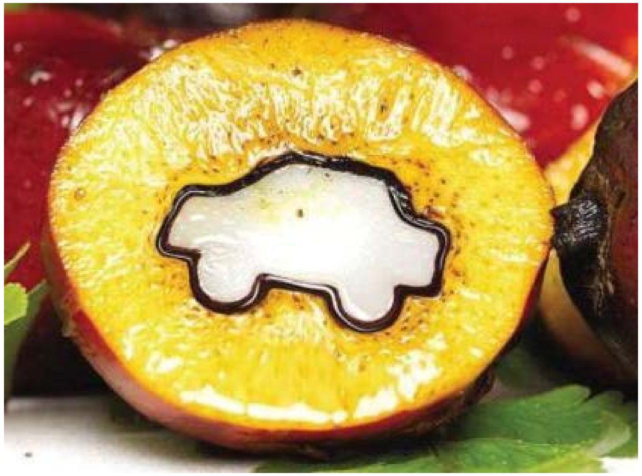
Environmental Implications of Jatropha Biofuel from a Silvi-Pastoral Production System in Central-West Brazil



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“Standardization of Environmental Life Cycle Assessments of Biofuels”

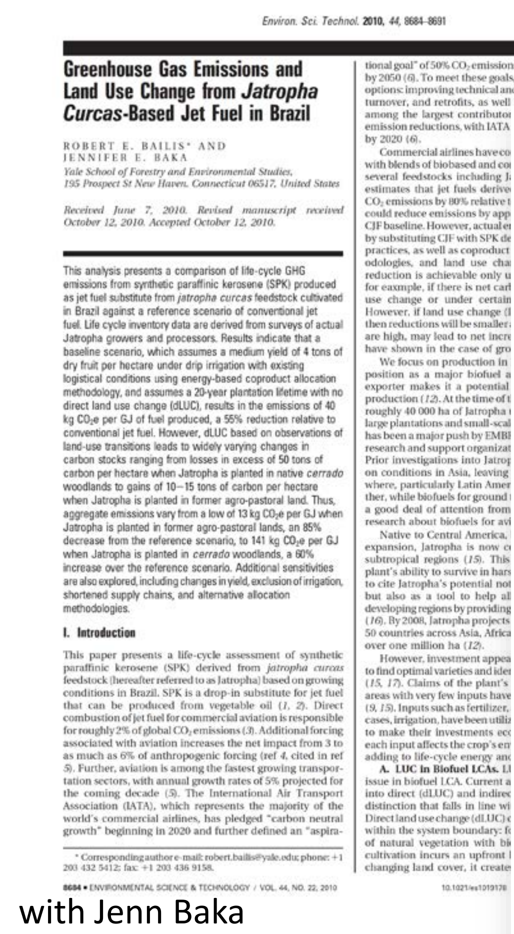
22 - 25 July 2014

Rob Bailis - Associate Professor; Yale School of Forestry & Environmental Studies

Outline

- Some background on Jatropha LCA
- The silvi-pastoral system
  - Co-production with cattle
  - Detoxification
  - Other innovations
- Results
- Future directions

Previous work…



Environ. Sci. Technol. **2010,** *44,* 8684–8691

Greenhouse Gas Emissions and Land Use Change from *Jatropha Curcas*-Based Jet Fuel in Brazil

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This analysis presents a comparison of life-cycle GHG emissions from synthetic paraffinic kerosene (SPK) produced as jet fuel substitute from *jatropha curcas* feedstock cultivated in Brazil against a reference scenario of conventional jet fuel. Life cycle inventory data are derived from surveys of actual Jatropha growers and processors. Results indicate that a baseline scenario, which assumes a medium yield of 4 tons of dry fruit per hectare under drip irrigation with existing logistical conditions using energy-based coproduct allocation methodology, and assumes a 20-year plantation lifetime with no direct land use change (dLUC), results in the emissions of 40 kg CO_2e per GJ of fuel produced, a 55% reduction relative to conventional jet fuel. However, dLUC based on observations of land-use transitions leads to widely varying changes in carbon stocks ranging from losses in excess of 50 tons of carbon per hectare when Jatropha is planted in native *cerrado* woodlands to gains of 10–15 tons of carbon per hectare when Jatropha is planted in former agro-pastoral land. Thus, aggregate emissions vary from a low of 13 kg CO_2e per GJ when Jatropha is planted in former agro-pastoral lands, an 85% decrease from the reference scenario, to 141 kg CO_2e per GJ when Jatropha is planted in *cerrado* woodlands, a 60% increase over the reference scenario. Additional sensitivities are also explored, including changes in yield, exclusion of irrigation, shortened supply chains, and alternative allocation methodologies.

I. Introduction

This paper presents a life-cycle assessment of synthetic paraffinic kerosene (SPK) derived from *jatropha curcas* feedstock (hereafter referred to as Jatropha) based on growing conditions in Brazil. SPK is a drop-in substitute for jet fuel that can be produced from vegetable oil (*1, 2*). Direct combustion of jet fuel for commercial aviation is responsible for roughly 2% of global CO_2 emissions (*3*). Additional forcing associated with aviation increases the net impact from 3 to as much as 6% of anthropogenic forcing (ref *4*, cited in ref *5*). Further, aviation is among the fastest growing transportation sectors, with annual growth rates of 5% projected for the coming decade (*5*). The International Air Transport Association (IATA), which represents the majority of the world's commercial airlines, has pledged "carbon neutral growth" beginning in 2020 and further defined an "aspirational goal" of 50% CO_2 emissions reductions from 2005 levels by 2050 (*6*). To meet these goals, airlines may rely on several options: improving technical and operational efficiency, fleet turnover, and retrofits, as well as biofuels (*7*). Biofuels are
among the largest contributor
emission reductions, with IATA
by 2020 (*6*).

Commercial airlines have co
with blends of biobased and co
several feedstocks including J
estimates that jet fuels derive
CO_2 emissions by 80% relative t
could reduce emissions by app
CJF baseline. However, actual e
by substituting CJF with SPK de
practices, as well as coproduct
odologies, and land use cha
reduction is achievable only u
for eaxmple, if there is net car
use change or under certain
However, if land use change (
then reductions will be smaller
are high, may lead to net incre
have shown in the case of gro

We focus on production in
position as a major biofuel a
exporter makes it a potential
production (*12*). At the time of t
roughly 40 000 ha of Jatropha
large plantations and small-sca
has been a major push by EMB
research and support organizat
Prior investigations into Jatro
on conditions in Asia, leaving
where, particularly Latin Ame
ther, while biofuels for ground
a good deal of attention from
research about biofuels for avi

Native to Central America,
expansion, Jatropha is now c
subtropical regions (*15*). This
plant's ability to survive in har
to cite Jatropha's potential no
but also as a tool to help al
developing regions by providing
(*16*). By 2008, Jatropha projects
50 countries across Asia, Africa
over one million ha (*12*).

However, investment appea
to find optimal varieties and ide
(*15, 17*). Claims of the plant's
areas with very few inputs have
(*9, 15*). Inputs such as fertilizer,
cases, irrigation, have been utili
to make their investments ec
each input affects the crop's en
adding to life-cycle energy an

A. LUC in Biofuel LCAs. L
issue in biofuel LCA. Current a
into direct (dLUC) and indire
distinction that falls in line wi
Direct land use change (dLUC)
within the system boundary: f
of natural vegetation with bi
cultivation incurs an upfront
changing land cover, it create

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10.1021/es1019178

with Jenn Baka

GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2011), doi: 10.1111/j.1757-1707.2011.01100.x

Carbon impacts of direct land use change in semiarid woodlands converted to biofuel plantations in India and Brazil

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Abstract

**We present an analysis of direct land use change (dLUC) resulting from the conve
semiarid woodlands in Brazil and India to *Jatropha curcas*, a perennial biofuel c
sites examined include prosopis woodlands, managed for woodfuel productio
periodic coppicing, in southern India, and unmanaged *caatinga* woodlands
Brazilian state of Minas Gerais. The jatropha plantations under consideration
pruned and unpruned stands and ranged from 2 to 4 years of age. Stocks of c
aboveground (AG) pools, including woody biomass, coarse debris, leaf lit
herbaceous matter, as well as soil organic carbon (SOC) were evaluated. The
plantations store 8–10 tons of carbon per hectare (t C ha^{-1}) in AG biomass and litt
managed with regular pruning in both India and Brazil. Unpruned trees, only e
in Brazil, store less biomass (and carbon), accumulating just 3 t C ha^{-1} in AG po
two woodlands that were replaced with jatropha show substantial differences i
pools: prosopis contains ~11 t C ha^{-1} in AG stocks of carbon, which was very clo
jatropha stand which replaced it. In contrast, *caatinga* stores ~35 t C ha^{-1} in AG
Moreover, no change in SOC was detected in land that was converted from Pro
jatropha. As a result, there is no detectable change in AG carbon stocks at the
South India where jatropha replaced prosopis woodlands. In contrast, large loss
carbon were detected in Central Brazil where jatropha replaced native *caating*
lands. These losses represent a carbon debt that would take 10–20 years to repa**

Keywords: biofuels, *Caatinga* woodlands, direct land use change (dLUC), greenhouse gas e
Jatropha curcas, *Prosopis juliflora*

Received 16 December 2010 and accepted 15 January 2011

Introduction

This paper presents an analysis of direct land use change (dLUC) resulting from the conversion of woodlands to biofuel plantations at semiarid sites in both India and Brazil. Each country is currently pursuing biofuel policies that call for rapid expansion of oilseed-based biofuel production in the near future. For example, Brazilian policy calls for a 40% blend of biodiesel by 2035 (Government of Brazil, 2006) and India's biofuel mandate calls for a 20% blend of biodiesel by 2017 (Government of India, 2009). In addition to production for the domestic market, export-oriented production to meet demand in other countries may increase future cultivation. This is particularly true in Brazil, which is already a major exporter of cane
soybeans (a common feedstock for
in the US and EU, USDA FAS, 200
biodiesel export constitutes a ma
the government's national biofuel
ernment of Brazil, 2006).

To date, research on carbon b
based biofuel has focused largely
and postharvest processes like oil
version to fuel. While land use
knowledged as having a potentia
life-cycle emissions, there has bee
search quantifying the actual effec
Instead, LUC research focuses indi
(iLUC), or on dLUC estimated wit
those published in the IPCCs 'Gu

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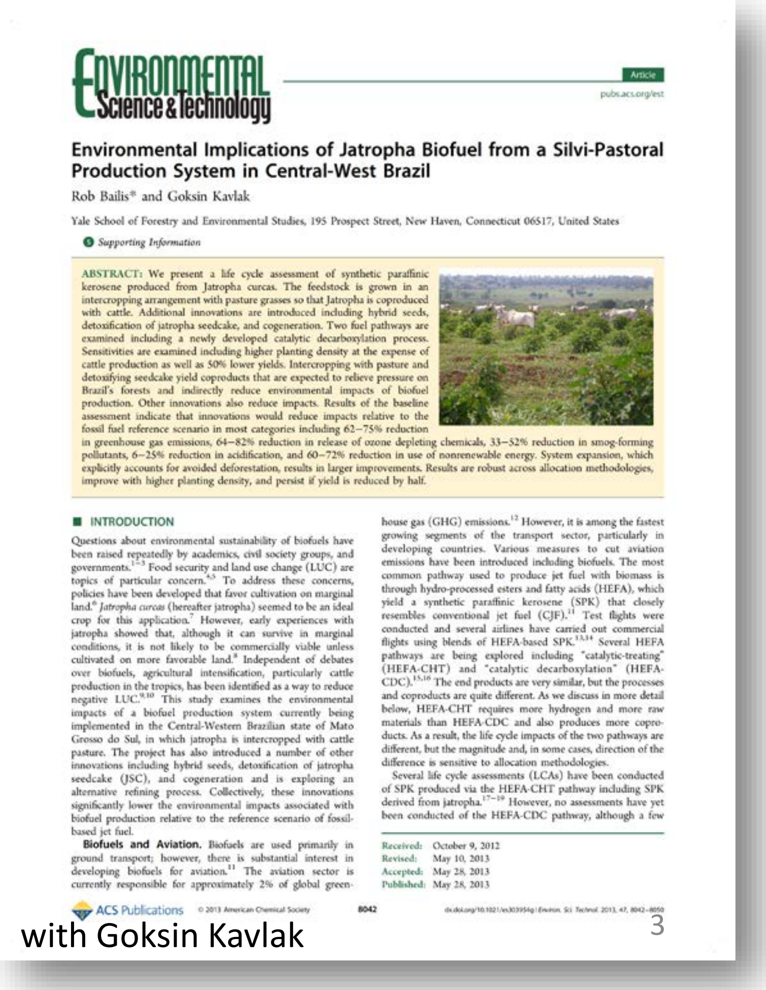
with Heather McCarthy



ENVIRONMENTAL Science & Technology

Article

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Environmental Implications of Jatropha Biofuel from a Silvi-Pastoral Production System in Central-West Brazil

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Supporting Information

ABSTRACT: We present a life cycle assessment of synthetic paraffinic kerosene produced from Jatropha curcas. The feedstock is grown in an intercropping arrangement with pasture grasses so that Jatropha is coproduced with cattle. Additional innovations are introduced including hybrid seeds, detoxification of jatropha seedcake, and cogeneration. Two fuel pathways are examined including a newly developed catalytic decarboxylation process. Sensitivities are examined including higher planting density at the expense of cattle production as well as 50% lower yields. Intercropping with pasture and detoxifying seedcake yield coproducts that are expected to relieve pressure on Brazil's forests and indirectly reduce environmental impacts of biofuel production. Other innovations also reduce impacts. Results of the baseline assessment indicate that innovations would reduce impacts relative to the fossil fuel reference scenario in most categories including 62–75% reduction in greenhouse gas emissions, 64–82% reduction in release of ozone depleting chemicals, 33–52% reduction in smog-forming pollutants, 6–25% reduction in acidification, and 60–72% reduction in use of nonrenewable energy. System expansion, which explicitly accounts for avoided deforestation, results in larger improvements. Results are robust across allocation methodologies, improve with higher planting density, and persist if yield is reduced by half.

INTRODUCTION

Questions about environmental sustainability of biofuels have been raised repeatedly by academics, civil society groups, and governments.[1−3] Food security and land use change (LUC) are topics of particular concern.[4,5] To address these concerns, policies have been developed that favor cultivation on marginal land.[6] *Jatropha curcas* (hereafter jatropha) seemed to be an ideal crop for this application.[7] However, early experiences with jatropha showed that, although it can survive in marginal conditions, it is not likely to be commercially viable unless cultivated on more favorable land.[8] Independent of debates over biofuels, agricultural intensification, particularly cattle production in the tropics, has been identified as a way to reduce negative LUC.[9,10] This study examines the environmental impacts of a biofuel production system currently being implemented in the Central-Western Brazilian state of Mato Grosso do Sul, in which jatropha is intercropped with cattle pasture. The project has also introduced a number of other innovations including hybrid seeds, detoxification of jatropha seedcake (JSC), and cogeneration and is exploring an alternative refining process. Collectively, these innovations significantly lower the environmental impacts associated with biofuel production relative to the reference scenario of fossil-based jet fuel.

Biofuels and Aviation. Biofuels are used primarily in ground transport; however, there is substantial interest in developing biofuels for aviation.[11] The aviation sector is currently responsible for approximately 2% of global greenhouse gas (GHG) emissions.[12] However, it is among the fastest growing segments of the transport sector, particularly in developing countries. Various measures to cut aviation emissions have been introduced including biofuels. The most common pathway used to produce jet fuel with biomass is through hydro-processed esters and fatty acids (HEFA), which yield a synthetic paraffinic kerosene (SPK) that closely resembles conventional jet fuel (CJF).[11] Test flights were conducted and several airlines have carried out commercial flights using blends of HEFA-based SPK.[13,14] Several HEFA pathways are being explored including "catalytic-treating" (HEFA-CHT) and "catalytic decarboxylation" (HEFA-CDC).[15,16] The end products are very similar, but the processes and coproducts are quite different. As we discuss in more detail below, HEFA-CHT requires more hydrogen and more raw materials than HEFA-CDC and also produces more coproducts. As a result, the life cycle impacts of the two pathways are different, but the magnitude and, in some cases, direction of the difference is sensitive to allocation methodologies.

Several life cycle assessments (LCAs) have been conducted of SPK produced via the HEFA-CHT pathway including SPK derived from jatropha.[17−19] However, no assessments have yet been conducted of the HEFA-CDC pathway, although a few

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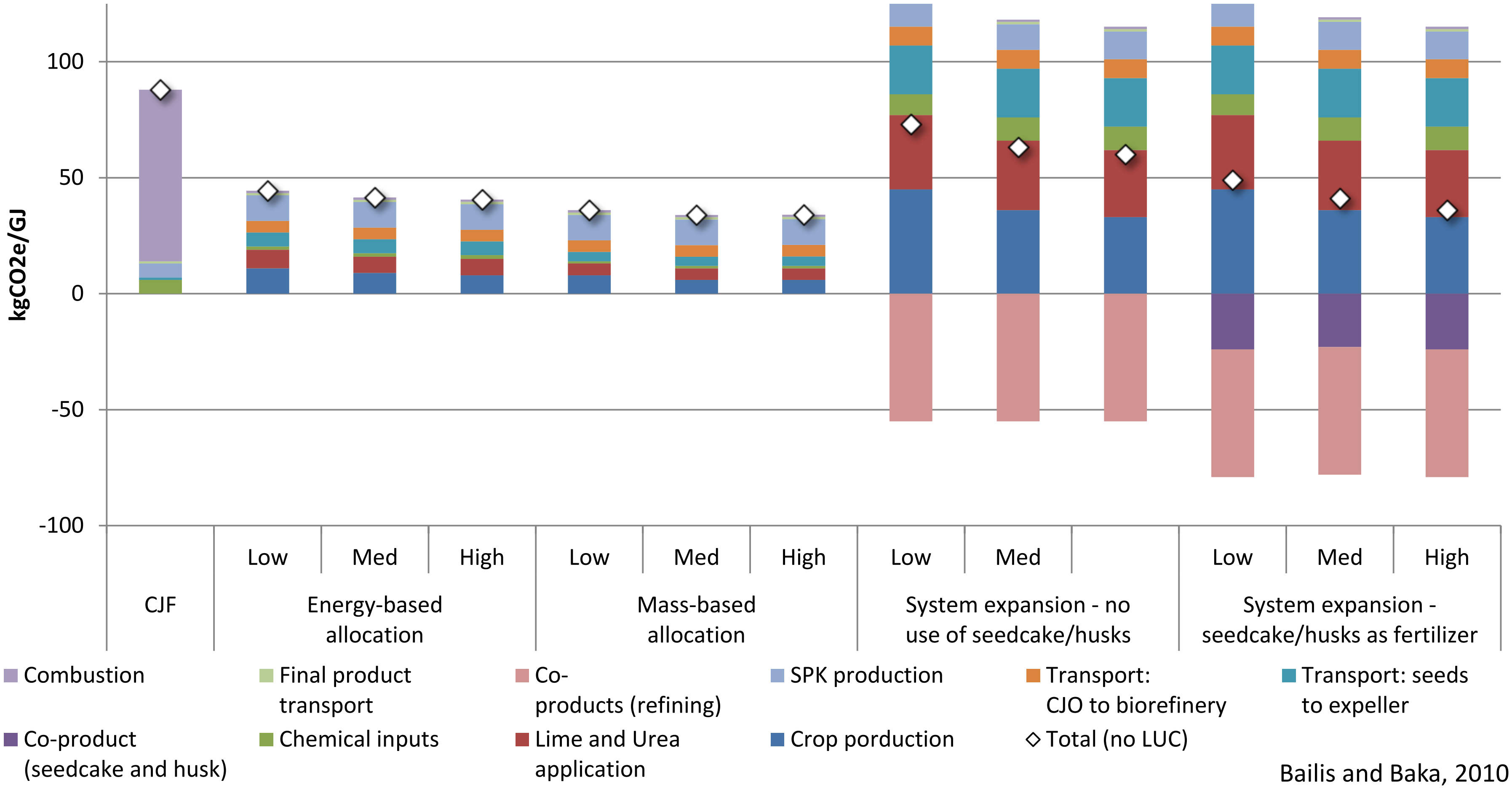
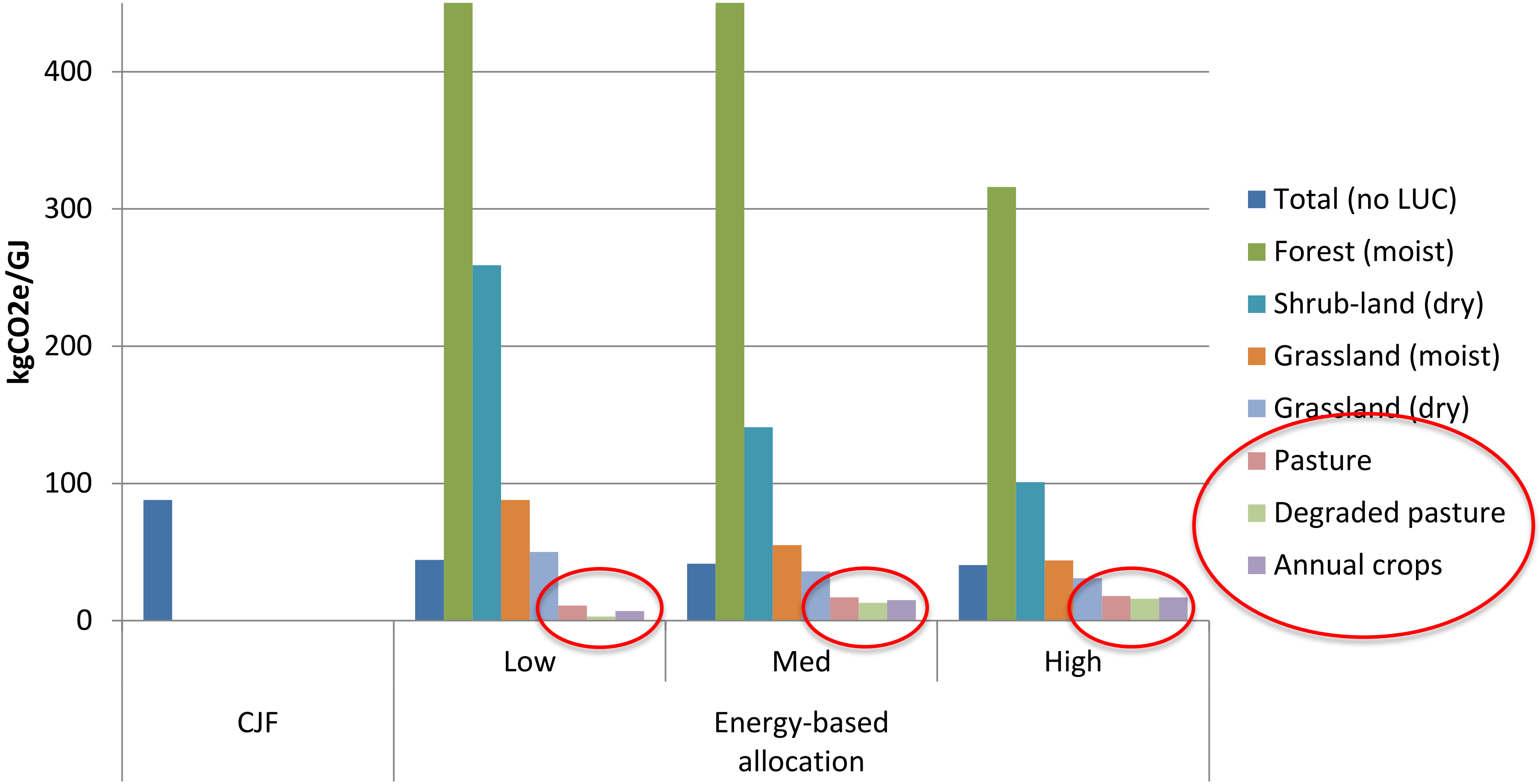
with Goksin Kavlak

Jatropha WTW GHGs using generic Brazilian conditions in 2009 (no LUC)



Bailis and Baka, 2010

What about LUC?



Bailis and Baka, 2010

Project-based LCA

- Site-specific silvi-pastoral production
- Utilizing existing pasture
  - 160 Mha of pasture in Brazil
  - 10 Mha is “degraded”
- Multiple innovations
- Generalizable to other perennial species?

Innovations

1. Silvipastoral production
    - Co-produce oilseeds and cattle
2. Detoxify press-cake and use animal feed
3. Use hybrid seeds
4. Oil extraction with locally produced ethanol
5. Cogeneration using husks and shells
6. Alternative refining pathway

Goal and Scope

Compare environmental impacts of conventional jet fuel to Jatropha-SPK produced in a novel silvi-pastoral system*

- System boundaries

  Farm + Oil Extraction + Refining

- Functional unit
  - 1 GJ of fuel
- Treatment of co-products
  - Mass, energy, and economic allocation
  - System expansion

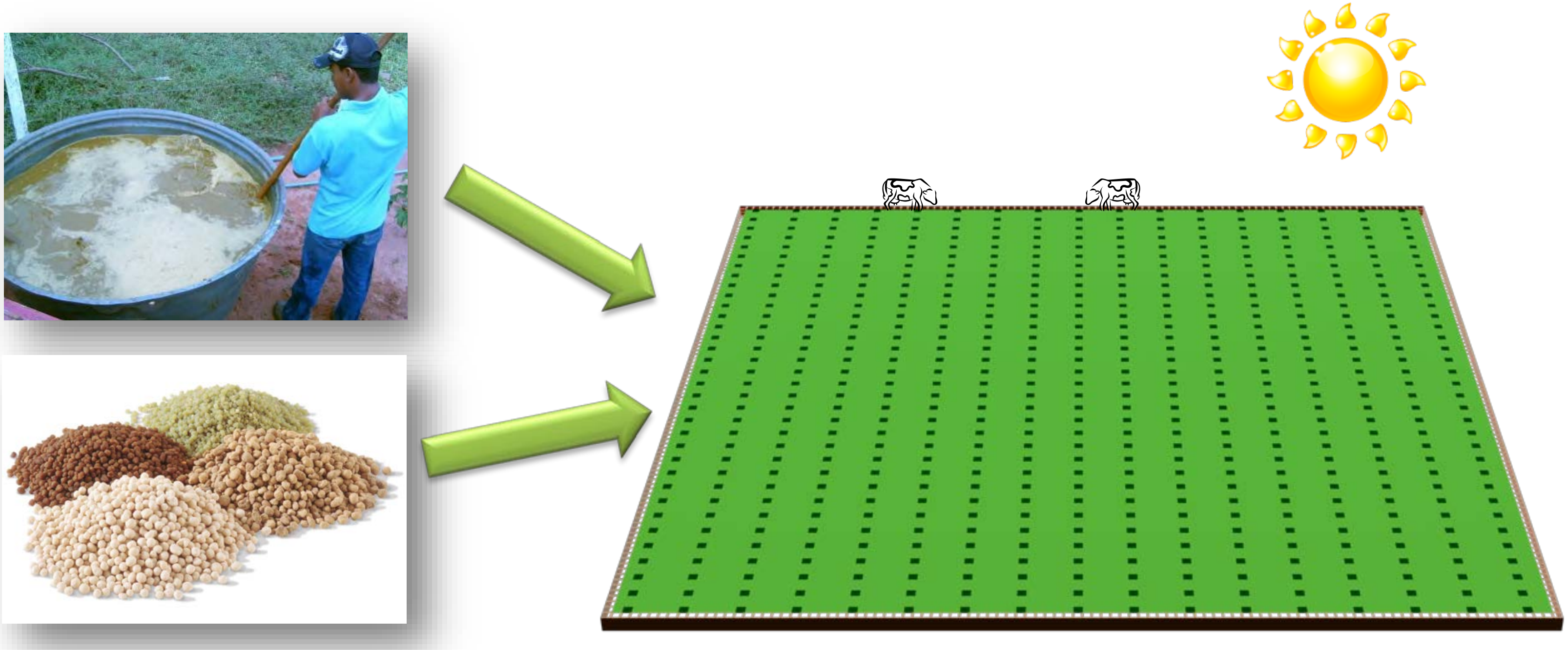
* SPK - synthetic paraffinic kerosene

Innovations

1. Co-produce oilseeds and cattle
2. Detoxify press-cake and use animal feed
3. Use hybrid seeds
4. Oil extraction with locally produced ethanol
5. Cogeneration using husks and shells
6. Alternative refining pathway

1. Co-production with cattle

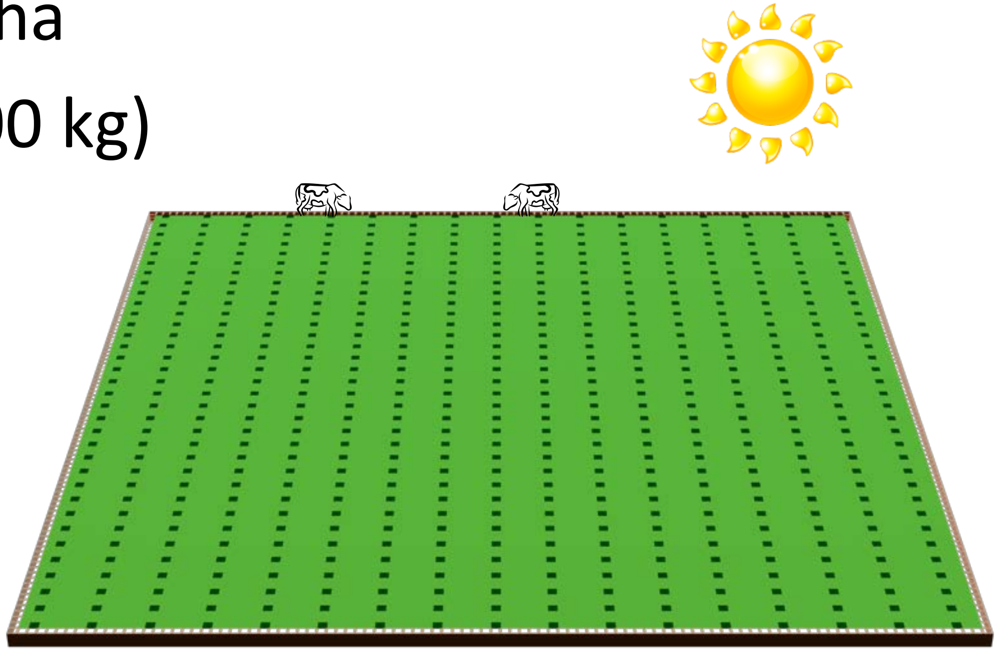
- Stocking 2 AU* per ha
- Inputs nourish pasture and Jatropha



* AU = Animal Unit - 450 kg live weight

1. Co-production with cattle

- Annual productivity per ha:
  - Jatropha 1.95 tons dry seed plus co-products
  - Pasture 10-17 t/ha
  - Cattle 2 UA (900 kg)

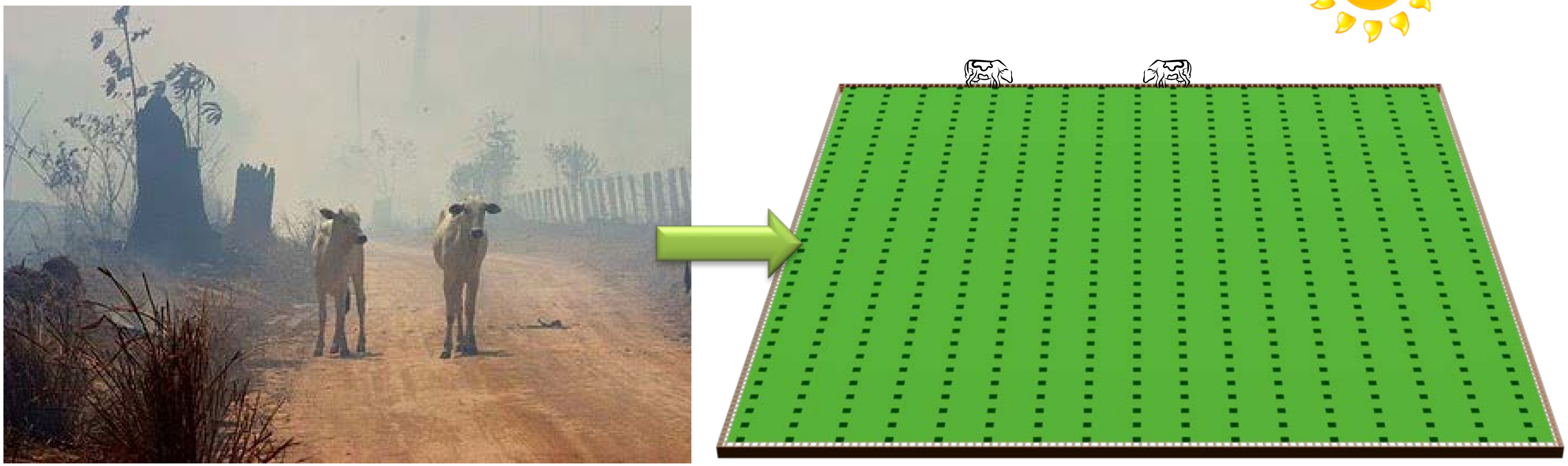


* UA = Unidade Animal = 450 kg live weight

1. Co-production with cattle

- Cattle produced here displace cattle produced elsewhere

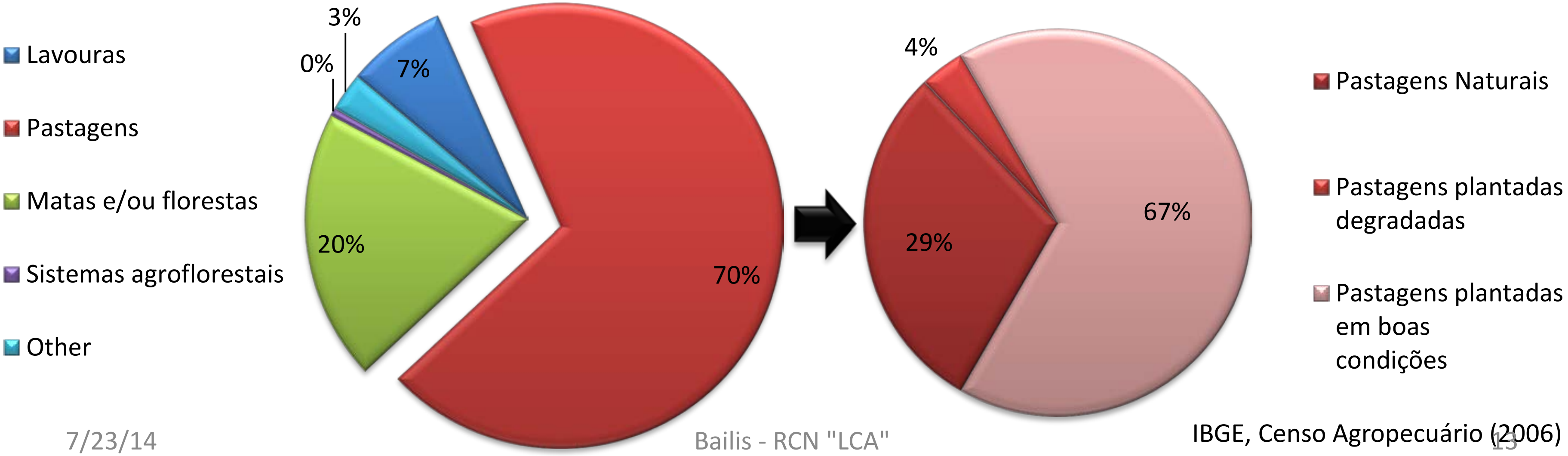
…where and by how much?



* UA = Unidade Animal = 450 kg live weight

1. Co-production with cattle

- Co-produced cattle might displace:
  - Cattle in managed, natural, or degraded pasture
  - Cattle grazing in recently deforested land



Land use in Mato Grosso do Sul (2006)

IBGE, Censo Agropecuário (2006)

1. Co-production with cattle

- Emissions from 1 AU:
  - Enteric fermentation: 56 kg CH_4 per year
  - Manure: 1 kg CH_4 and 1.2 kg N_2O per year
  - Inputs: NPK, diesel…
  - Land cover change:
    - Degraded – small increase in C
    - Managed pasture – no change C
    - Forest – large C emissions avoided

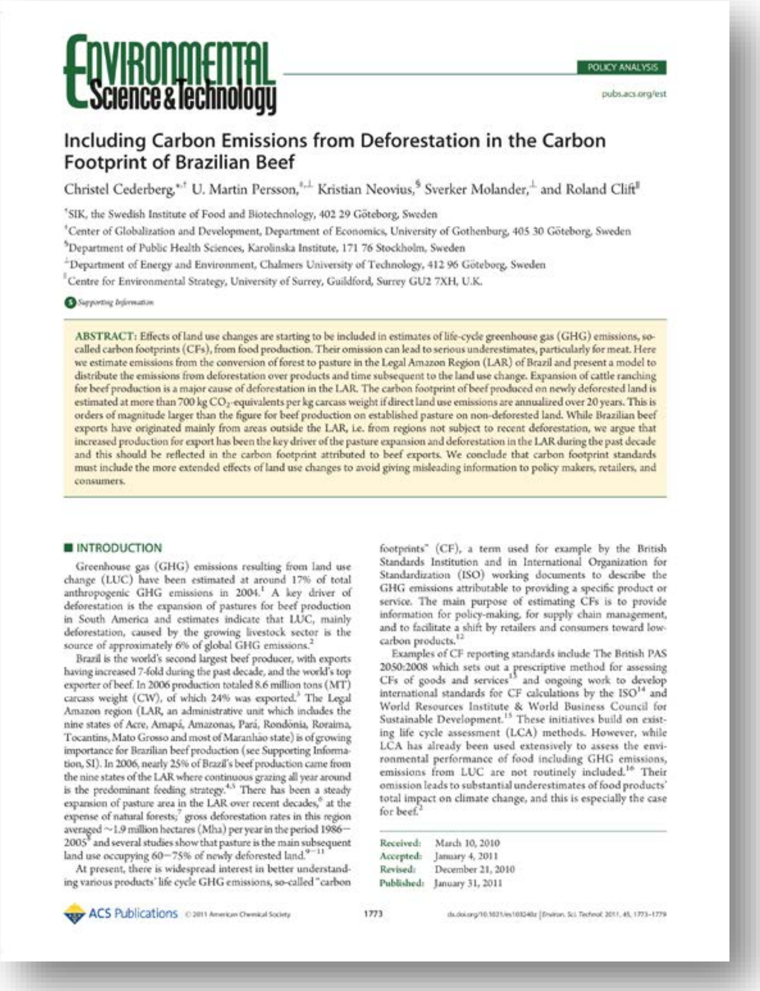
      Stocking rate in forest regions 0.9 AU/ha

      Carbon stocks ~ 150 t-C/ha (IPCC)

1. Co-production with cattle

Cederberg et al (2011):

- ~6% of Brazil's cattle were produced on recently cut forest in LAR
- 44 kg CO2e/kg cattle averaged over all regions
- 352 kgCO$_2$e per FU



ENVIRONMENTAL Science & Technology

POLICY ANALYSIS

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Including Carbon Emissions from Deforestation in the Carbon Footprint of Brazilian Beef

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Supporting Information

ABSTRACT: Effects of land use changes are starting to be included in estimates of life-cycle greenhouse gas (GHG) emissions, so-called carbon footprints (CFs), from food production. Their omission can lead to serious underestimates, particularly for meat. Here we estimate emissions from the conversion of forest to pasture in the Legal Amazon Region (LAR) of Brazil and present a model to distribute the emissions from deforestation over products and time subsequent to the land use change. Expansion of cattle ranching for beef production is a major cause of deforestation in the LAR. The carbon footprint of beef produced on newly deforested land is estimated at more than 700 kg CO$_2$-equivalents per kg carcass weight if direct land use emissions are annualized over 20 years. This is orders of magnitude larger than the figure for beef production on established pasture on non-deforested land. While Brazilian beef exports have originated mainly from areas outside the LAR, i.e. from regions not subject to recent deforestation, we argue that increased production for export has been the key driver of the pasture expansion and deforestation in the LAR during the past decade and this should be reflected in the carbon footprint attributed to beef exports. We conclude that carbon footprint standards must include the more extended effects of land use changes to avoid giving misleading information to policy makers, retailers, and consumers.

INTRODUCTION

Greenhouse gas (GHG) emissions resulting from land use change (LUC) have been estimated at around 17% of total anthropogenic GHG emissions in 2004.[1] A key driver of deforestation is the expansion of pastures for beef production in South America and estimates indicate that LUC, mainly deforestation, caused by the growing livestock sector is the source of approximately 6% of global GHG emissions.[2]

Brazil is the world's second largest beef producer, with exports having increased 7-fold during the past decade, and the world's top exporter of beef. In 2006 production totaled 8.6 million tons (MT) carcass weight (CW), of which 24% was exported.[3] The Legal Amazon region (LAR, an administrative unit which includes the nine states of Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, Tocantins, Mato Grosso and most of Maranhão state) is of growing importance for Brazilian beef production (see Supporting Information, SI). In 2006, nearly 25% of Brazil's beef production came from the nine states of the LAR where continuous grazing all year around is the predominant feeding strategy.[4,5] There has been a steady expansion of pasture area in the LAR over recent decades,[6] at the expense of natural forests;[7] gross deforestation rates in this region averaged ~1.9 million hectares (Mha) per year in the period 1986–2005[8] and several studies show that pasture is the main subsequent land use occupying 60–75% of newly deforested land.[9−11]

At present, there is widespread interest in better understanding various products' life cycle GHG emissions, so-called "carbon footprints" (CF), a term used for example by the British Standards Institution and in International Organization for Standardization (ISO) working documents to describe the GHG emissions attributable to providing a specific product or service. The main purpose of estimating CFs is to provide information for policy-making, for supply chain management, and to facilitate a shift by retailers and consumers toward low-carbon products.[12]

Examples of CF reporting standards include The British PAS 2050:2008 which sets out a prescriptive method for assessing CFs of goods and services[13] and ongoing work to develop international standards for CF calculations by the ISO[14] and World Resources Institute & World Business Council for Sustainable Development.[15] These initiatives build on existing life cycle assessment (LCA) methods. However, while LCA has already been used extensively to assess the environmental performance of food including GHG emissions, emissions from LUC are not routinely included.[16] Their omission leads to substantial underestimates of food products' total impact on climate change, and this is especially the case for beef.[2]

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2. Press-cake detox

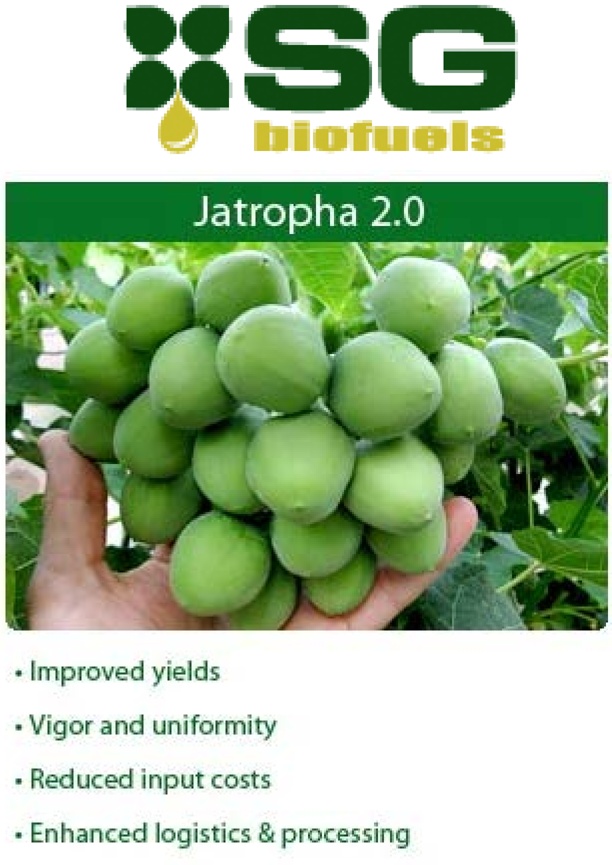
- Press-cake detoxification
  - 1 dry ton of seed yields 250kg of Jatropha seedcake (JSC)
    - 60% protein
  - Assume product displaces soymeal
    - 19% domestic animal feed market in Brazil (USDA)
    - Corn has bigger market share
    - maybe more realistic to displace maize?

2. Press-cake detox

- Press-cake detoxification
  - Substitution on a protein basis
    - 1 kg Jatropha presscake ≈ 1.3 kg soymeal
  - 0.7 kg CO_2e/kg soymeal (EcoInvent, 2010)
  - 16-18 kgCO_2e per FU via soymeal displacement

3. Hybrid seeds

- Yield
  - – Originally expected 3.5 kg/tree
  - – Revised down to 2.4 kg/tree
    - Tested sensitivity @ 1.2 kg/tree
- Spacing
  - – 8x1 with large alleys for pasture
  - – Considered monoculture @ 4x1



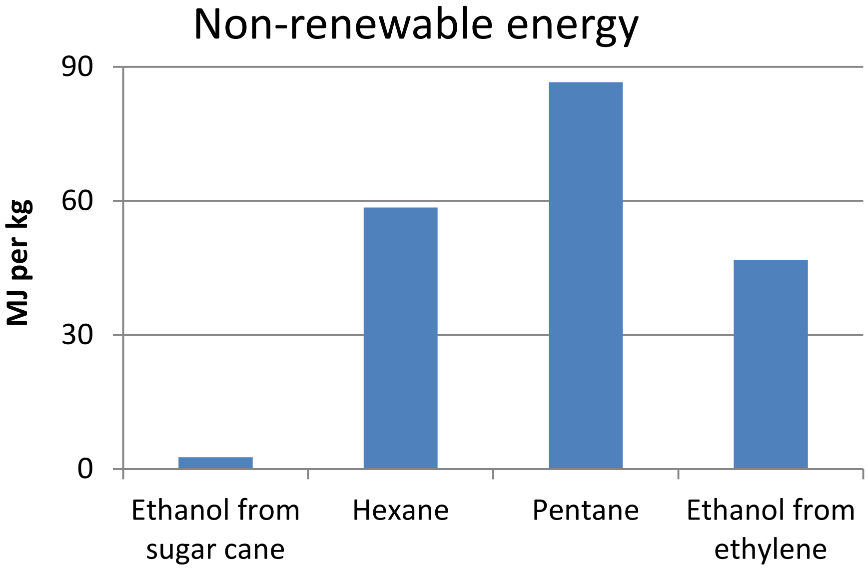
SG biofuels

Jatropha 2.0

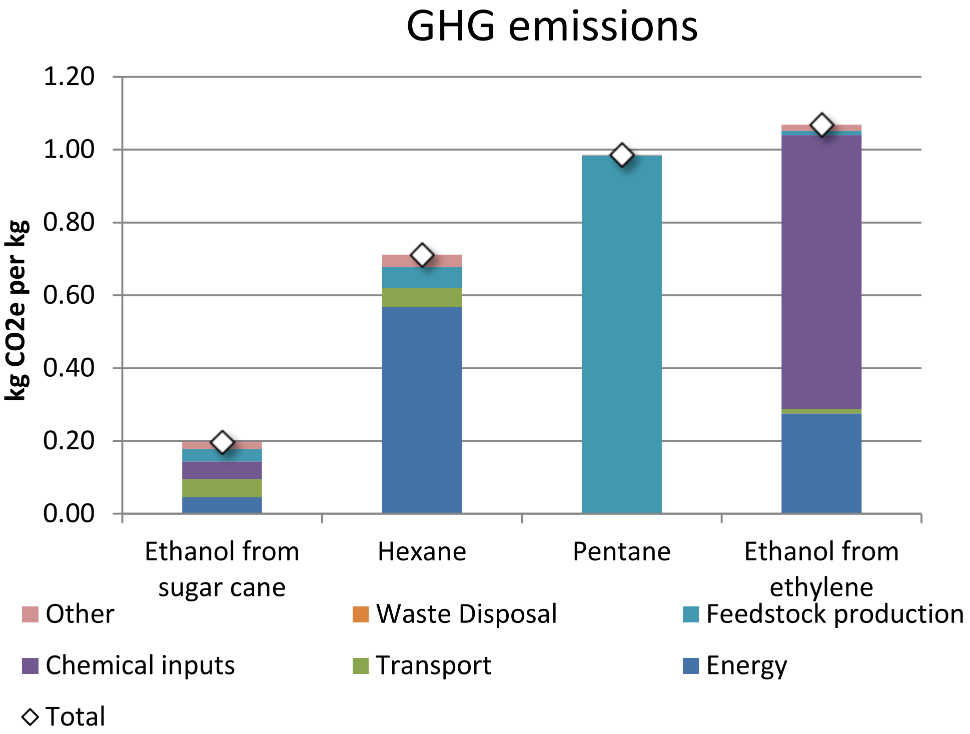
- Improved yields
- Vigor and uniformity
- Reduced input costs
- Enhanced logistics & processing

4. Ethanol as solvent

- Replace hexane or pentane
  - Saves energy and reduces emissions



Non-renewable energy



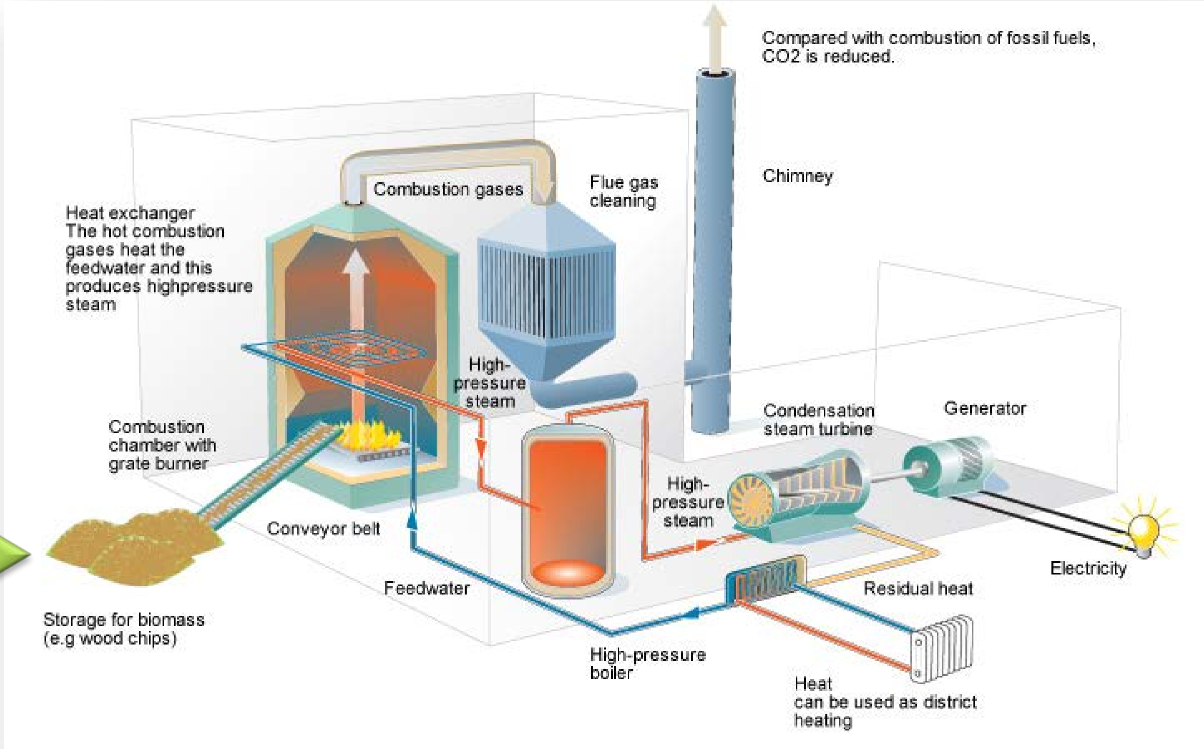
GHG emissions

5. Cogeneration

- Cogen using seedcake and husks

1 FU yields

~ 100 kg husk and shell

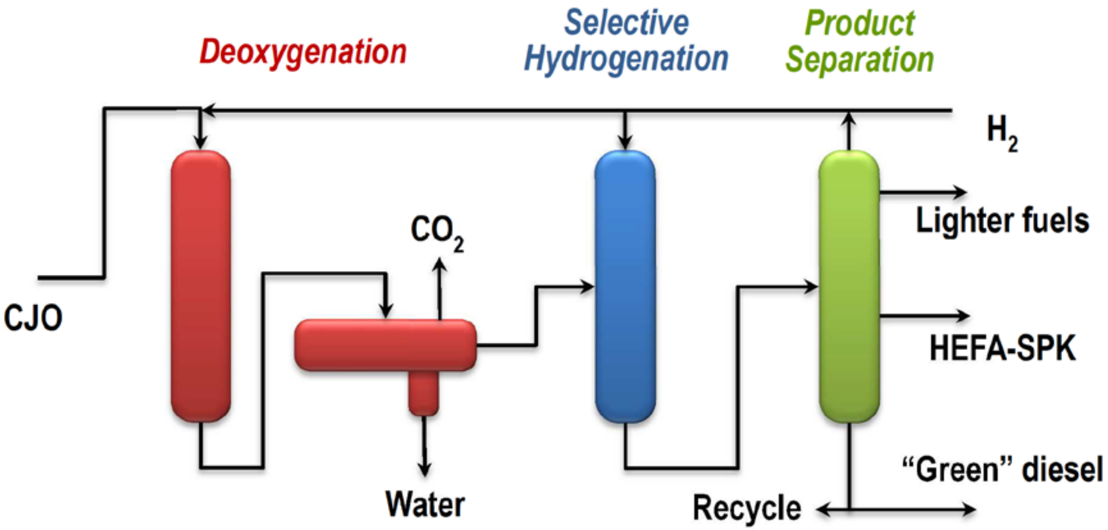


94 kWh electricity

- 11 kWh used internally
- 83 kWh exported to grid

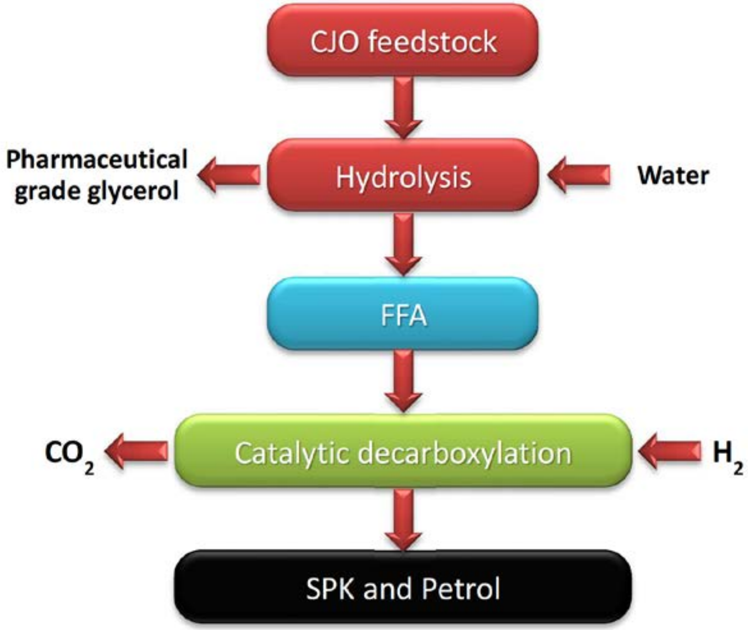
6. Alternative refining pathways

Catalytic hydro-treatment (UOP)



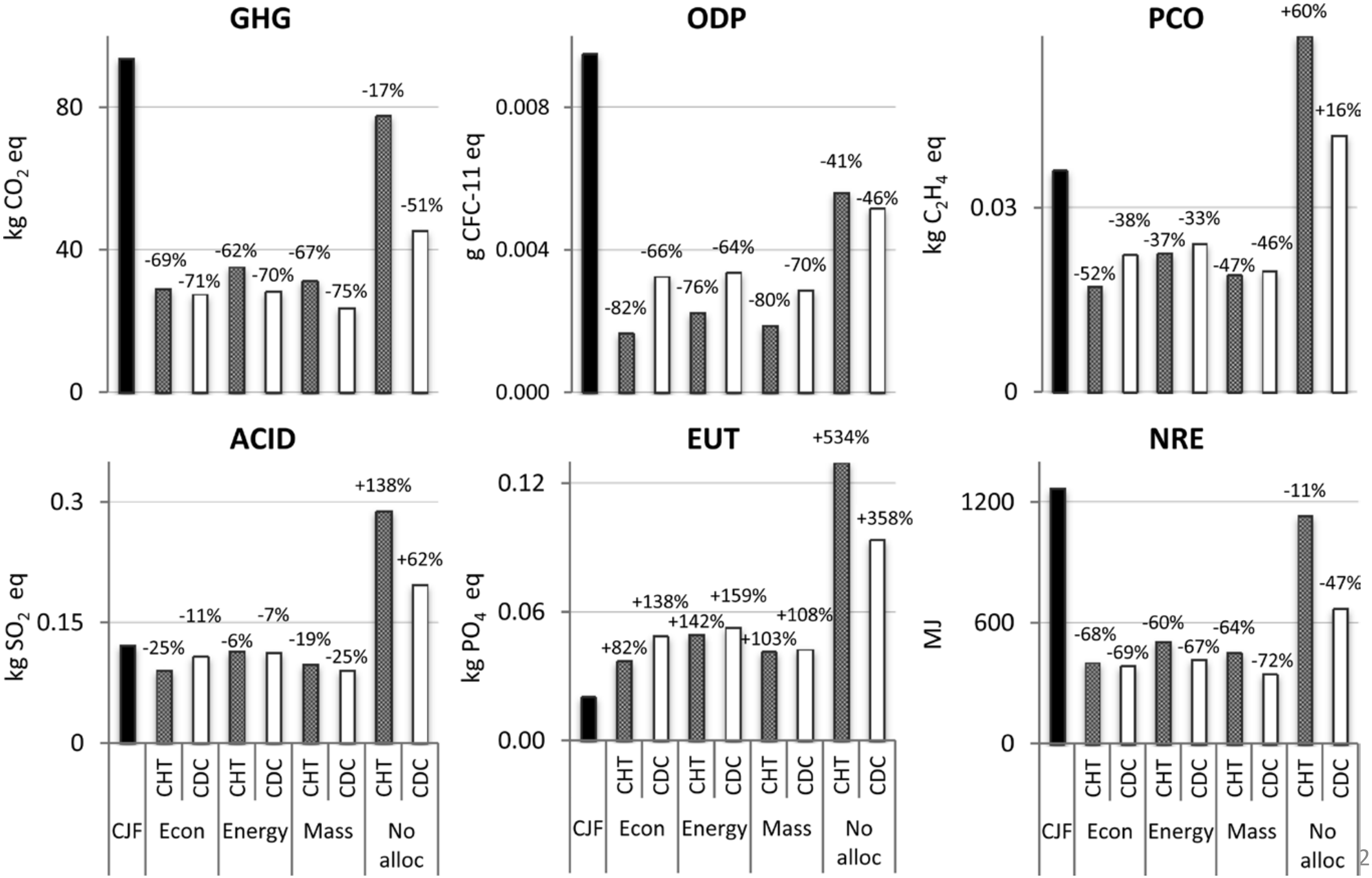
From http://www.uop.com/green-jet-fuel/

Catalytic decarboxylation (AliphaJet)



From http://www.syngest.com/AliphaJet/images/img_flow_graphic.jpg

Results (system expansion not shown)



Results

- Reduced impacts in most indicators
- Improvements are robust across allocation methodologies
- Improvements persist if yields are 50% lower than expected

Remaining questions

- Carbon dynamics:
  - trees, pasture, and soil?
- Reality check on results:
  - Soy and cattle displacement
- The project failed and SG pulled out of Brazil…why?
- What are future prospects for silvipastoral-based production of oilseed feedstocks?

Aeronave da GOL é abastecida no Rio com bioquerosene; no detalhe, fruto da macaúba e cana-de-açúcar, usados na produção de biocombustível

Una aeronave de gol es abastecida en río de janeiro con bioqueroseno; en el detalle, fruto de la macaúba y caña de azúcar, usados en la producción de biocombustible

"A Gol aircraft is fueled with bio-kerosene in Rio; in particular, macaúba fruit and cane sugar, used to produce biofuel."

From p. 141 of *this month's* GOL in-flight magazine

Thanks! Obrigado! Gracias!

- AIRBUS AN EADS COMPANY for funding the Jatropha research

Collaboration with Goksin Kavlak (Yale), SG Biofuels, JetBio and Rio Pardo Bioenergia

Land use change

- Little impact shifting from managed/degraded pasture to Jatropha:
    - 1 t-C per ha lost from managed pasture
        - ~11.6 kg CO2e/GJ lost over 20 years
    - 3 t-C gained in degraded pasture
        - ~5.0 kg CO2e/GJ gained over 20 years

GHG reduction requirements in a sample of existing sustainability initiatives

Initiative	Allocation	GHG Reduction requirement	ILUC	LUC	Time frame
US-RFS	Displacement method	Conventional biofuels: **20% lifecycle GHG threshold** (below gasoline) Advanced biofuels: 50% lifecycle GHG threshold Biomass-based diesel: 50% lifecycle GHG threshold Cellulosic biofuel: 60% lifecycle GHG threshold	Yes	Yes	100 year with 2% discount rate OR 30 year with 0% discount rate
CA-LCFS	GREET methodology	**10%** reduction in GHG emissions across fleet	Yes	Yes	30 year project horizon
UK RTFO	Substitution approach preferred but economic also permitted	Targets to overall level of GHG saving achieved by the biofuel supplied in each obligation period: **2008–2009, 40%, 2009–2010, 45%, 2010–2011, 50%, etc.** The level of GHG saving is an overall target for all fuels and feedstock reported by a fuel supplier Will follow the EC-RED Directive	X	Yes	No dLUC with a carbon payback time over 10 years
Dutch NTA 8080	Based on energy content	**For heat and power**: at least 70% if reference case is Dutch mixture of electricity or coal, or at least 50% if reference case is natural gas. **For transportation fuels:** at least 50%; for flows of biomass for which in the EC-RED ‘‘a typical GHG emission saving of less than 50% is included as transition period till 2012, a minimum of 35%	X	Yes	Annualized emissions based on 20 years
EC-RED	Based on energy content	At least **35% GHG emission** reduction compared to reference fuel Rising to **50% on January 2017 and 60% in 2018** for biofuels and bioliquids produced in installations in which production started on or after January 2017.	X	Yes	Annualized emissions with 20 yrs timeframe
RSB	Guidelines under development	Biofuel shall have lower GHG emissions than the fossil fuel baseline and shall contribute to the minimization of overall GHG emissions. The threshold (**10, 40 and 70% reductions are under discussion**) will be set at the conclusion of the test period	?	Yes	Based on IPCC methodology

Scenarios

Scenario	Description
Fossil fuel reference	Average US kerosene-based jet fuel
Baseline Jatropha SPK	Jatropha in Brazilian conditions with no innovations
CJO co-production with cattle	Energy Allocation Mass Allocation Economic Allocation No accounting for cattle Accounting for cattle but no avoided LUC Accounting for cattle and avoided LUC

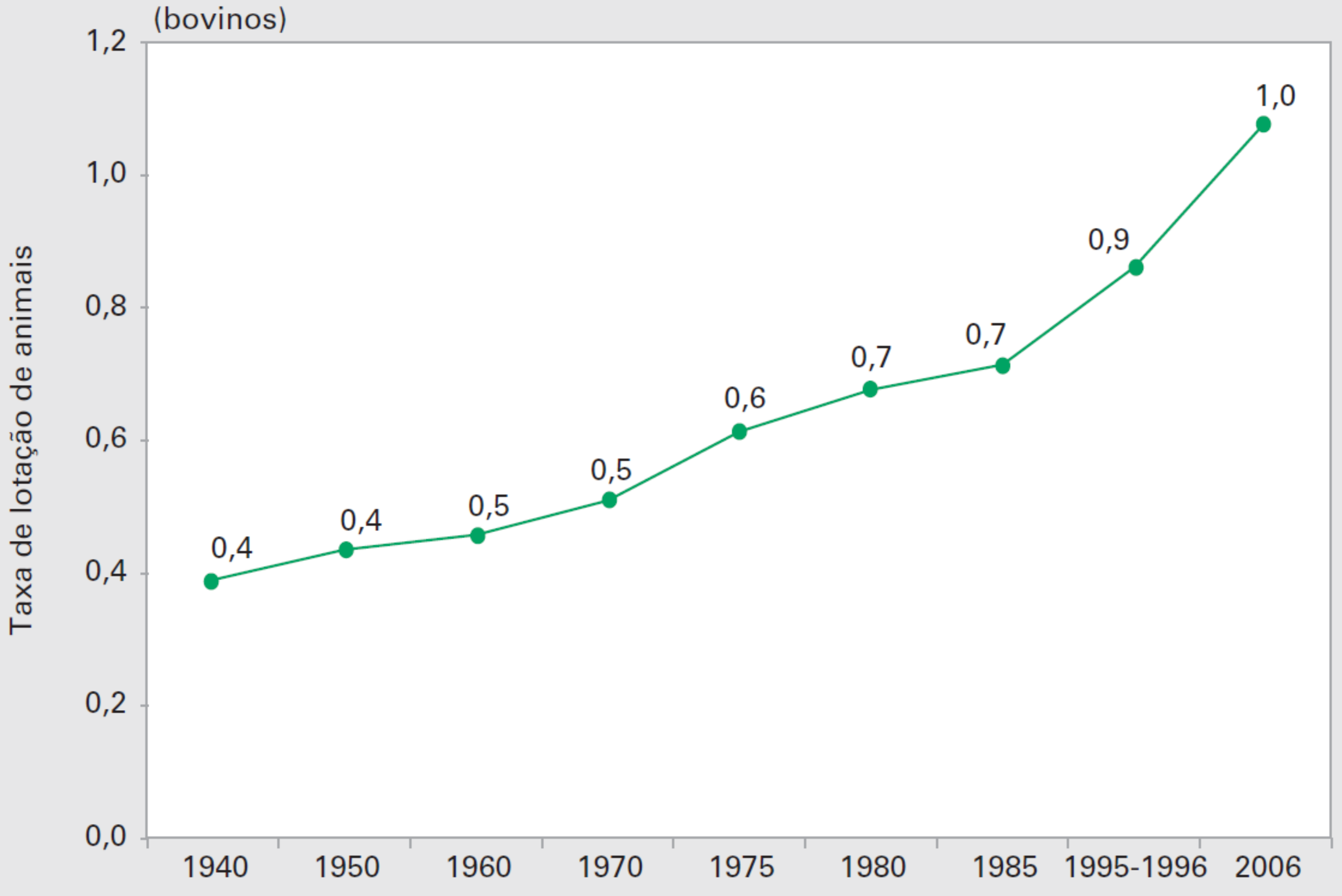
LCA methodologies

- Our approach:
  - Collect primary data
  - Follow accepted LCA protocols
    - Allocate with system expansion when possible
  - Use LCA software common to industry and academia
  - Undergo extensive peer review

Allocation

Milling Products	Mass (kg per ton of dry seed)	mass %	energy (MJ /kg)	energy %	Value (R$/ton)	value (%)
shells	390	28%	19	22%	100	5%
husks	380	28%	19	22%	100	4%
CJO	360	26%	39.6	43%	1681	71%
Cake (or meal)	250	18%	18.3	14%	700	20%
TOTAL (fruit)	1380		24		621	

Gráfico 21 - Evolução da taxa de lotação animal (bovinos) em relação à área total de pastagens - Brasil - 1940/2006

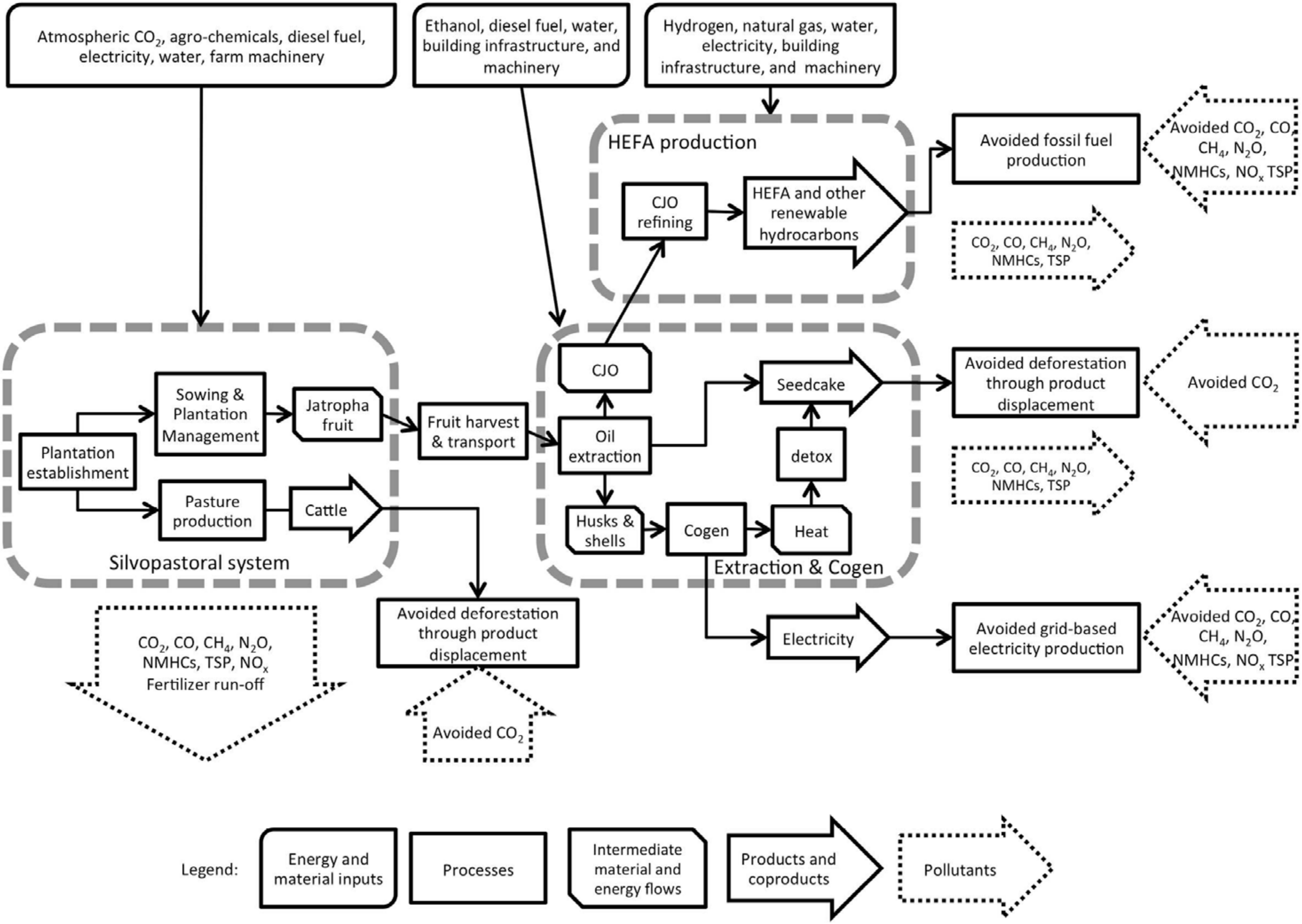


Fonte: IBGE, Censo Agropecuário 1940/2006.

Allocation factors

Table S1: Factors used to allocate impacts among co-products by energy, mass or economic value (8x1 spacing) [a]

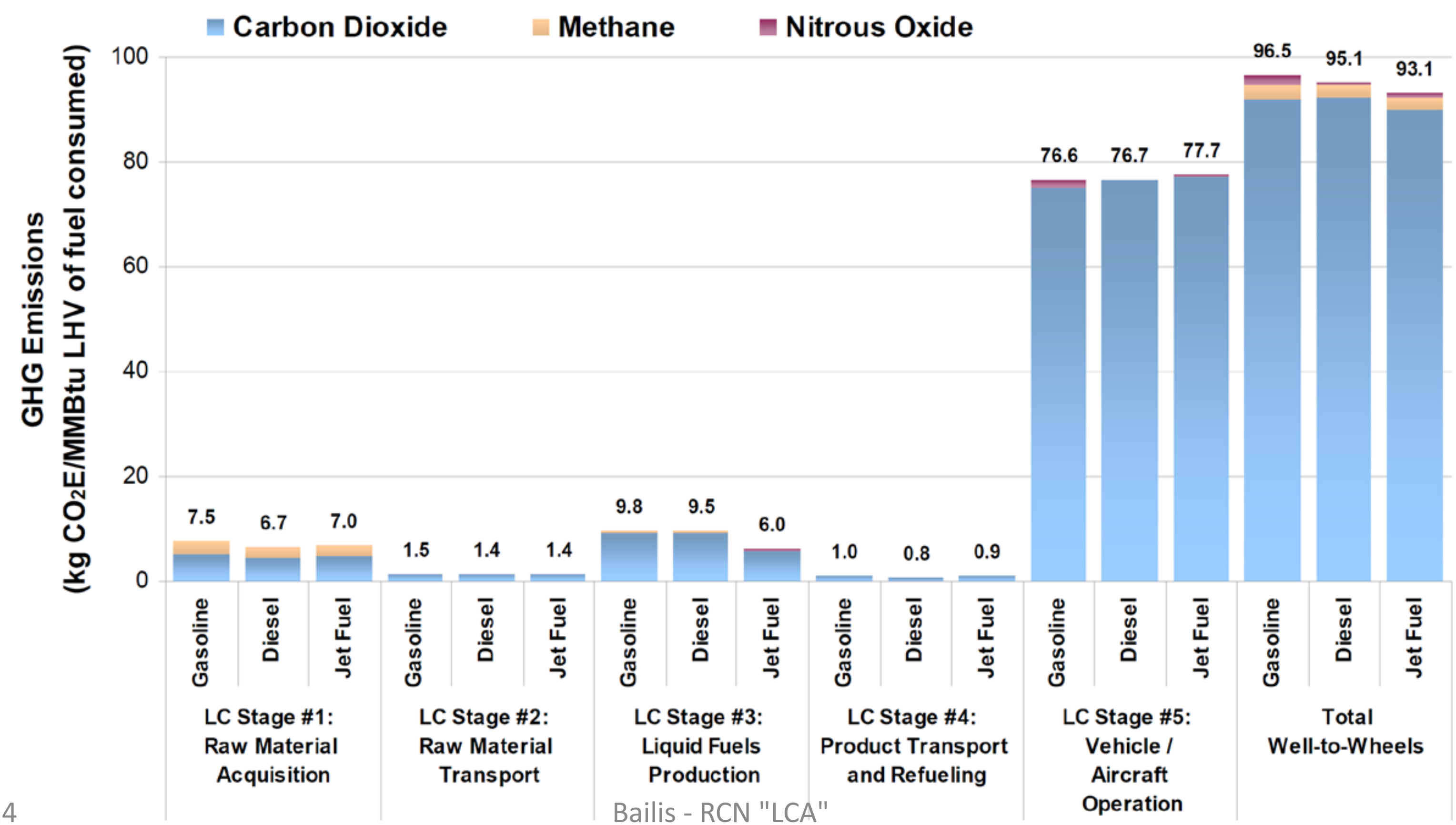
	Mass		Energy		Economic value	
1. Crop production	**Units produced per ton of dry seed**	**%**	**Calorific value (MJ/unit)**	**%**	**Economic value (R$/unit) [b]**	**%**
Jatropha fruit (inc. husk)	1380 kg	88%	12.2	96%	0.39	64%
Cattle (carcass wt) [c]	111 kg	12%	7.8	4%	2.66	36%
2. Oil Extraction [d]						
CJO	360 kg	59%	39.6	67%	1.70	71%
JSC	250 kg	41%	18.3	22%	0.55	20%
Electricity to grid	640 kWh	NA	3.6	11%	0.12	9%
3 a. Oil refining: HEFA-CHT[e]						
J-SPK	174 kg	56%	44.3	58%	10	53%
Other hydrocarbons	133 kg	43%	42.0	42%	18	47%
3 b. Oil refining: HEFA-CDC[f]						
J-SPK	238	80%	44.3	86%	10	97%
Other hydrocarbons	58	20%	28.7	14%	2.1	3%


Atmospheric CO₂, agro-chemicals, diesel fuel, electricity, water, farm machinery
Ethanol, diesel fuel, water, building infrastructure, and machinery
Hydrogen, natural gas, water, electricity, building infrastructure, and machinery
HEFA production
CJO refining
HEFA and other renewable hydrocarbons
Avoided fossil fuel production
Avoided CO₂, CO, CH₄, N₂O, NMHCs, NOₓ TSP
CO₂, CO, CH₄, N₂O, NMHCs, TSP
CJO
Seedcake
Avoided deforestation through product displacement
Avoided CO₂
Sowing & Plantation Management
Jatropha fruit
Fruit harvest & transport
Oil extraction
detox
Plantation establishment
CO₂, CO, CH₄, N₂O, NMHCs, TSP
Pasture production
Cattle
Husks & shells
Cogen
Heat
Silvopastoral system
Extraction & Cogen
Avoided deforestation through product displacement
Electricity
Avoided grid-based electricity production
Avoided CO₂, CO, CH₄, N₂O, NMHCs, NOₓ TSP
CO₂, CO, CH₄, N₂O, NMHCs, TSP, NOₓ Fertilizer run-off
Avoided CO₂
Legend:
Energy and material inputs
Processes
Intermediate material and energy flows
Products and coproducts
Pollutants

Reference scenario

- Fossil jet fuel

Figure 7-11. GHG Emissions for Liquid Fuels Produced Domestically



NETL, 2008

Sensitivity to spacing and yield

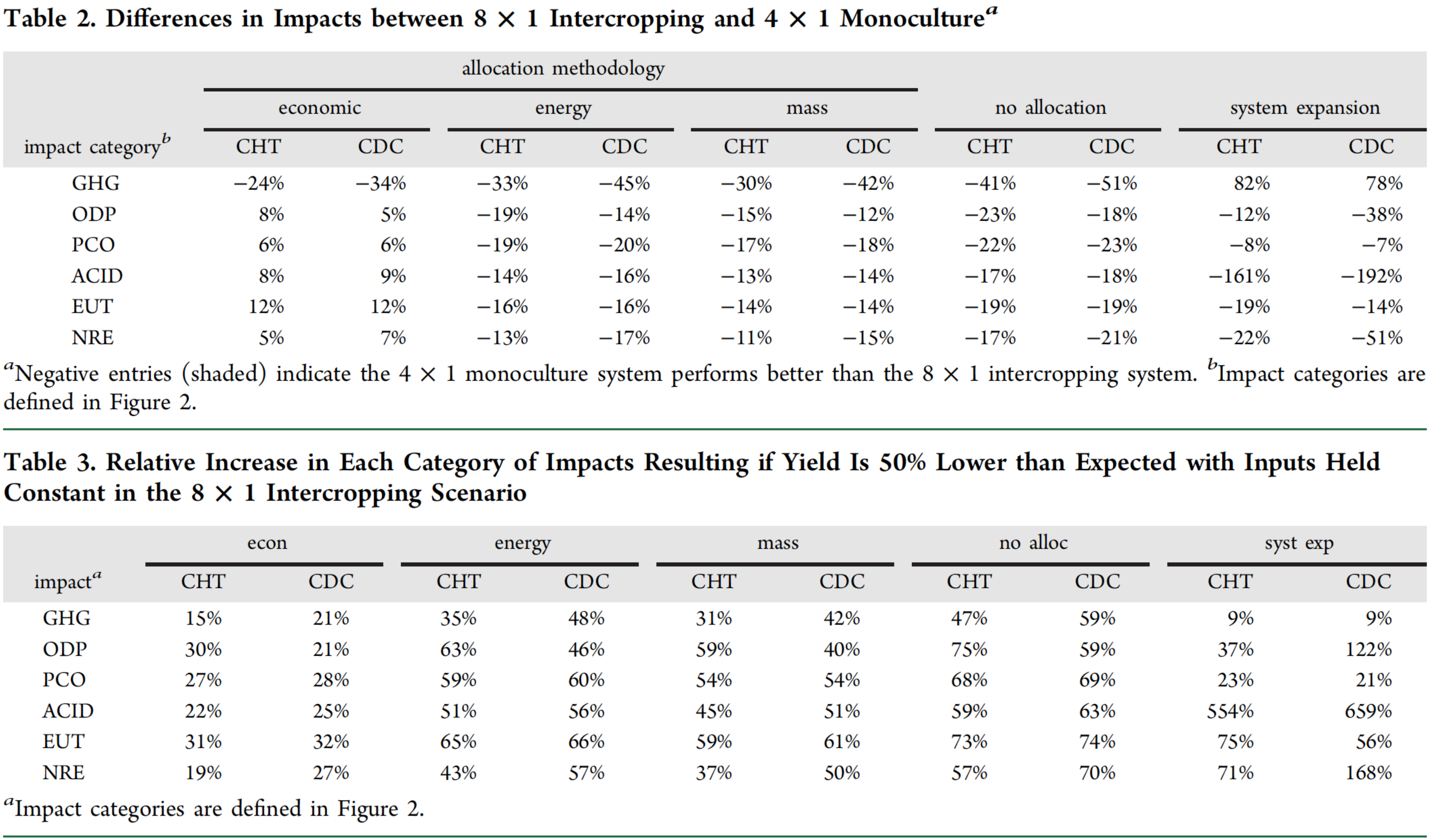


Table 2. Differences in Impacts between 8 × 1 Intercropping and 4 × 1 Monoculture[a]

	allocation methodology									
	economic		energy		mass		no allocation		system expansion	
impact category[b]	CHT	CDC	CHT	CDC	CHT	CDC	CHT	CDC	CHT	CDC
GHG	−24%	−34%	−33%	−45%	−30%	−42%	−41%	−51%	82%	78%
ODP	8%	5%	−19%	−14%	−15%	−12%	−23%	−18%	−12%	−38%
PCO	6%	6%	−19%	−20%	−17%	−18%	−22%	−23%	−8%	−7%
ACID	8%	9%	−14%	−16%	−13%	−14%	−17%	−18%	−161%	−192%
EUT	12%	12%	−16%	−16%	−14%	−14%	−19%	−19%	−19%	−14%
NRE	5%	7%	−13%	−17%	−11%	−15%	−17%	−21%	−22%	−51%

[a] Negative entries (shaded) indicate the 4 × 1 monoculture system performs better than the 8 × 1 intercropping system. [b] Impact categories are defined in Figure 2.

Table 3. Relative Increase in Each Category of Impacts Resulting if Yield Is 50% Lower than Expected with Inputs Held Constant in the 8 × 1 Intercropping Scenario

	econ		energy		mass		no alloc		syst exp	
impact[a]	CHT	CDC	CHT	CDC	CHT	CDC	CHT	CDC	CHT	CDC
GHG	15%	21%	35%	48%	31%	42%	47%	59%	9%	9%
ODP	30%	21%	63%	46%	59%	40%	75%	59%	37%	122%
PCO	27%	28%	59%	60%	54%	54%	68%	69%	23%	21%
ACID	22%	25%	51%	56%	45%	51%	59%	63%	554%	659%
EUT	31%	32%	65%	66%	59%	61%	73%	74%	75%	56%
NRE	19%	27%	43%	57%	37%	50%	57%	70%	71%	168%

[a] Impact categories are defined in Figure 2.

Results – system expansion