The Role of Biofuels in a Sustainable World

Lee Lynd
Thayer School of Engineering, Dartmouth
Mascoma Corp.

FAPESP
Sao Paulo, Brazil
September 10, 2009

The sustainable resource imperative

The biofuel imperative

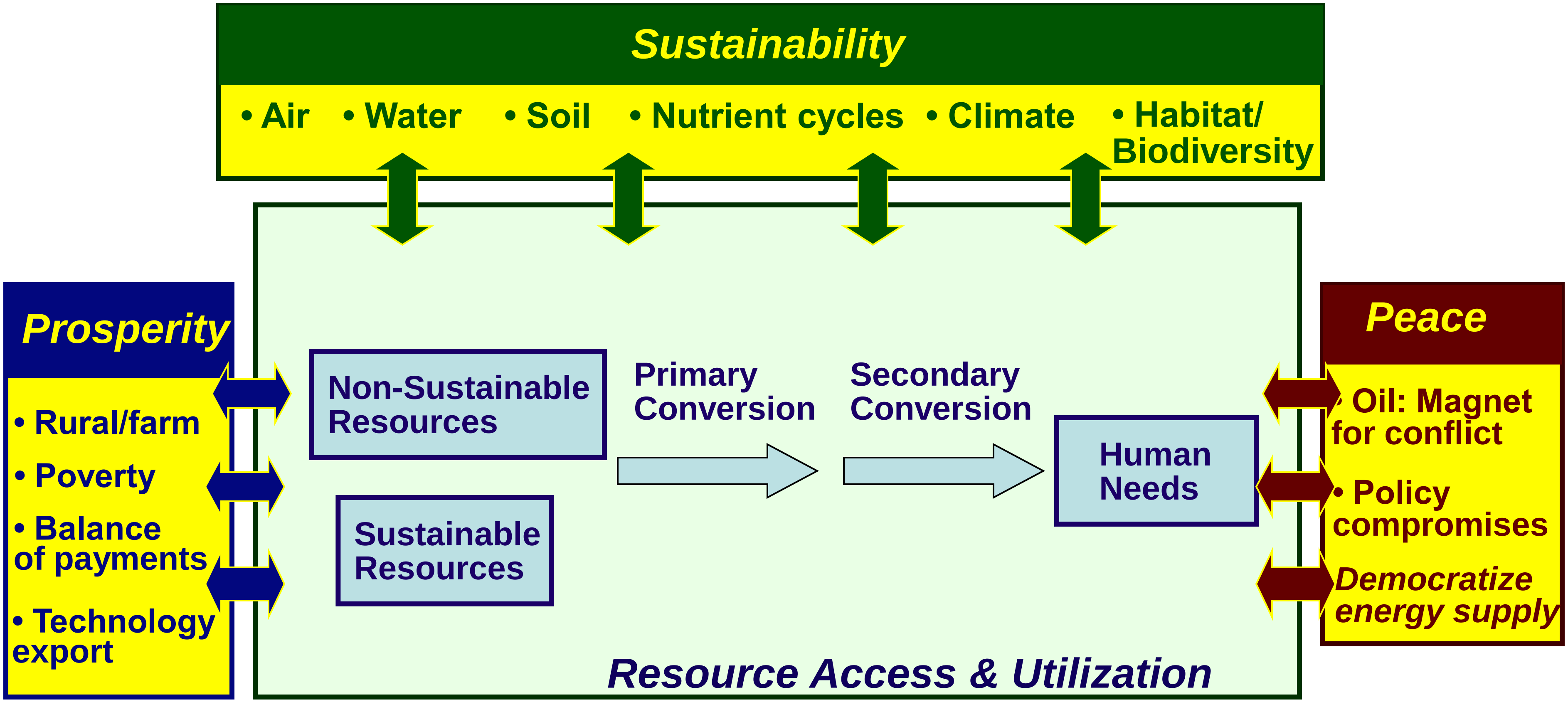
Cellulosic raw materials

<u>Understanding and meeting the bioenergy land use challenge</u>

The Global Sustainable Bioenergy project

1. The sustainable resource transition, the defining challenge of our time, requires multiple, large, complementary, and currently improbable changes.

Prerequisites for the well being of human society…



Sustainability

- Air
- Water
- Soil
- Nutrient cycles
- Climate
- Habitat/ Biodiversity

Prosperity

- Rural/farm
- Poverty
- Balance of payments
- Technology export

Non-Sustainable Resources

Sustainable Resources

Primary Conversion

Secondary Conversion

Human Needs

Resource Access & Utilization

Peace

- Oil: Magnet for conflict
- Policy compromises

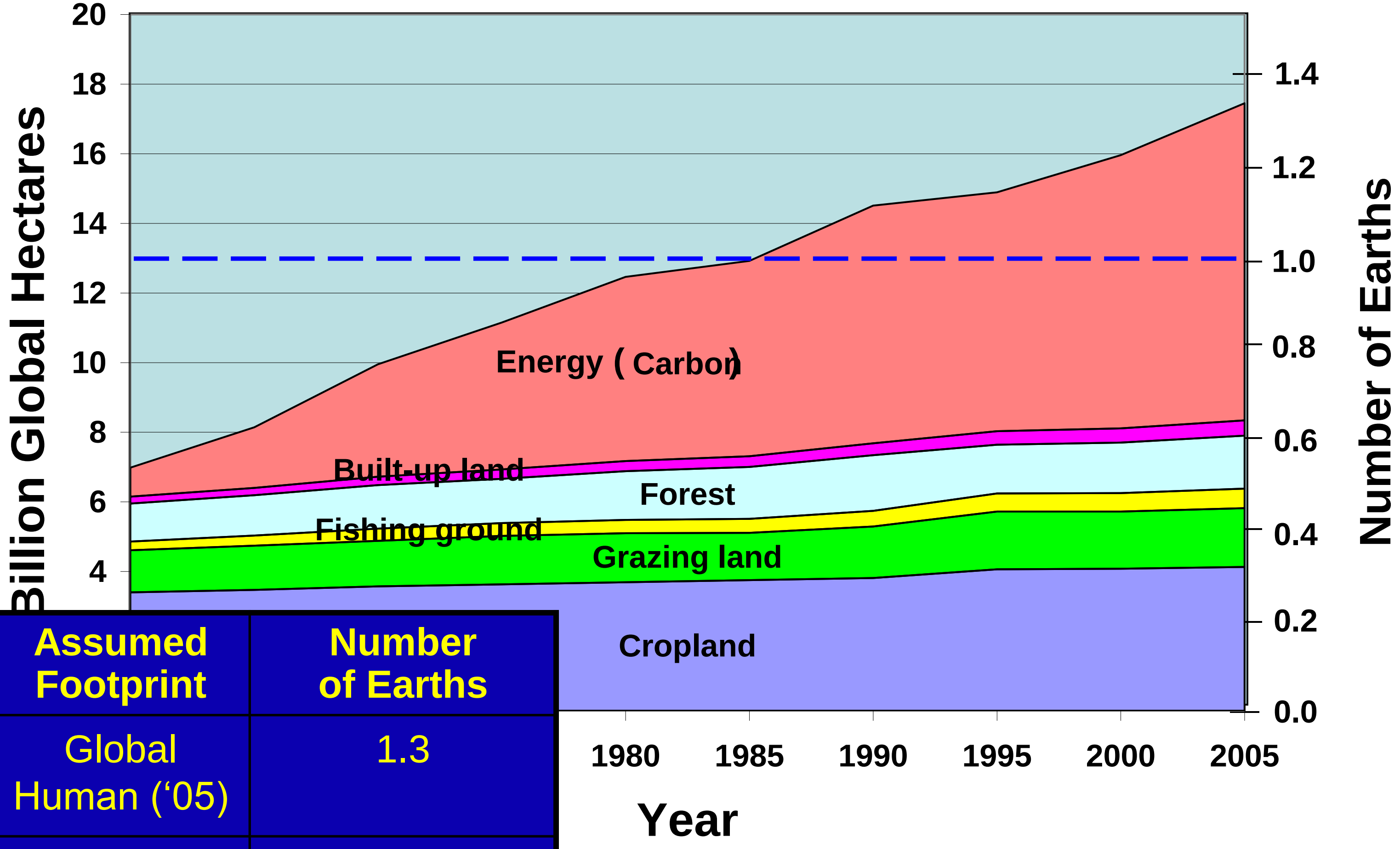
Democratize energy supply

… are dominated by resource access and utilization, particularly energy

Today & always

A convergence of factors makes this critical now - defining challenge of our time

Environmental "footprint": *Land area required to provide for resource consumption & waste assimilation on a sustainable basis*



Population	**Assumed Footprint**	**Number of Earths**
6.5 billion (2005)	Global Human ('05)	1.3
6.5 billion	India	0.4
6.5 billion	Germany	2.0
6.5 billion	USA	4.5
10 billion	Germany	3.1

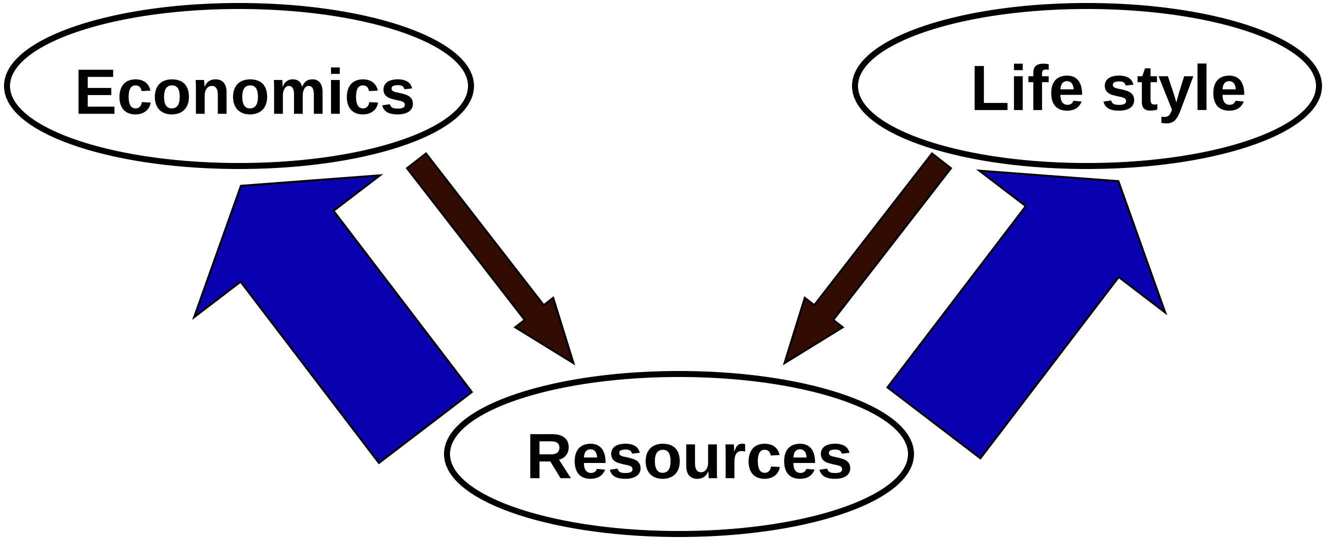
Updated from Wackernagel et al., PNAS, 2002
Global Footprint Network, *Living Planet Report, 2008*

Resource Transitions in Human History

	Hunting & Gathering	Transition I	**Preindustrial Agricultural**	Transition II	**Industrial, Non-sustainable resource base**	Transition III	**Industrial, Sustainable resource base**
		~ 2000 BC		1750 AD		2010?	
Primary occupation	Food, nomadic		Food, farms		Manufacturing & Services		We'll see
Primary energy/ power	Wood, human		Wood, draught animals		Fossil, machines		Sustainable mix, Information-linked machines
World population		50 million		750 million		~7 billion	
Transition time		Millennia		Centuries		Decades	
Interdependence	Individuals/ small groups		Farms/ villages		Cities/countries		Global

Transition III: More people, less time, potential for global collapse

We tend to focus on economics and lifestyle choices determining resource consumption, which does occur in the short term



Over longer time periods, history clearly teaches us that the dominant direction of cause and effect is in fact the reverse: resource use and availability determine economics and lifestyle

Societies with degraded resource bases have repeatedly and reliably collapsed (J. Diamond, *Collapse*)

Pre-transition economics are relevant during resource transitions but usually irrelevant after them

The Sustainable Resource Transition

Our circumstances are changing radically

Past: Few resource constraints, low prices, resource capital

Future: Multiple resource constraints, high prices, resource income

Big, systemic challenges require big, systemic solutions

Viable paths to a sustainable world (all sectors, resources)

Almost never feature

- Single, isolated changes
- New supply without increased resource utilization efficiency

Almost always feature

Multiple, large, complementary changes

Confronting the improbable

Currently probable trends are not sustainable

We must thus look beyond such trends to find sustainable futures

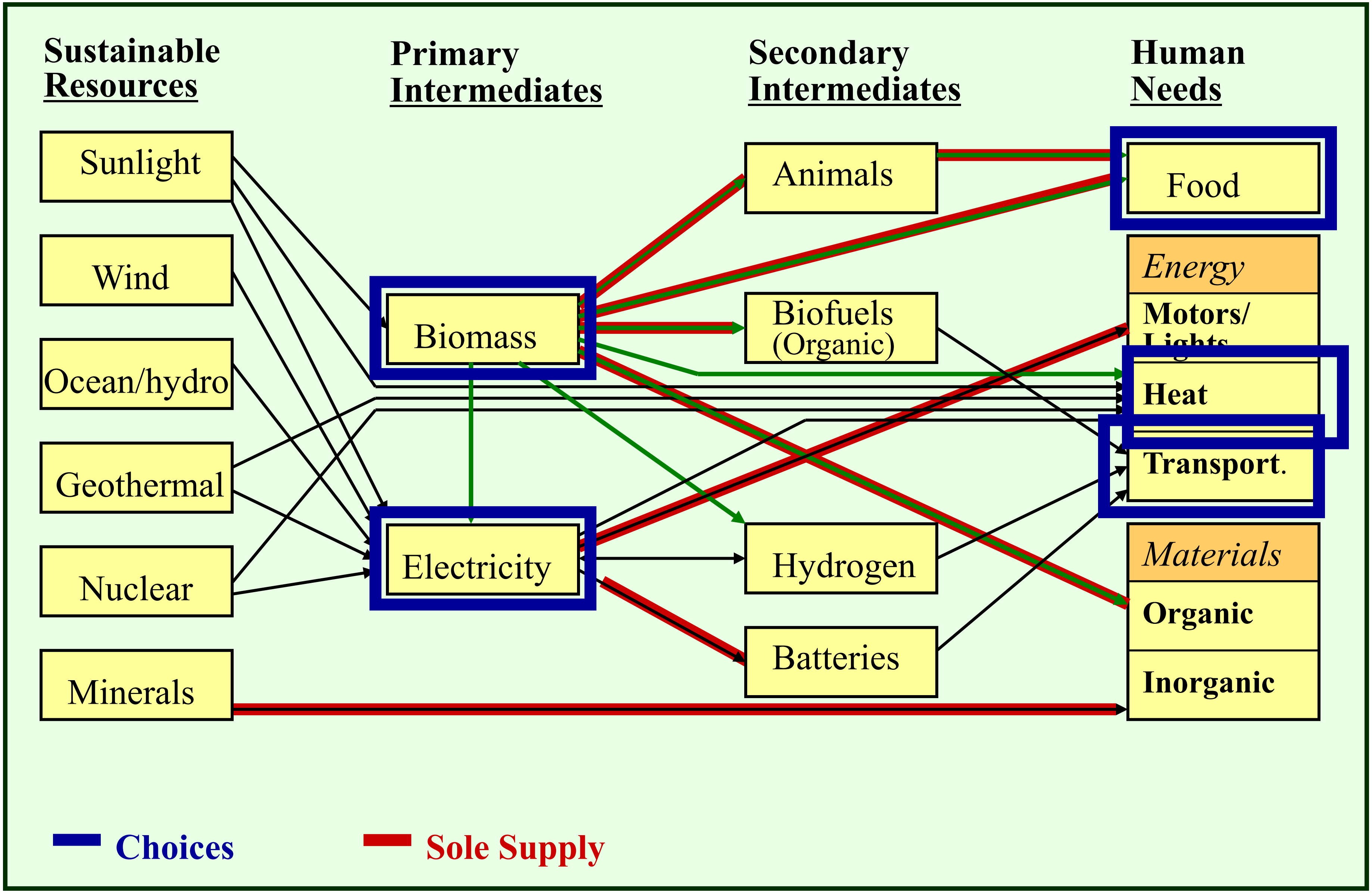
Business as usual is a fantasy rather than a baseline

The first step in realizing currently improbable futures is to show that they are possible

1. The sustainable resource transition, the defining challenge of our time, requires multiple, large, complementary, and currently improbable changes.

2. **To achieve a sustainable transportation sector, we very likely must produce biofuels in large amounts.**

Imagining a Sustainable World



Sustainable Resources

Sunlight

Wind

Ocean/hydro

Geothermal

Nuclear

Minerals

Primary Intermediates

Biomass

Electricity

Secondary Intermediates

Animals

Biofuels (Organic)

Hydrogen

Batteries

Human Needs

Food

Energy

Motors/ Lights

Heat

Transport.

Materials

Organic

Inorganic

🟦 **Choices**

🟥 **Sole Supply**

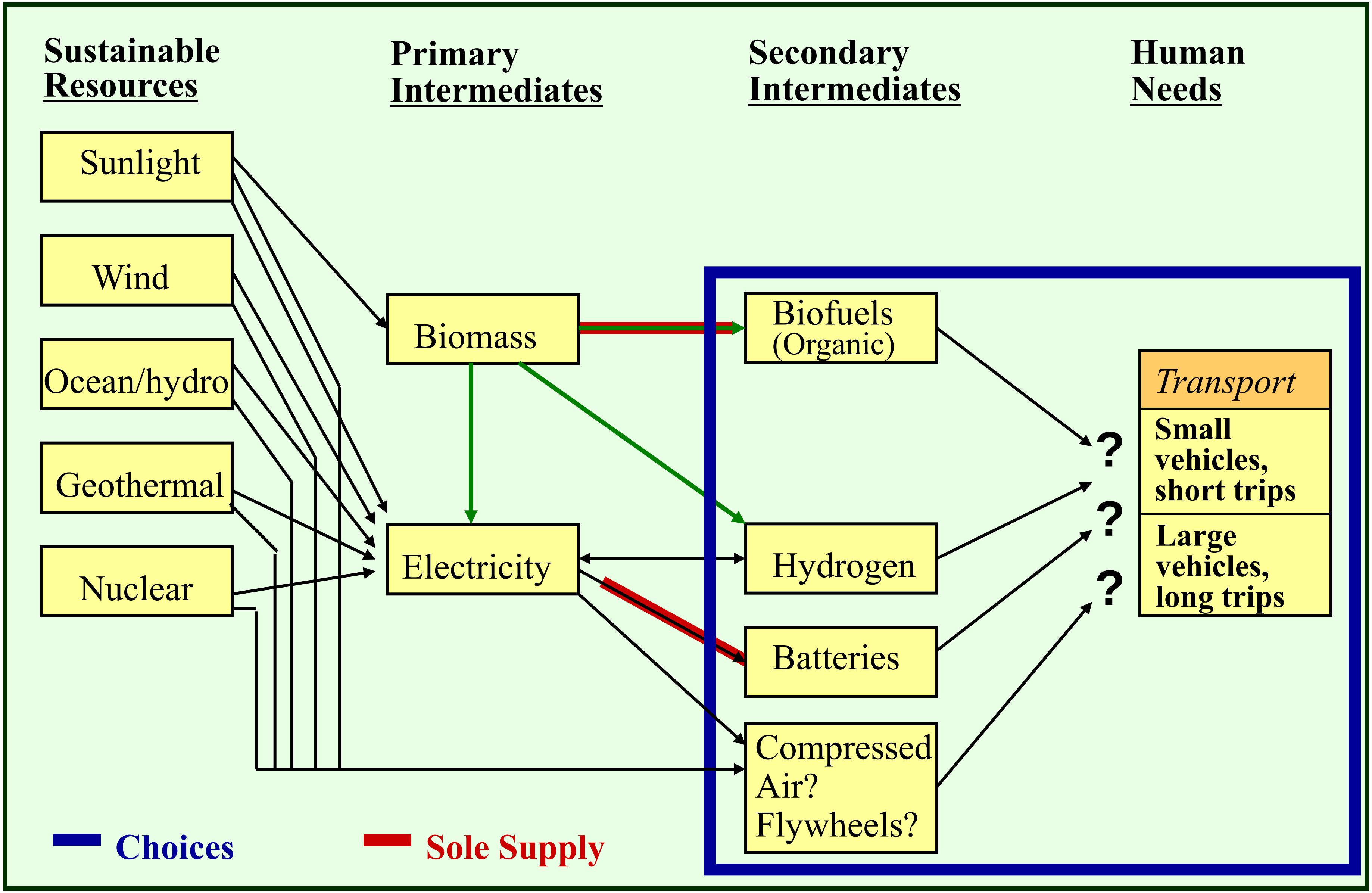
Sustainable Resources: A Closer Look

End Use	Sustainable Resource(s)	Size of Demand (relative)
Food (& Feed)	**Biomass**	**Large**
Organic Materials	**Biomass**	Small
Transportation Energy Storage		**Large**
Liquid @ 1 atm	**Biomass**	
Other	***All***	
Electricity	***All***	**Large**
Heat	***All***	**Large**

Biomass: the only foreseeable sustainable source of food, feed, organic materials, liquid fuels

Transportation: Highest priority large-scale end-use for biomass after food - in many countries

Imagining a Sustainable World: Transport Options



Sustainable Resources

Primary Intermediates

Secondary Intermediates

Human Needs

Sunlight

Wind

Ocean/hydro

Geothermal

Nuclear

Biomass

Electricity

Biofuels (Organic)

Hydrogen

Batteries

Compressed Air? Flywheels?

?

?

?

Transport

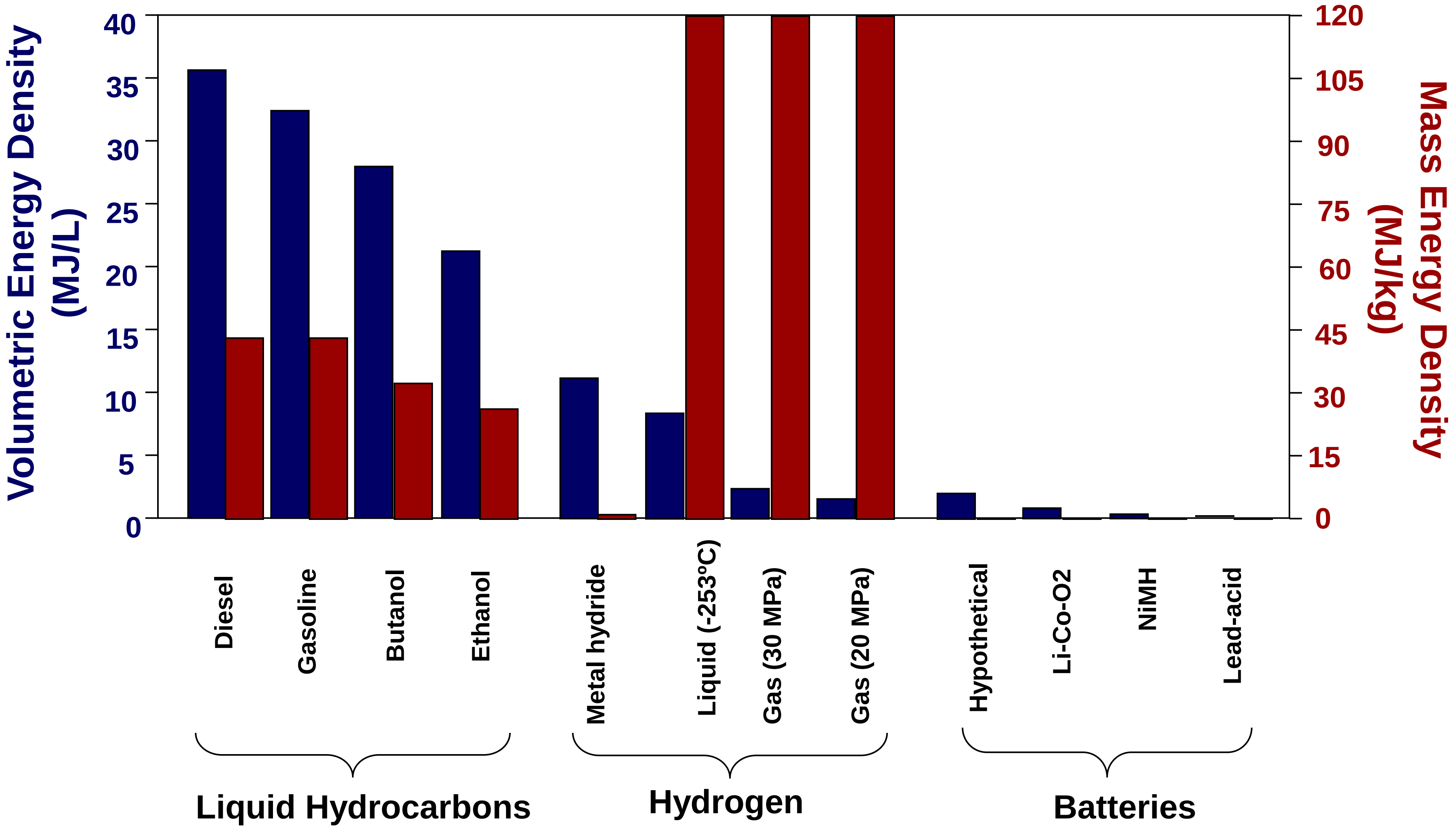
Small vehicles, short trips

Large vehicles, long trips

🟦 **Choices**

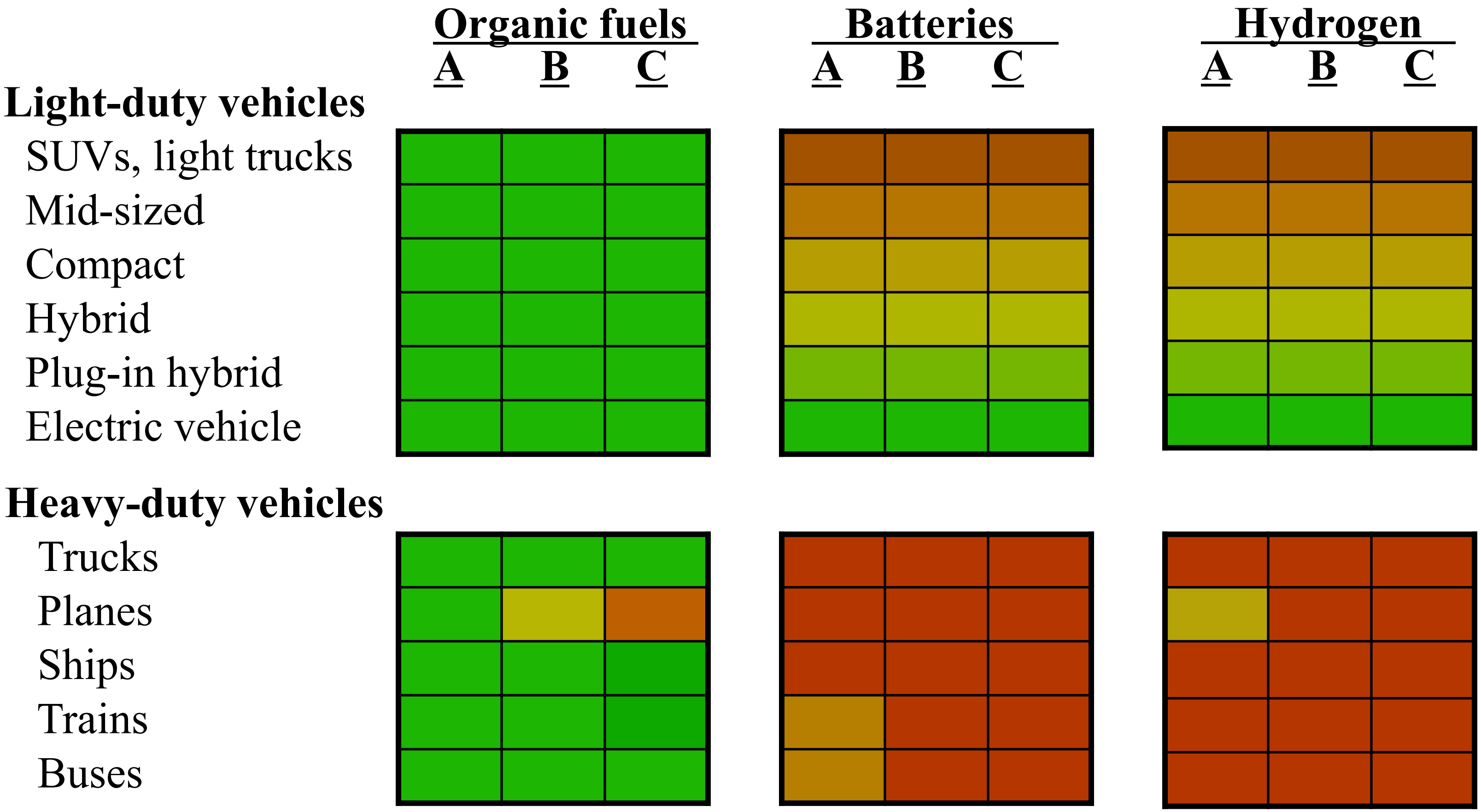
🟥 **Sole Supply**

Transportation Energy Storage: A Closer Look



Sources:
http://www.transportation.anl.gov/software/GREET/index.html
http://www.hydrogen.org/Knowledge/w-i-energiew-eng2.html
http://gcep.stanford.edu/pdfs/assessments/ev_battery_assessment.pdf

Some vehicle-energy storage combinations are more feasible than others



Organic fuels A B C

Batteries A B C

Hydrogen A B C

Light-duty vehicles

SUVs, light trucks

Mid-sized

Compact

Hybrid

Plug-in hybrid

Electric vehicle

Heavy-duty vehicles

Trucks

Planes

Ships

Trains

Buses

Electrification (batteries) impractical for most heavy duty applications

Hydrogen faces many challenges, particularly if from low-C sources

Even with extensive LDV electrification, organic fuels provide ≥ 50% mobility

Achieving a sustainable transportation sector without biofuels is unlikely

1. The sustainable resource transition, the defining challenge of our time, requires multiple, large, complementary, and currently improbable changes.

2. To achieve a sustainable transportation sector, we very likely must produce biofuels in large amounts.

3. **For very biofuel production at very large scale (≥ 25% of global mobility), sugar cane is the most meritorious among current biofuel feedstocks and cellulosic biomass is a particularly promising future feedstock.**

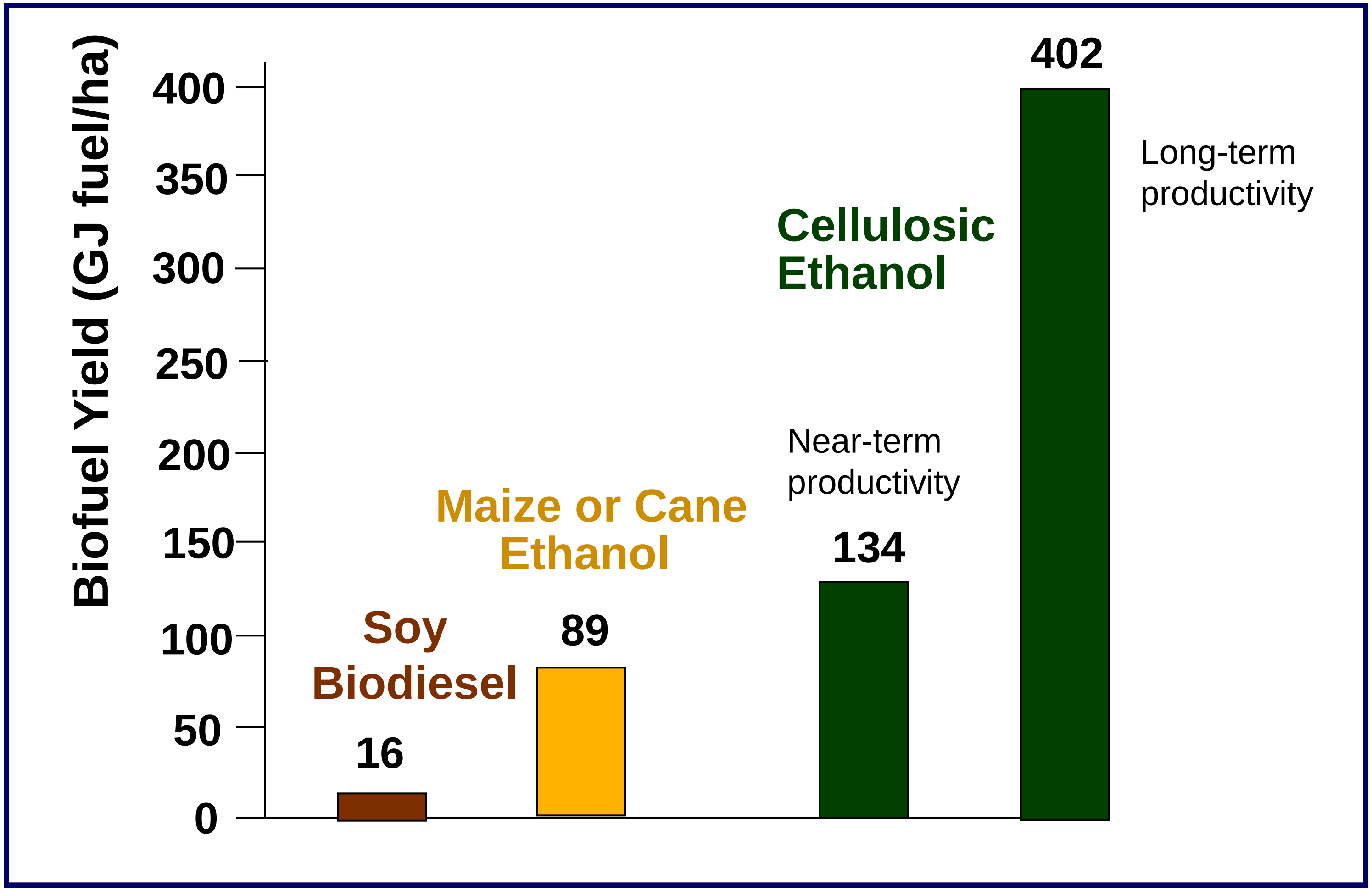
Energy Carrier	Representative Price	
	Common Units	$/GJ
Fossil		
Petroleum	$50/bbl	9
Natural gas	$10/kscf	11
Coal	$55/ton	2.5
w/ carbon capture @	$150/ton C	6.5
Electricity	$0.045/kWh	11 (generated)
	$0.085/kWh	23 (delivered)
Biomass		
Soy oil	$0.50/lb	30.0
Corn kernels	$3.5/bu	10
Sugar cane	$93/ton	6.0
Cellulosic crops[a]	$60/ton	4.0
Cellulosic residues		Some < 0

[a] e.g. switchgrass, short rotation poplar

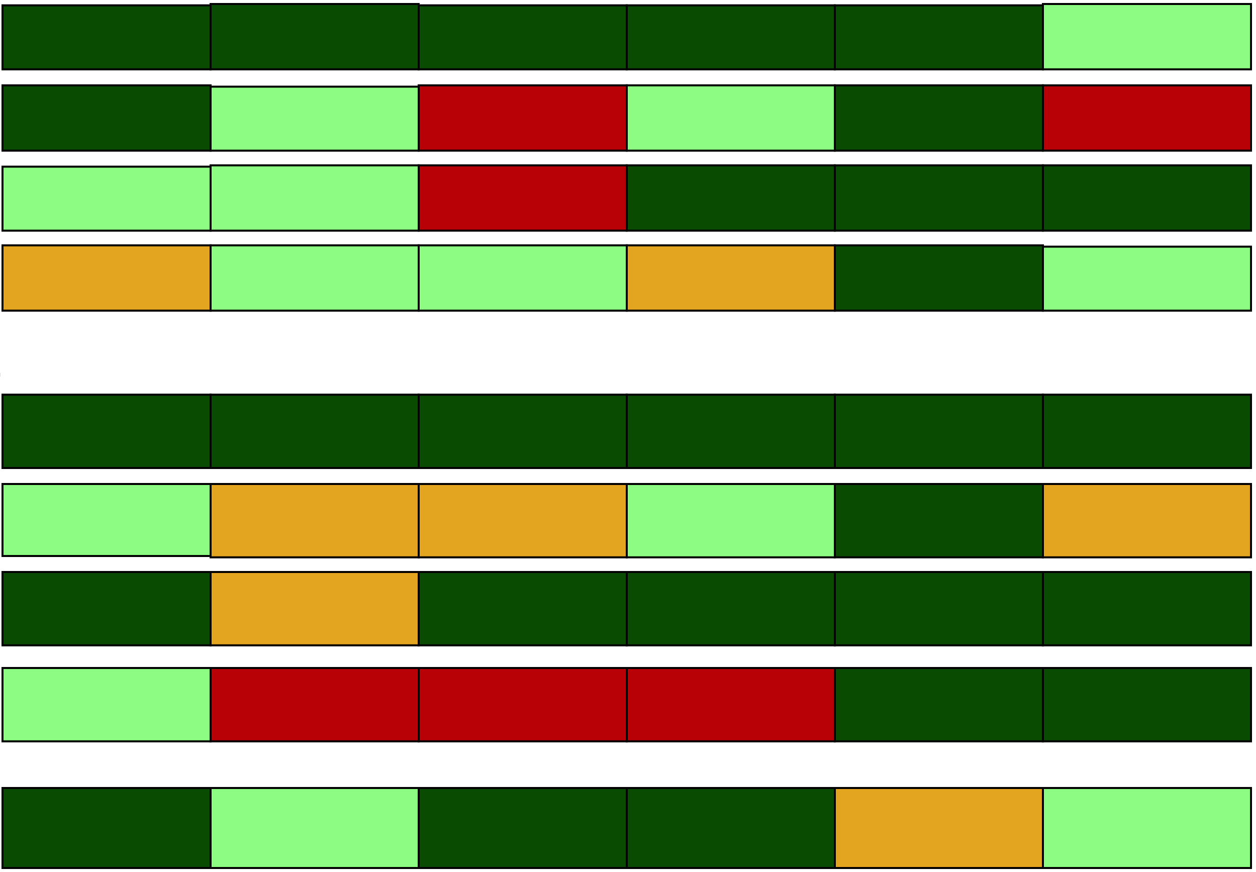
Modified from Lynd et al., Nature Biotech., 2008

At $4/GJ, the purchase price of cellulosic biomass is *competitive with oil at $23/bbl.*

Comparative Land Productivity of Biofuel Options



Crop Yields (U.S. except Cane)	Fuel Yields
Near-term celllulosic: 5 dry ton/acre	Cellulosic ethanol 91 gal gasoline eq./ton (RBAEF)
Long-term cellulosic: 15 dton/acre	Corn ethanol: 2.8 gal/bushel
Corn: 160 bushel/acre	Soy oil: 18% of bean (dry basis)
Cane: 3 tons sugar (dry)/acre	0.47 kg ethanol/kg sugar
Soy: 42 bushel/acre	Biodiesel yield: 0.95 kg/kg soy oil



	Sugar Cane	Maize	Oil seeds	Palm Oil	Cellulosic	Algae
Feedstock production						
Rural Economic Development	🟩	🟩	🟩	🟩	🟩	🟢
Low Cost	🟩	🟢	🟥	🟢	🟩	🟥
Land efficiency (fuel/ha)	🟢	🟢	🟥	🟩	🟩	🟩
Geographical range	🟧	🟢	🟢	🟧	🟩	🟢
Sustainability & Environment						
Manageable process effluents	🟩	🟩	🟩	🟩	🟩	🟩
Water quality & soil fertility	🟢	🟧	🟧	🟢	🟩	🟧
GHG emission reduction	🟩	🟧	🟩	🟩	🟩	🟩
Potential responsiveness to food/habitat concerns	🟢	🟥	🟥	🟥	🟩	🟩
Processing cost (current)	🟩	🟢	🟩	🟩	🟧	🟢

Sugar cane is the most meritorious of first generation biofuel feedstocks but has limited geographical range.

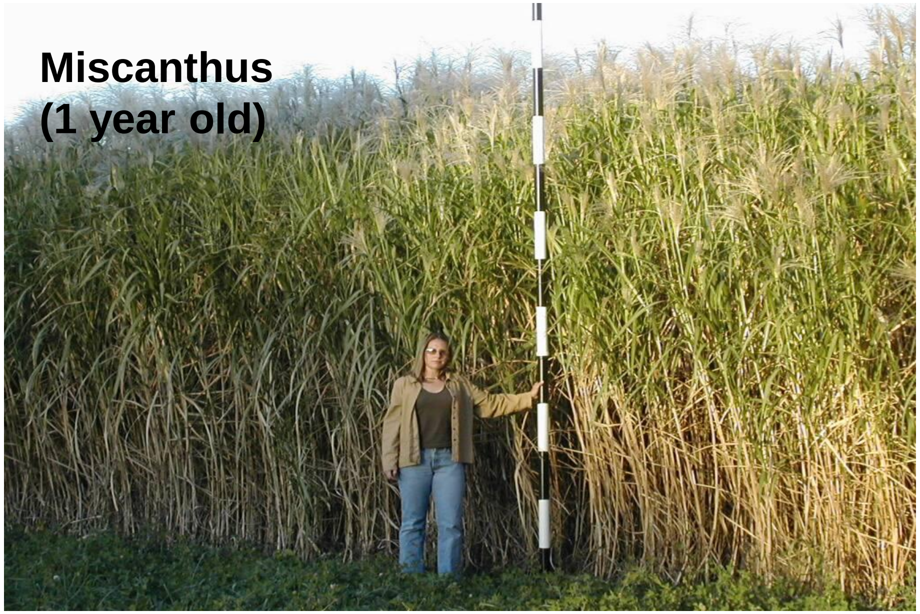
Cellulosic biofuels score well in all metrics except processing cost.

Algae is potentially attractive but the cost of feedstock production is a large and perhaps insurmountable challenge.

Very favorable
Favorable
Unfavorable
Very unfavorable

Examples of Cellulosic Biomass

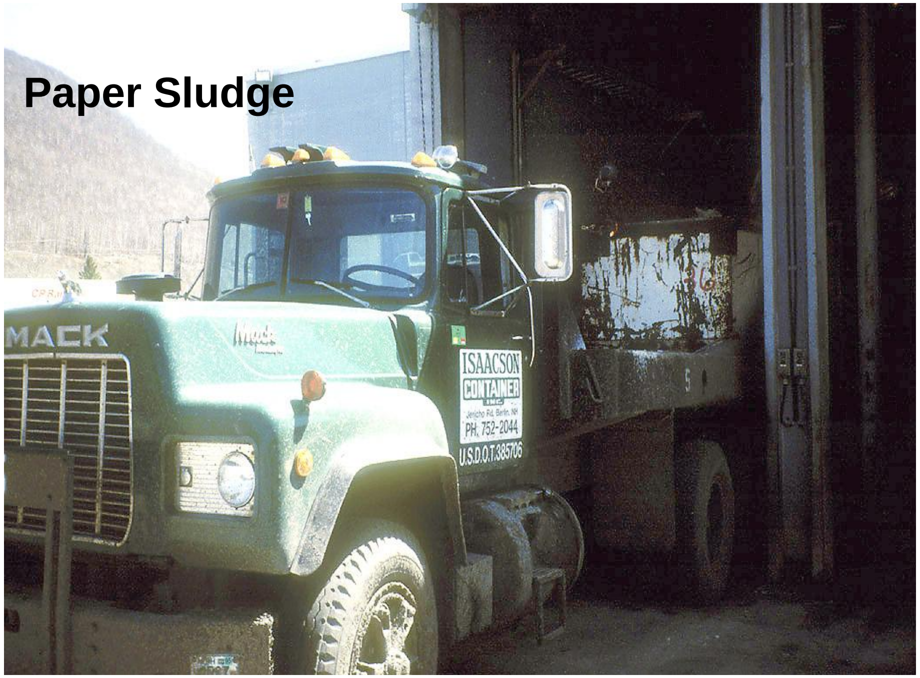
Wood chips



Miscanthus
(1 year old)

Bagasse

QuickTime™ and a
decompressor
are needed to see this picture.



Paper Sludge

1. The sustainable resource transition, the defining challenge of our time, requires multiple, large, complementary, and currently improbable changes.

2. To achieve a sustainable transportation sector, we very likely must produce biofuels in large amounts.

3. For very biofuel production at very large scale ($\geq$ 25% of global mobility), sugar cane is the most meritorious among current biofuel feedstocks and cellulosic biomass is a particularly promising future feedstock.

4. Large-scale biofuel production is impeded by two barriers:

a) Technology: The cost of processing, and particularly biomass recalcitrance, is the key barrier. Recent breakthroughs involving consolidated bioprocessing suggest that this barrier will be overcome.

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b) Land use:

Working hypothesis: It is possible to produce cellulosic biofuels in large amounts while maintaining food production, wildlife habitat, and avoiding significant carbon emissions from land use change.

Biofuels Resource Sufficiency: Positive Studies

United States

Biomass will eventually provide over 90% of U.S. chemical and over 50% of U.S. fuel production (NRC, 1999, *Biobased Industrial Products*,).

20% of petroleum demand in 2025 (Lovins et al., 2004, *Winning the Oil End Game*).

50 % current transportation sector energy use, and potentially nearly all gasoline, by 2050 (Greene et al., 2004, *Growing Energy*)

1.3 billion tons of biomass could be available in the mid 21st century - 1/3 of current transport fuel demand (Perlack et al., 2005, *"Billion Tons Study"*).

Goal of 100 billion gallons of ethanol by 2025 (Ewing & Woolsey, 2006, *A High Growth Strategy for Ethanol)*

90 billion gallon of biofuel could be produced by 2030 (GM & Sandia, 2009)

Worldwide

Biomass becomes the largest energy source supporting humankind by a factor of 2 (Johanssen et al., 1993, *Renewables-Intensive Global Energy Scenario*).

Biomass potential comparable to total worldwide energy demand (Woods & Hall, 1994; Yamamoto, 1999; Fischer & Schrattenholzer, 2001; Hoogwijk et al., 2005)

Biofuels Resource Sufficiency: Negative Studies

David Pimentel's group (at least 11 papers, 1979 to 2008)

"Use of biomass energy as a primary fuel in the United States would be impossible while maintaining a high standard of living"

"Large-scale biofuel production is not an alternative to the current use of oil and is not even an advisable option to cover a significant fraction of it."

Others

Power density of photosynthesis is too low for biofuels to have an impact on greenhouse gas reduction (Hoffert et al., 2002)

Impractically large land requirements for biomass energy production on a scale comparable to energy/petroleum use (Trainer, 1995; Kheshgi, 2000; Avery, 2006)

"The Clean Energy Scam" (Grunwald; May 2008; *Time*)

"National governments should cease to create new mandates for biofuels and investigate ways to phase them out." (Organization for Economic Cooperation and Development, August 2008)

"Mandating the use and production of these fuels without fully understanding their effect on food production and the environment - as current US biofuel policy does - is irresponsible and dangerous." (Statement by 5 environmental groups calling for biofuel policy revamp, 2009).

How can presumably reasonable people with access to the same information reach such different conclusions about biofuel resource sufficiency?

Ultimately, questions related to the availability of land for biomass energy production and the feasibility of large-scale provision of energy services are determined as much by world view as by hard physical constraints… To a substantial degree, the starkly different conclusions reached by different analysts on the biomass supply issue reflect different expectations with respect to the world's willingness or capacity to innovate and change. *Lynd et al., "Thirteen Energy Myths, 2007"*

Change Fostering Sustainability

	Current	Mature
Motivated	Innovation: - Change: +	Innovation: + Change: +
Indifferent	Innovation: - Change: -	Innovation: + Change: -

Technological Maturity

Advanced technology and motivation to solve energy challenges may seem optimistic, or improbable

…but it is entirely unrealistic to expect to meet these challenges without both

It has been suggested that we should forego the biofuel option because of land use challenges. A dispassionate response entails asking

What are our alternatives? (Already addressed)

What benefits would be missed?

What are the prospects for gracefully resolving these challenges?

Benefits missed if we forego the biofuel option

Energy security

Rural economic development

Environmental

- GHG emission reduction
- Reduced demand for unconventional petroleum (shale oil, tar sands)
- Increased use of low-carbon electricity to displace coal if less electricity needed for transport

Without biofuels, achieving a sustainable transportation sector is unlikely

Given these observations, it makes sense to approach with urgency the question: Can biofuel land use challenges be resolved gracefully?

Dimensions of Innovation & Change Impacting Biofuel Feedstock Availability

I.A. Integrate feedstock production into managed lands

- Double crops
- Coproduce feed and feedstocks - e.g. early-cut grass in lieu of soy, perhaps other strategies
- Increase harvest from underutilized pasture, range, and/or CRP land
- Sustainably harvest ag. residues, perhaps enhanced by new crop rotations
- Develop crop varieties with increased yields of non-nutritive cellulosic biomass (more residues)
- Sustainably harvest forest residues
- On abandoned, degraded, steep cropland

I.B. Produce food more land-efficiently

- Change animal feeding practices, e.g. pasture intensification, forage pretreatment
- Increase crop productivity, especially feed crops

I.C. Change diet

- Amount & kind of animal products

I.D. Decrease fuel demand

- Energy efficient cars
- Public transportation
- Smart growth

II.A. Mature biomass production

- High productivity
- Broad site range
- Low inputs
- High digestibility

II.B. Mature conversion technology

- Advanced pretreatment
- CBP
- Advanced process engineering

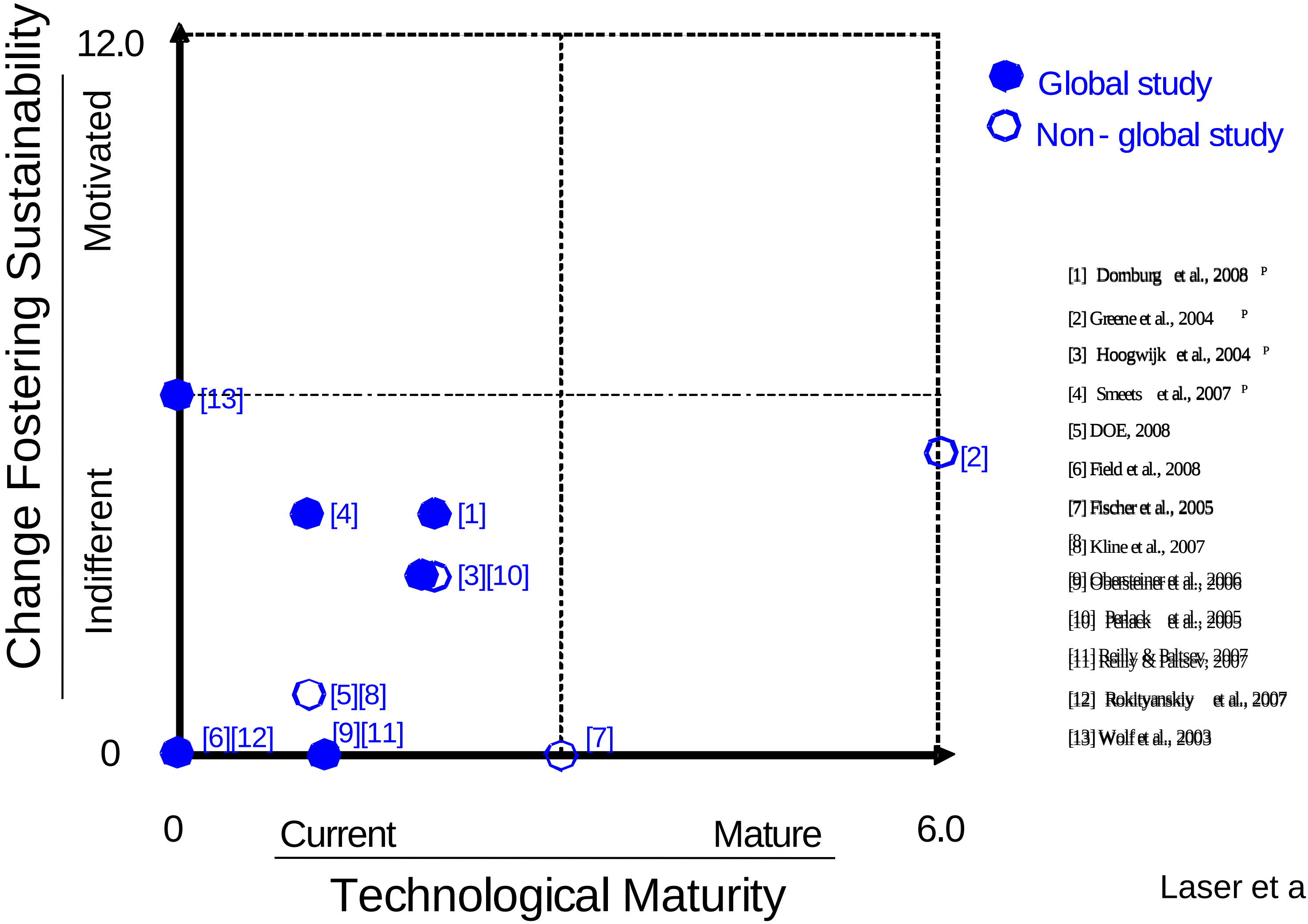
Consideration of Innovation & Change in Recent Studies Examining Biofuel Feasibility

	I. CHANGE TO ACHIEVE SUSTAINABILITY					II. TECHNOLOGY		
STUDY	**I.A. Feedstock integration**	**I.B. Food production efficiency**	**I.C. Changing diet**	**I.D. Lower fuel demand**	**Total**	**II.A. Mature feedstock production**	**II.B. Mature cellulosic conversion**	**Total**
Dornburg et al., 2008	1	2	0	1	**4**	2	0	**2**
Greene et al., 2004	2	0	0	3	**5**	3	3	**6**
Hoogwijk et al., 2004	1	0	1	1	**3**	2	0	**2**
Smeets et al., 2007	1	3	0	0	**4**	1	0	**1**
Leite et al., 2008	0	0	0	0	**0**	1	0	**1**
DOE, 2008	1	0	0	0	**1**	1	0	**1**
Field et al., 2008	0	0	0	0	**0**	0	0	**0**
Fischer et al., 2005	0	0	0	0	**0**	3	0	**3**
Fischer & Schrattenholzer, 2001	1	1	0	0	**2**	1	0	**1**
Kline et al., 2007	1	0	0	0	**1**	1	0	**1**
Moreira, 2006	1	0	0	0	**1**	0	0	**0**
Obersteiner et al., 2006	0	0	0	0	**0**	1	0	**1**
Perlack et al., 2005	1	2	0	0	**3**	2	0	**2**
Reilly & Paltsev, 2007	0	0	0	0	**0**	1	0	**1**
Rokityanskiy et al., 2007	0	0	0	0	**0**	0	0	**0**
Wolf et al., 2003	0	3	3	0	**6**	0	0	**0**

3	Extensive consideration
2	Moderate consideration
1	Minimal consideration
0	Not considered

Laser et al., in preparation

Consideration of Innovation & Change in Recent Studies Examining Biofuel Feasibility



[1] Domburg et al., 2008 ^{P}

[2] Greene et al., 2004 ^{P}

[3] Hoogwijk et al., 2004 ^{P}

[4] Smeets et al., 2007 ^{P}

[5] DOE, 2008

[6] Field et al., 2008

[7] Fischer et al., 2005

[8] Kline et al., 2007

[9] Obersteiner et al., 2006

[10] Perlack et al., 2005

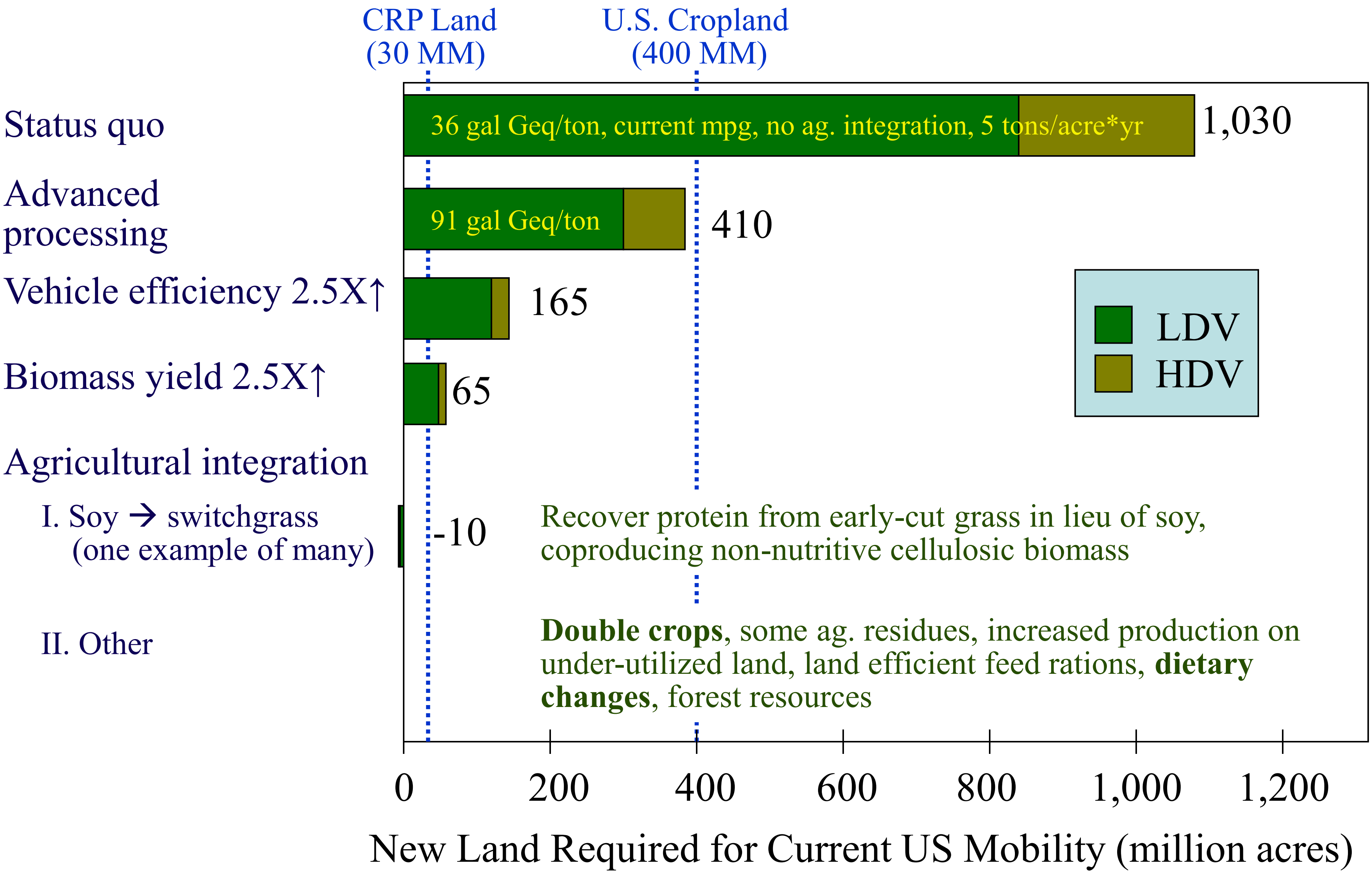
[11] Reilly & Paltsev, 2007

[12] Rokityanskiy et al., 2007

[13] Wolf et al., 2003

Laser et al., in preparation

New Land Required to Satisfy Current U.S. Mobility Demand



Recover protein from early-cut grass in lieu of soy, coproducing non-nutritive cellulosic biomass

Double crops, some ag. residues, increased production on under-utilized land, land efficient feed rations, **dietary changes**, forest resources

Integrating Feedstock Production Into Managed Land

- **Food production is usually assumed to remain static**, or extrapolated, in analyses of biomass supply.

- Yet **new demand** for non-nutritive cellulosic biomass due to cost-competitive processing technology would likely bring **large changes**.

- Given a new value proposition, farmers would **rethink what and how they plant**.

*Over the last century, the constant challenge in the world's functional breadbaskets has been supporting rural economies in the face of productive capacity exceeding demand - hence very **little policy or analytical effort has been devoted to feeding the world in a land efficient manner***

Integrating Feedstock Production Into Managed Land: Examples

Double cropping

US potential (gas equivalent):

- protein displacement: 44 billion gal*

\+ protein displacement: ~ 88 billion gal

A. Heggenstaller, M. Liebman, R. Anex

* 240 mmacres*0.67*3 tons/acre*91 gal GGE/ton

Dietary change (U.S.)

Halve per capita beef consumption with corresponding increase in poultry makes available an amount of land with fuel production potential exceeding global gasoline demand in some scenarios

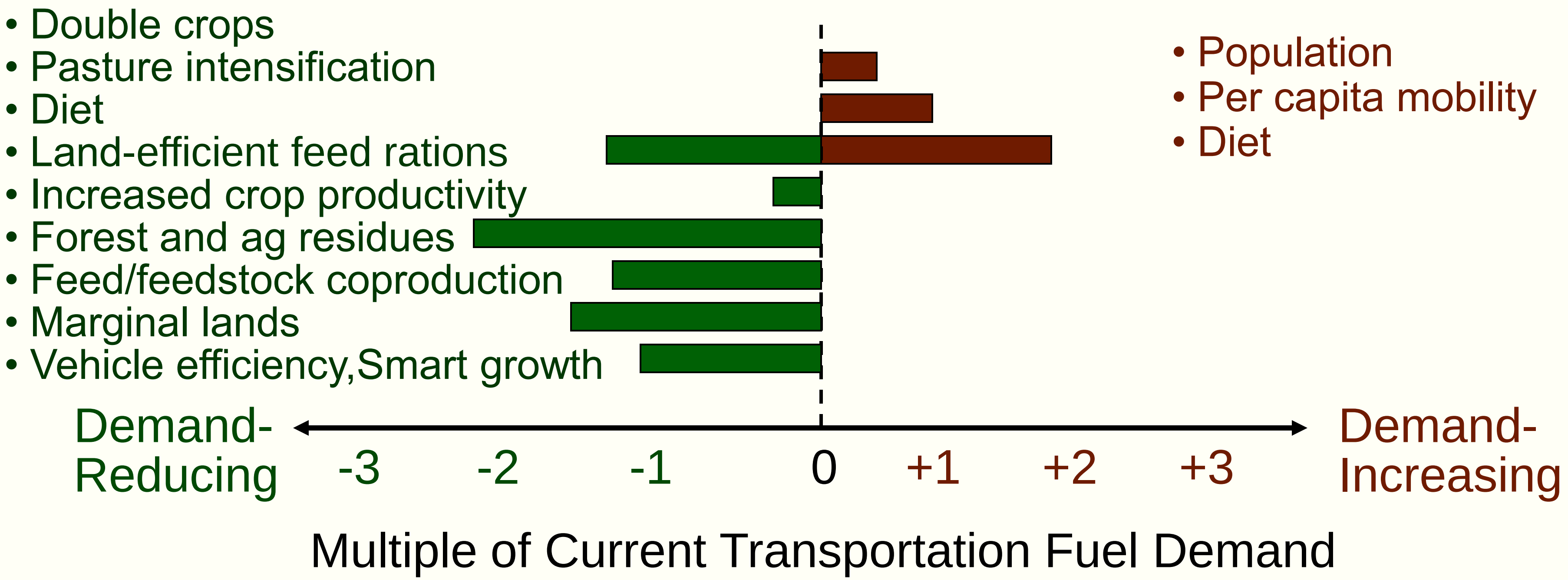
Pasture intensification (Brazil)

If grazing density were doubled, 100 million ha at 10,000L/ha would produce 1 trillion liters of fuel, 3/4 of global gasoline demand

These and other examples suggest that the widely-held assumption that increased biofuel production necessarily means compromising food production or wildlife habitat is not correct.

Underway Analyses

Quantitative evaluation of land use impacts (global)



- Double crops
- Pasture intensification
- Diet
- Land-efficient feed rations
- Increased crop productivity
- Forest and ag residues
- Feed/feedstock coproduction
- Marginal lands
- Vehicle efficiency,Smart growth

- Population
- Per capita mobility
- Diet

Multiple of Current Transportation Fuel Demand

In-preparation manuscripts

Impact of Diet on Biofuel Production Potential

Reconfiguration of Agriculture to Co-Produce Fuel and Food

Strategic Analysis of Sustainable Transportation Options

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   b) Land use:

   Working hypothesis: It is possible to produce cellulosic biofuels in large amounts while maintaining food production, wildlife habitat, and avoiding significant carbon emissions from land use change.

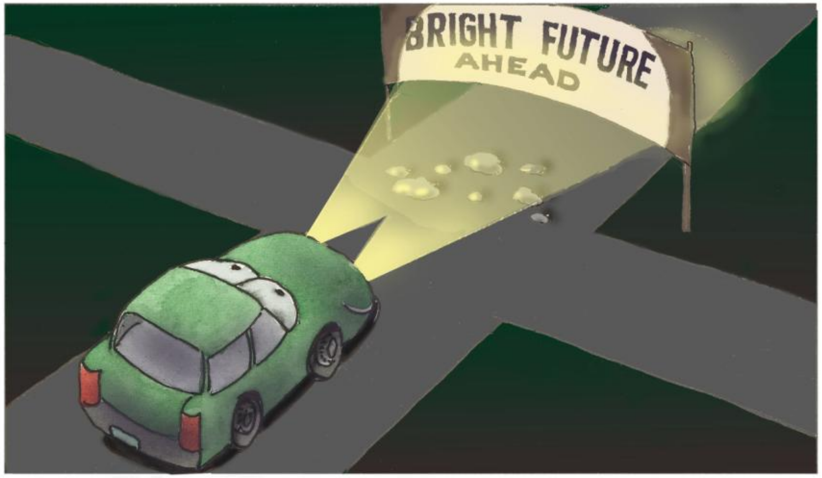
5. The Global Sustainable Bioenergy project seeks to explore these issues in more detail

Global Sustainable Bioenergy: Feasibility & Implementation Paths - "GSB Project"

Project initiated (June, 2009)

- International Organizing Committee formed
- Joint statement in *Issues in Science and Technology*
- Web site launched

Key Question: *Is it physically possible for bioenergy to meet a substantial fraction of future world mobility and/or electricity demand while our global society also meets other important needs.*



"High Beams" Approach

Staged structure

1. Meetings, assemble international team, scope project, get support
2. Address key question posed above unconstrained by current realities
3. Work back to the present considering policy, economic, transition, and development issues

GSB Project: Stage 1 Meetings & Organizing Committee

Representation	Host Institutions, Location	Meeting Chairs/ Organizing Committee Members	Dates
European Union	Kluyver Center for Genomics of Industrial Fermentations, Delft, The Netherlands	• Andre Faaij, Utrecht University • Patricia Osseweijer, Delft University of Technology	February, 24-26, 2010
Africa	University of Sellenbosch, Stellenbosch, South Africa	• Emile van Zyl, University of Stellenbosch • August Temu, World Agroforestry Centre, Nairobi	March, 17-19, 2010
South America	University of São Paulo, São Paulo, Brazil	▪José Goldemberg, University of São Paulo ▪Carlos Henrique de Brito Cruz, FAPESP, São Paulo	March, 22-24, 2010
North America	▪ University of Minnesota, Minneapolis/St. Paul, USA	• John Foley, University of Minnesota	May, 2010
Asia, Oceania	TBD	Reinhold Mann, Battelle Science and Technology, Malaysia	June 2010?

Steering Committee: Nathanael Greene, Natural Resources Defense Council

Lee Lynd (Chair), Dartmouth, Mascoma Corp.

Tom Richard, Pensylvania State University