26. Havlik P, Schneider UA, Schmid E, Böttcher H, Fritz S, Skalsky R et al. (2010) Global land-use implications of first and second generation biofuel targets, *Energy Policy, in press*

27. Hellmann F and Verburg PH (2010) Impact assessment of the European biofuel directive on land use and biodiversity, *Journal of Environmental Management* **91** 1389-1396

28. Jyothi HS and Raju VT (2003) Study on marketing of croosandra, jasmine and rose flowers in east Godavari district of Andhra Pradesh, *Agricultural Marketing* ISSN 0002-1555 XLVI (2)

29. Balooni K (2003) Economics of wastelands afforestation in India, a Review. *New Forests* 26: 101–136

30. Balooni K and Singh K (2007) Prospects and problems of afforestation of wastelands in India: A synthesis of macro- and micro-perspectives. *Geoforum* 38 1276–1289

31. Karnataka State Planning Board (2008) Karnataka : A vision for development, Government of Karnataka, Bangalore

32. Korobeinikov A, Read P, Parshotam A ,Lermit J (2010) Modelling regional markets for co-produced timber and biofuel, *Ecological Economics* **69**, 553-561

33. KSAMB, Karnataka State Agriculutral Marketing Board, Online Market Information System, Available at http://www.ksamb.gov.in/index.asp last accessed Feburary 14, 2011

34. Lambin EF, Geist HJ, Lepers E (2003) Dynamics of land-use and land-cover change in tropical regions, *Annual Review of Environment and Resources* **28,** 205-241

35. Lapola DM, Priess JA, Bondeau A (2009) Modeling the land requirements and potential productivity of sugarcane and jatropha in Brazil and India using the LPJmL dynamic global vegetation model, *Biomass and Bioenergy* **33(8),** 1087-0195

36. Liaquat AM, Kalam MA, Masjuki HH, Jayed MH (2010) Potential emissions reduction in road transport sector using biofuel in developing countries, *Atmospheric Environment* **44**, 3869-3877

37. Maps of India (2010) Business- Karnataka Sugar Industry, Maps of India, Available at http://business.mapsofindia.com/sugar-industry/karnataka.html Last accessed on February 15, 2011.

38. Meyer WB and Turner BL (1994) Changes in Land Use and Land Cover, Cambridge University Press, Cambridge

39. Mimler M and Priess JA (2008) Design and Implementation of a generic modeling framework- a platform for integrated land use modeling, Center for Environmental Systems Research, Kassel University Press, University of Kassel, Germany

40. Ministry of Agriculture (2004) Directory of wholesale agricultural produce assembling markets in India, Government of India, Nagpur
41. Ministry of Agriculture (2010) Draft National Food Security bill, Government of India, New Delhi
42. Ministry of New and Renewable Energy (2009) National Policy on Biofuels, Government of India, New Delhi
43. Ministry of Statistics and Programme Implementation (2010) Manual on Agricultural Prices, Central Statistics Office, CSO-MAPM-2010 Government of India, New Delhi
44. Mueller SA, Anderson JE, Wallington TJ (2011) Impact of biofuel production and other supply and demand factors on food price increases in 2008, *Biomass and Bioenergy, in press*
45. Münier B, Birr-Pedersen K, Schou JS (2004) Combined ecological and economic modelling in agricultural land use scenarios, *Ecological Modelling* **174** 5-18
46. Musters CJM, De Graff HJ, Ter Keurs WJ (1998) Defining socio-environmental systems for sustainable development. Ecological Economics **26** 243-258
47. Nagothu U S (2001) Fuelwood and fodder extraction and deforestation: mainstream views in India discussed on the basis of data from the semi-arid region of Rajasthan, *Geoforum* **32** 319-332
48. NOVODB (2007) Jatropha an alternate source for biodiesel, Ministry of Agriculture, Government of India, Gurgaon
49. NRSA (National Remote Sensing Agency),Department of Space and DOLR (Department of Land Resources), Ministry of Rural Development (2005), Wastelands Atlas of India, Government of India, New Delhi
50. OECD (2008) Rising food prices: causes and consequences, Available at http://www.oecd.org/dataoecd/54/42/40847088.pdf Last accessed on February 15, 2011
51. Openshaw K (2000) A review of Jatropha curcas: an oil plant of unfulfilled promise, *Biomass and Bioenergy* **19**, 1-15
52. Overmars K P, Stehfest E, Ros J P M and Prins A G (2011) Indirect land use change emissions related to EU biofuel consumption: an analysis based on historical data, *Environmental Science and Policy*, in press
53. Parton W J, Hartman M, Ojima D, Schimel D (1998) DAYCENT and ist land surfact submodel: description and testing, *Global and Planetary Change* **19**(1-4),35-48

54. Planning and Statistics Department (2006) Karnataka Human Development Report 2005 Investing in Human Development, Government of Karnataka, Bangalore
55. Planning Commission (2007) Karnataka Development Report, ISSN 81-7188-579-9 Government of India
56. Priess JA, Schweitzer C, Wimmer F, Batkhishig O, Mimler M (2011) The consequences of land-use change and water demands in Central Mongolia, *Land Use Policy* **28**, 4-10
57. Priess JA, Mimler M, Klein AM, Schwarze S, Tscharntke T and Steffan-Dewenter I (2007) Linking deforestation scenarios to pollination services and economic returns in coffee agroforestry systems, *Ecological Applications* **17** (2), 407–417
58. Purushothaman S and Kashyap S (2010) Trends in land use and crop acreages in Karnataka and their repercussions, *Karnataka Journal of Agricultural Science* **23** (2), 330-333
59. Rathmann R, Szklo A and Schaeffer R (2010) Land use competition for production of food and liquid biofuels: an analysis of the arguments in the current debate, *Renewable Energy* **35** 14-22
60. Ravindranath NH and Balachandra P (2009) Sustainable bioenergy for India: Technical, economic and policy analysis, *Energy Policy* **34**, 1003-1013
61. Ravindranath NH and Hall DO (Eds) (1995), Biomass, Energy and Environment, a developing country perspective from India, Oxford University Press, UK.
62. Ravindranath NH, Lakshmi CS, Manuvie R, Balachandra P (2010) Biofuel production and implications for land use, food production and environment in India, *Energy Policy in press*
63. Rejinders L and Huibregts MAJ (Eds.) (2009) Climate effects and non-greenhouse gas emissions associated with transport biofuel life cycles, Chapter 4, In: Biofuels for Road Transport- A Seed to Wheel Perspective, Green Energy and Technology ISSN 1865-3529, Springer, Germany
64. Romijn HA (2010) Land clearing and greenhouse gas emissions from Jatropha biofuels on African Miombo woodlands, *Energy Policy in press*
65. Romjin HA and Calniels MCJ (2011) The Jatropha biofuels sector in Tanzania 2005-2009: evolutions towards sustainability? *Research Policy in press*

66. Sankhayan PL and Hofstad O (2001) A village-level economic model of land clearing, grazing and wood harvesting for sub-Saharan Africa: with a case study in southern Senegal. *Ecological Economics* **38** 423-440
67. Schubert R, Schellnhuber HJ, Buchmann N Epiney, Greißhammer, Kulessa M, Messner D, Rahmstorf, Schmid J (Eds).(2009), In: Future Bioenergy and Sustainable Land Use, German Advisory Council on Global Chnage (WBGU), Earthscan Publications, Berlin
68. Schweitzer C, Priess JA and Das S (2011) SITE- a generic land-use modelling framework, *Environmental Modelling and Software*, *accepted February 2011*
69. Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A *et al.* (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change, *Science* **319** 1238-1240
70. Shinoj P, Raju SS, Kumar P, Msangi S, Yadav P, *et al.* (2010) An economic assessment along the Jatropha based biodiesel value chain in India, *Agricultural Economics and Research Review* Vol 23 (Conference Number) 393-404
71. Sruhsaker TT (1987) Forestry issues and conservation in Uganda, *Biological Conservation* **39**, 209-234
72. Sullivan S (1999) The impacts of people and livestock on topographically diverse open wood and shrub-lands in arid north-west Namibia, *Global Ecology and Biogeography* **8** 257-277
73. Thrän D, Seidenberger T, Zeddies J, Offermann R (2010) Global biomass potentials — Resources, drivers and scenario results, E*nergy for Sustainable Development,* **14**(3), 200-205
74. Tilman D, Hill J and Lehman C (2006) Carbon-negative biofuels from low-input high-biodiversity grassland and biomass *Science* **314**,1598- 1600
75. Turner II B L, Skole D L, Sanderson S, Fisher G, Fresco L O *et al.* (1995) Land-use and land-cover change. Science / Research Plan. Stockholm and Geneva: IGBP Report No. 35 and HDP Report No. 7, 132
76. Urban Development Department, Bangalore (2009) Urban Development Policy for Karnataka (Draft), Government of Karnataka
77. Veldkamp A and Lambin EF (2001) Predicting land use change, *Agriculture, Ecosystems and Environment* **85**, 1-6

78. Veldkamp A and Verburg P (2004) Modelling land use change and environmental impact, *Journal of Environmental Management* **72**, 1-3

79. Verburg PH, Schot PP ,Dijst MJ and Veldkamp A (2004) Land use change modelling: current practices and research priorities *GeoJournal* **61**, 309-324

80. Zhang X, Izaurralde RC, Manowitz D, West TO, Post W M *et al.* (2010) An integrative modeling frameowork to evaluate the productivity and sustainability of biofuel crop production systems *Global Change Biology, Bioenergy*, **2,** 258-277

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Erklärung

Hiermit erkläre ich eidesstattlich, dass ich diese Dissertation selbstständig und ohne fremde Hilfe verfasst, andere als die von mir angegebenen Quellen und Hilfsmittel nicht benutzt und die den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.

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