Gracefully Reconciling Large-Scale Bioenergy Production With Competing Demands

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Scientific Issues on Biofuels
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Twice in history, major changes in the resources used by humanity have resulted in transformative changes in day-to-day life and societal organization, appropriately called revolutions

		Agricultural Revolutions		Industrial Revolution	
	Hunting & Gathering	→	**Preindustrial Agricultural**	→	**Presustainable Industrial**
		~ 4000 BC…		1750 AD…	
Population:		50 million		750 million	
Duration:		Millennia		Several centuries	
Scale of societal integration/ collapse:	Small groups		Farms/ villages		Cities/countries

Lynd, Bioenergy: In Search of Clarity, Submitted.

Today: There are abundant indications that a third revolution is required

	Agricultural Revolution		Industrial Revolution		**Sustainability Revolution**	
Hunting & Gathering	→	**Preindustrial Agricultural**	→	**Presustainable Industrial**	→	**Sustainable Industrial**
	~ 4000 BC…		1750 AD…		**2010… ?**	

	Hunting & Gathering	Preindustrial Agricultural	Presustainable Industrial	Sustainable Industrial
Population:		50 million	750 million	**~7 billion**
Duration:		Millennia	Several centuries	**< a century**
Scale of societal integration/ collapse:	Small groups	Farms/ villages	Cities/countries	**Global**

The sustainability revolution: More people, less time, higher risk

The defining challenge of our time

Lynd, Bioenergy: In Search of Clarity, Submitted.

The Sustainability Revolution

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 and currently improbable changes

Embracing the improbable

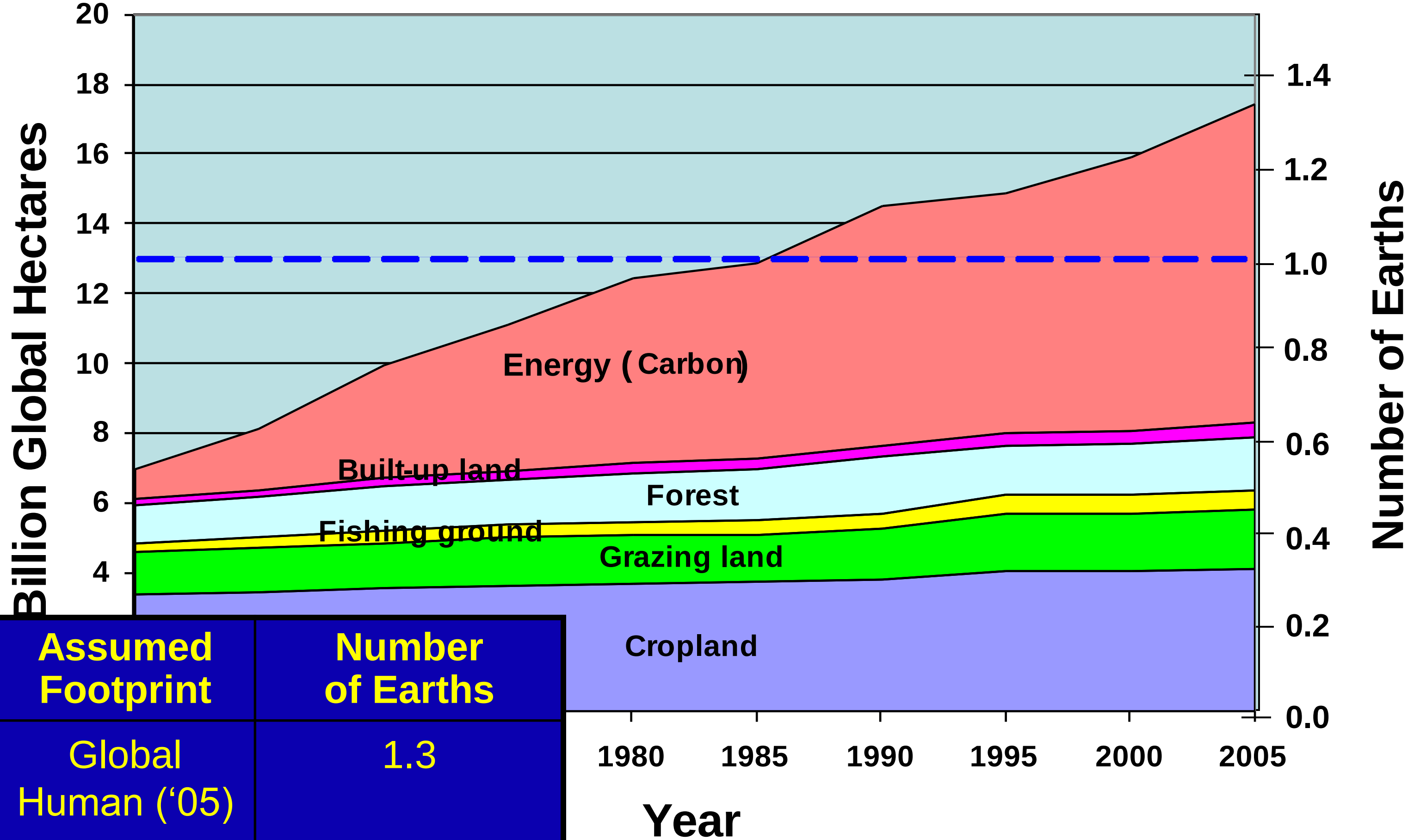
Currently probable trends are not sustainable

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

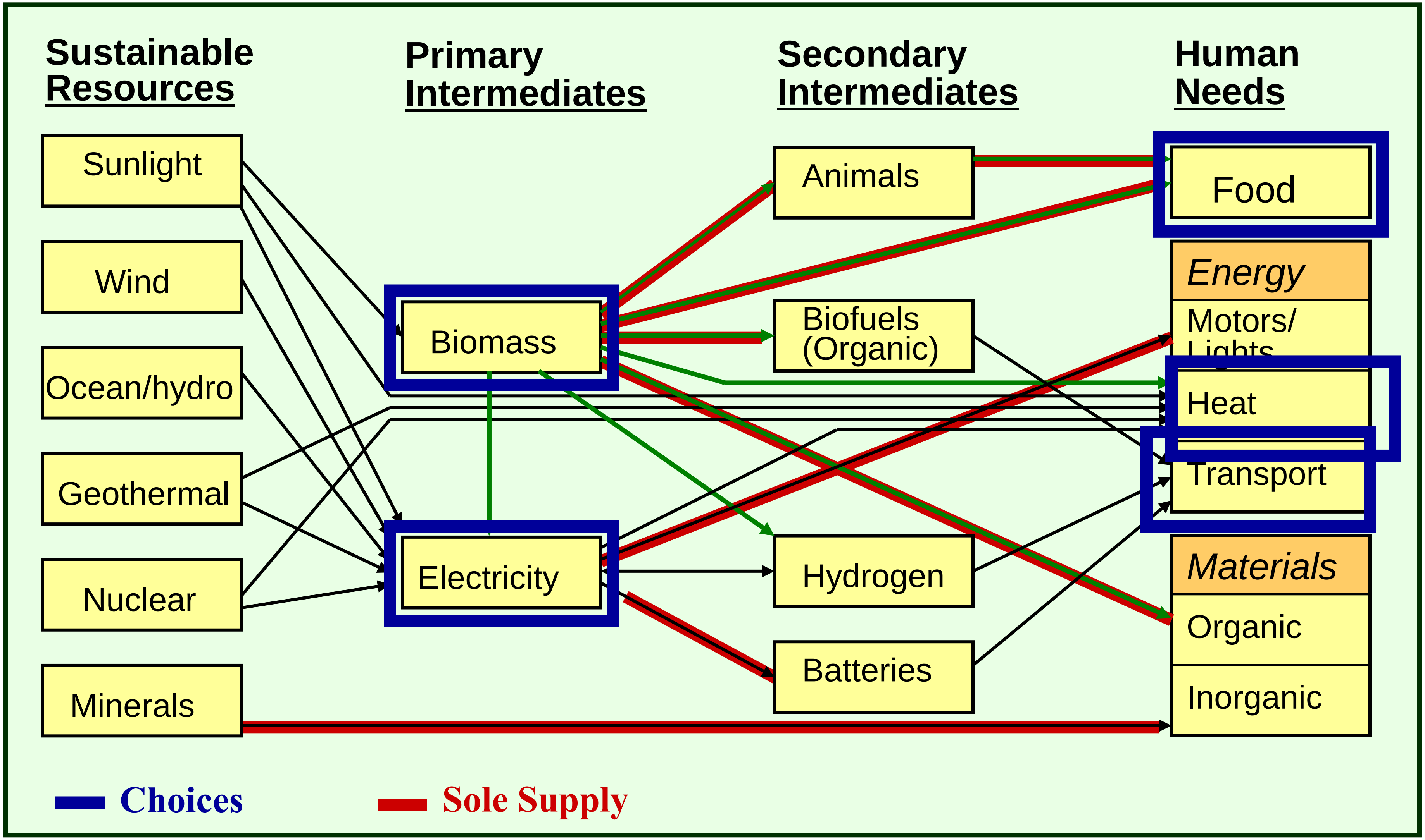
Environmental "footprint": *Land area required to provide for resource consumption & waste assimilation on a sustainable basis*



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*

Imagining a Sustainable World

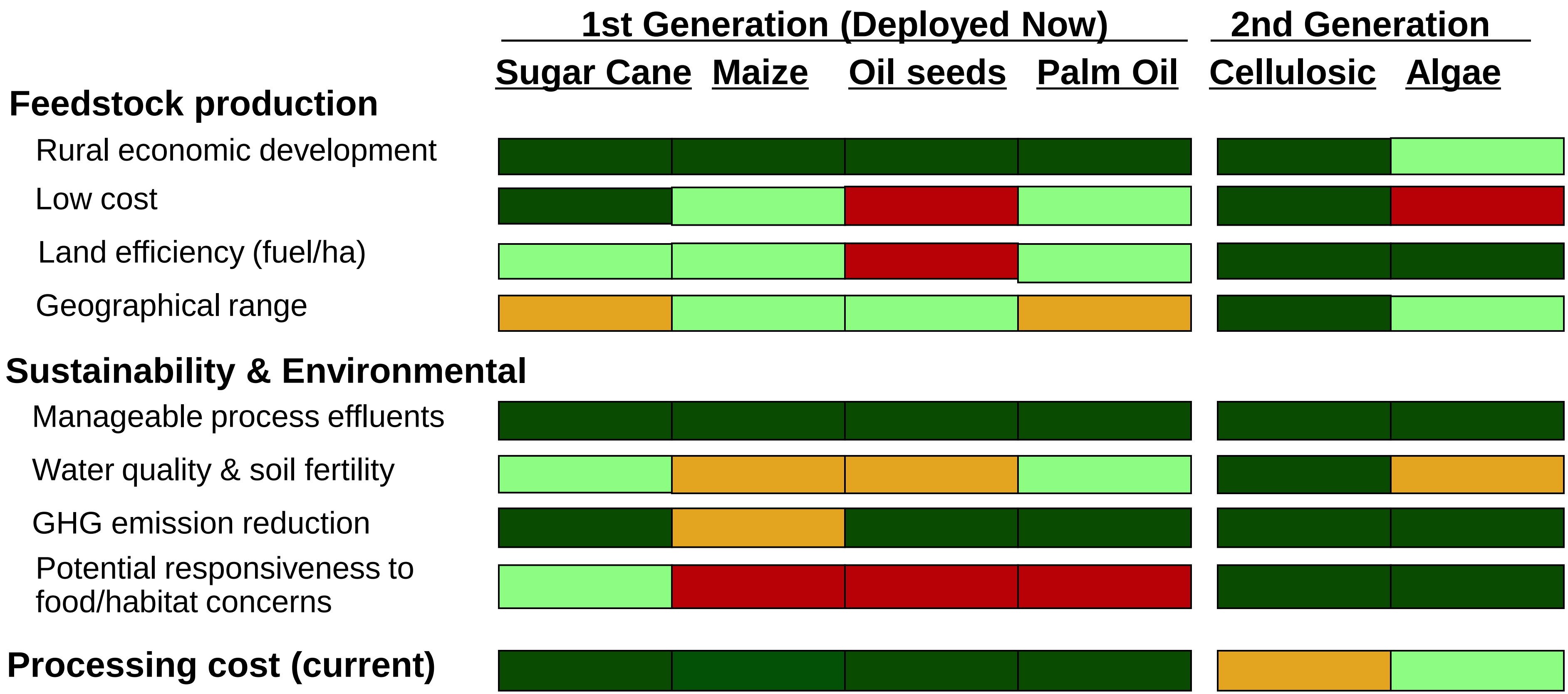


Biomass

Central and essential role in a sustainable world

The only foreseeable sustainable source of food, organic fuels, and organic materials

Feedstocks: Dominant Determinants of Cost, Scale, Sustainability



Very favorable

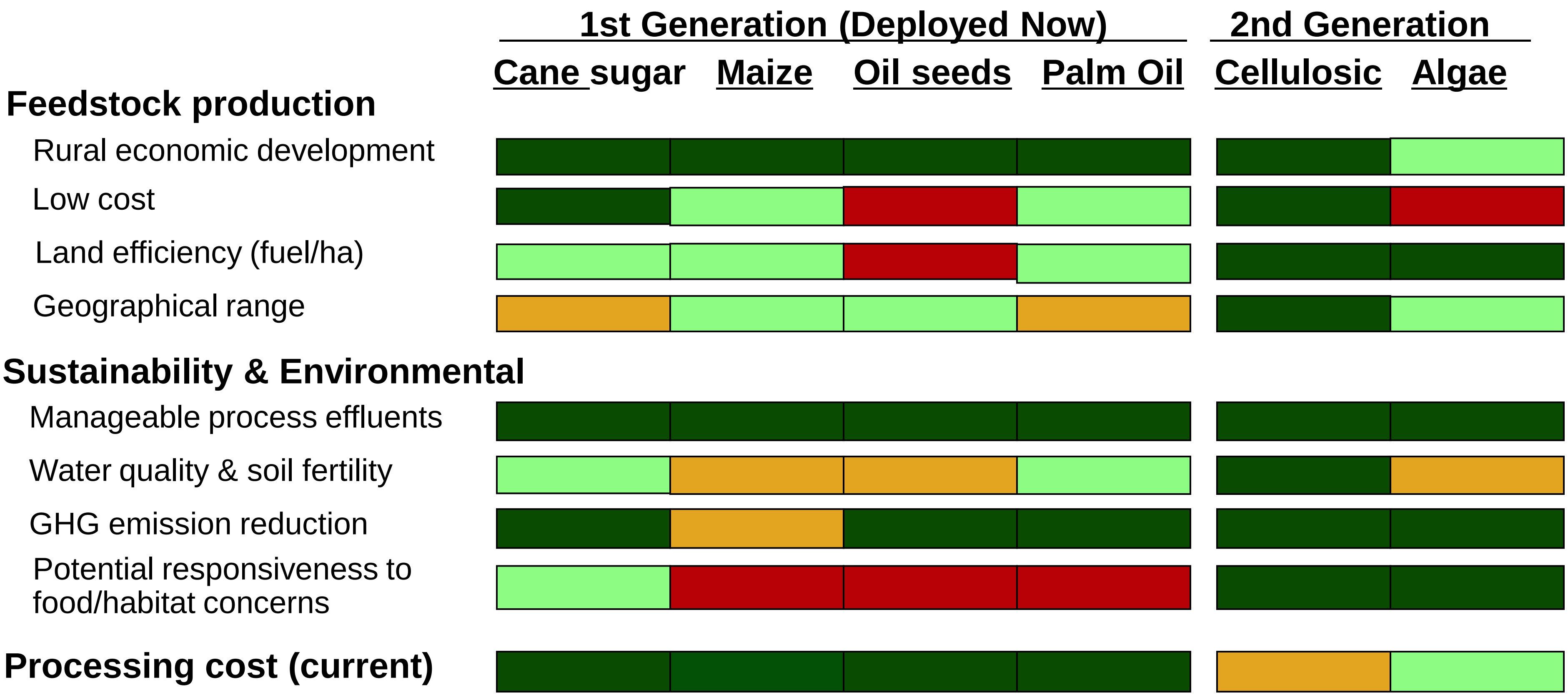
Favorable

Unfavorable

Very unfavorable

- Sugar cane: Most meritorious of 1st gen. feedstocks, range restricted.
- Cellulosic biomass: Focus of all studies foreseeing very large-scale, widespread biofuel production
- Algae: Some distinctive & attractive features, worthy of study. The potential for algae production at a cost per unit energy $\leq$ foreseeable petroleum prices has not been presented.

Feedstocks: Dominant Determinants of Cost, Scale, Sustainability



Very favorable

Favorable

Unfavorable

Very unfavorable

The "first generation" and "second generation" classification has its limitations – e.g. as a basis for policy

In many ways, cane sugar has more in common with cellulosic than other first generation feedstocks

- Perennial vs annual, with associated land use benefits
- Process energy from residues → large greenhouse gas benefits

Comparative Purchase Price of Energy Carriers

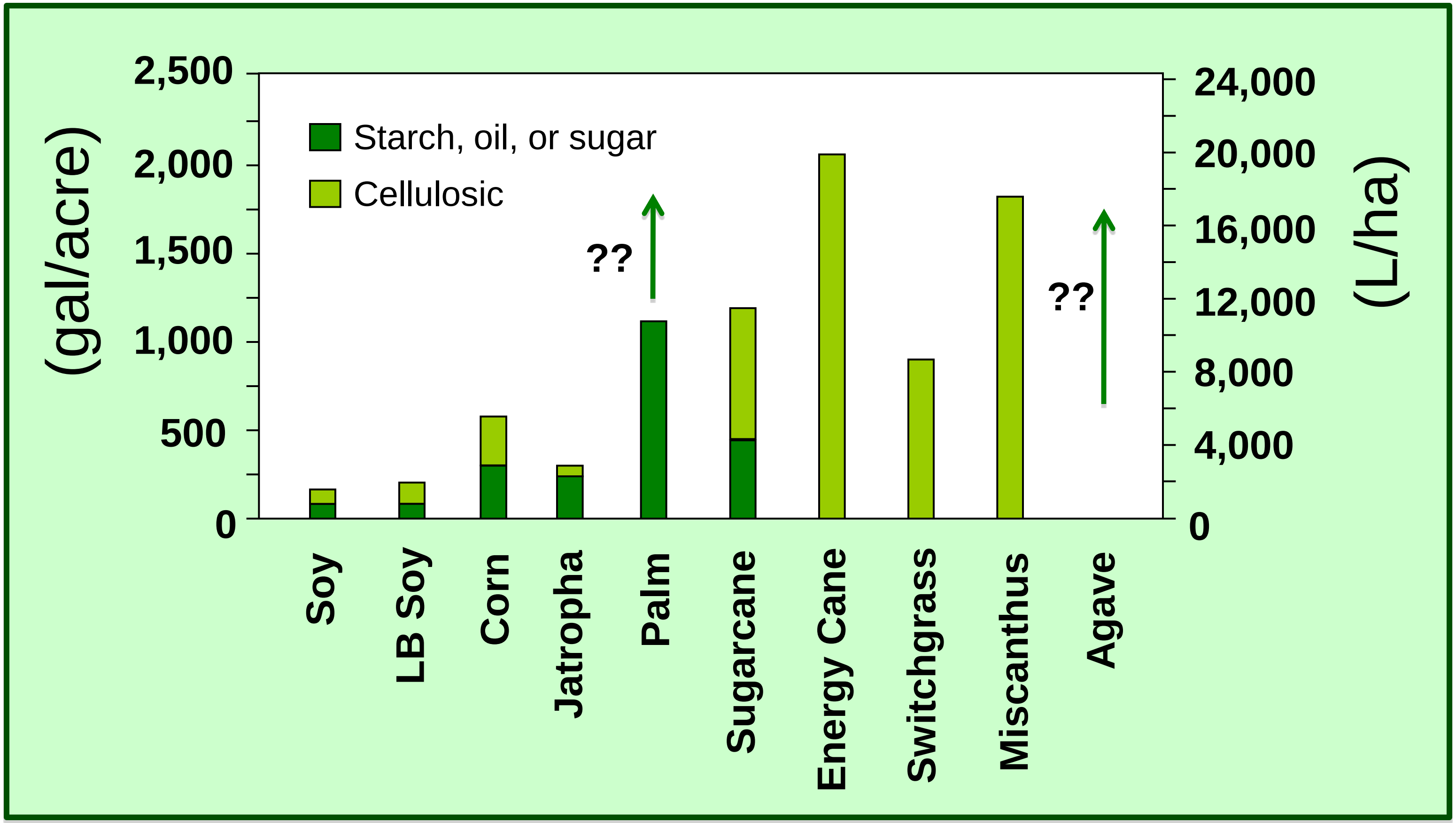
Energy Carrier	Representative Purchase Price: Common Units	$/GJ
Fossil		
Petroleum	$70/bbl	12.6
Natural gas	$10/kscf	11
Coal	$55/ton	2.5
w/ carbon capture @	$150/ton C	6.5
Electricity	$0.045/kWh	11 (generated)
	$0.085/kWh	23 (delivered)
Biomass		
Soy oil	$0.50/lb	30
Corn kernels	$3.5/bu	10
Sugar cane	$93/ton	6.0
Cellulosic crops[a]	$60/ton	4.0
Cellulosic residues		Most < 4

[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 Bioenergy Feedstocks



Acknowledging uncertainties & simplifications in single-valued representations, robust conclusions about land-efficient biofuel production can be drawn

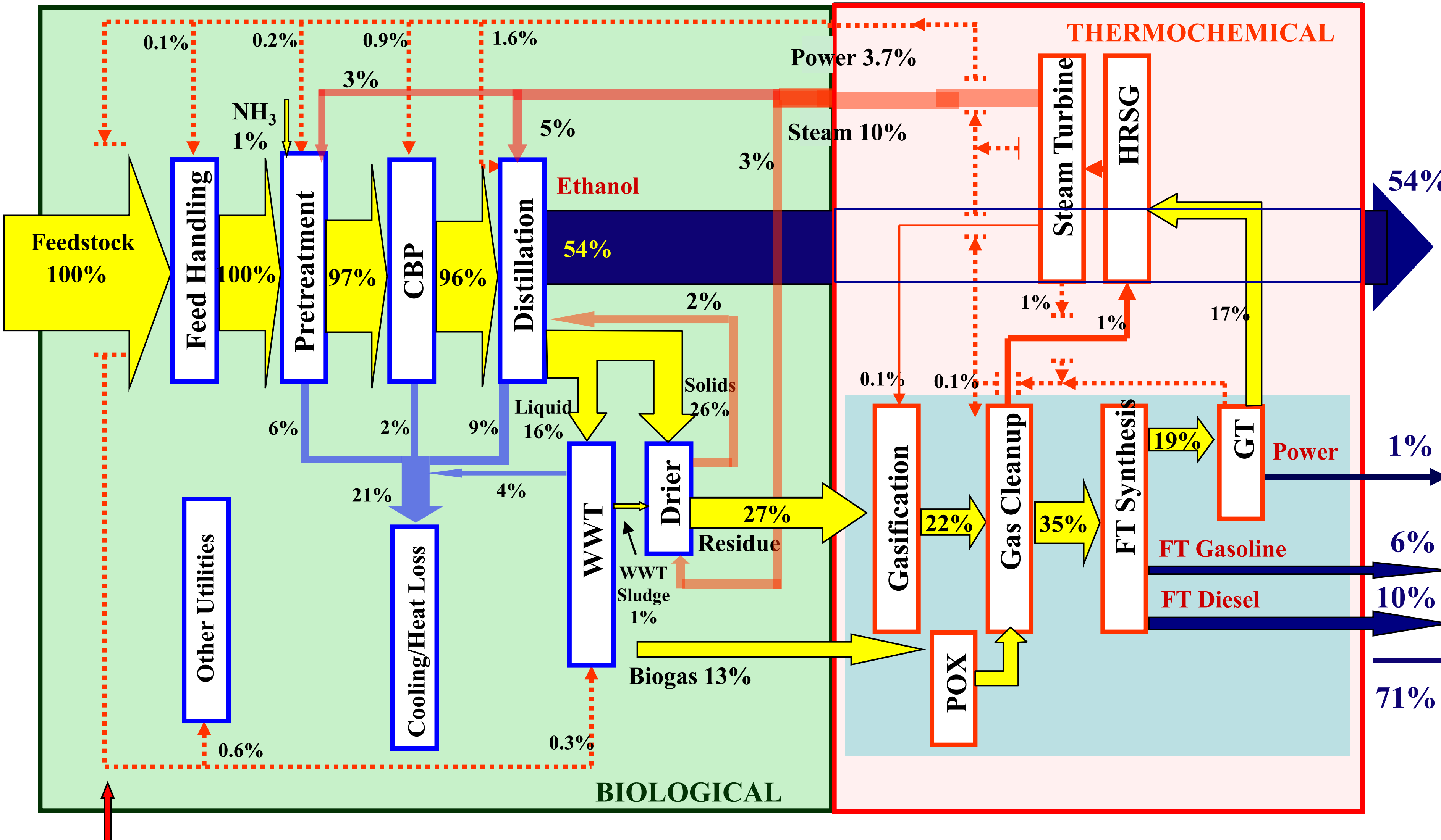
Harvest the whole plant

Grow plants with composition optimized for photosynthesis rather than accumulation of sugar, starch, or oil

Fundamental rather than incidental

Process Energy Flows (mature technology, RBAEF scenario)

Energy out:energy in very favorable for cellulosic & sugar cane biofuels



Ag Inputs (Farming, feedstock transport) ~ 7 %

Energy out/Energy in = 71/7 = ~10

Laser et al., BioFPr, 2009

Bioenergy and CO_2 Emissions

Potential for a carbon-neutral cycle
Carbon must be removed from the atmosphere by photosynthesis before biomass can be converted to fuel/electricity and exit a tailpipe/smokestack

Potential for carbon-negative cycle
Soil carbon accumulation - e.g. with perennial crops - can sequester carbon, as can CO_2 recovery from processing facilities

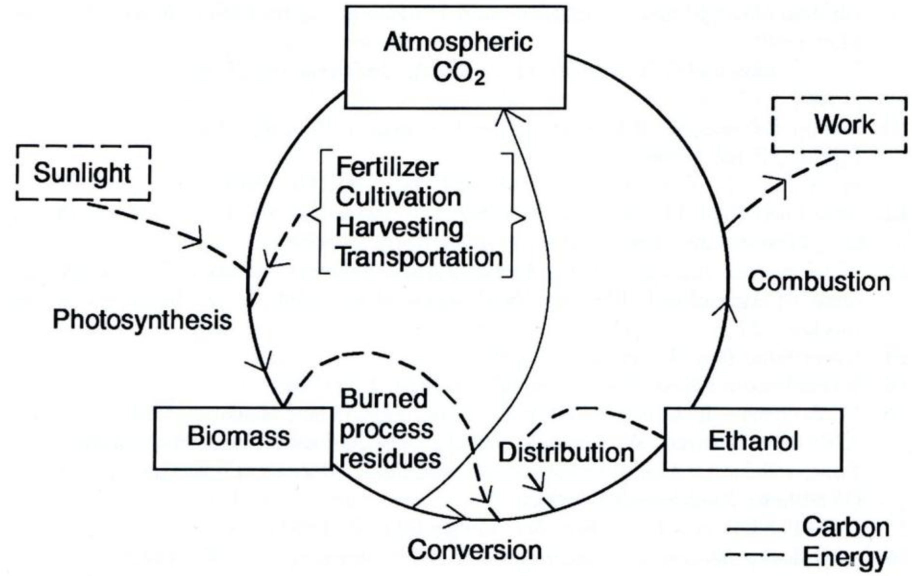


Fig. 2. Carbon and energy flows for production and utilization of fuel alcohol from biomass. [Adapted from (*53*) with permission of Humana Press, copyright 1989]

Lynd et al., Science, 1991

Tailpipe carbon capture not practical for mobile applications

Realization of the low carbon potential of bioenergy requires

Use low-carbon sources for process energy, e.g. process residues,

Avoid large carbon emissions in the course of land clearing

Notwithstanding its potential, anticipation and realization of large-scale cellulosic bioenergy production are impeded by two key factors:

Recalcitrance of cellulosic biomass

Difficulty of converting cellulosic biomass to reactive intermediates such as sugars or synthesis gas, addressable by improved processing technology

Land use concerns

Competition with food supplies

Carbon emissions & habitat loss from clearing of wild lands

Could we produce enough biomass to meaningfully impact “mega challenges”?

Focus of this talk, Global Sustainable Bioenergy Project

Strong Negative Assessments

"Use of biomass energy as a primary fuel in the United States would be impossible while maintaining a high standard of living" (Giampetro & Pimentel, 1990)

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

"Any substantial increase in biomass harvesting for the purpose of energy production would deprive other species of their food sources and cause the collapse of ecosystems worldwide" (Huesemann, 2004)

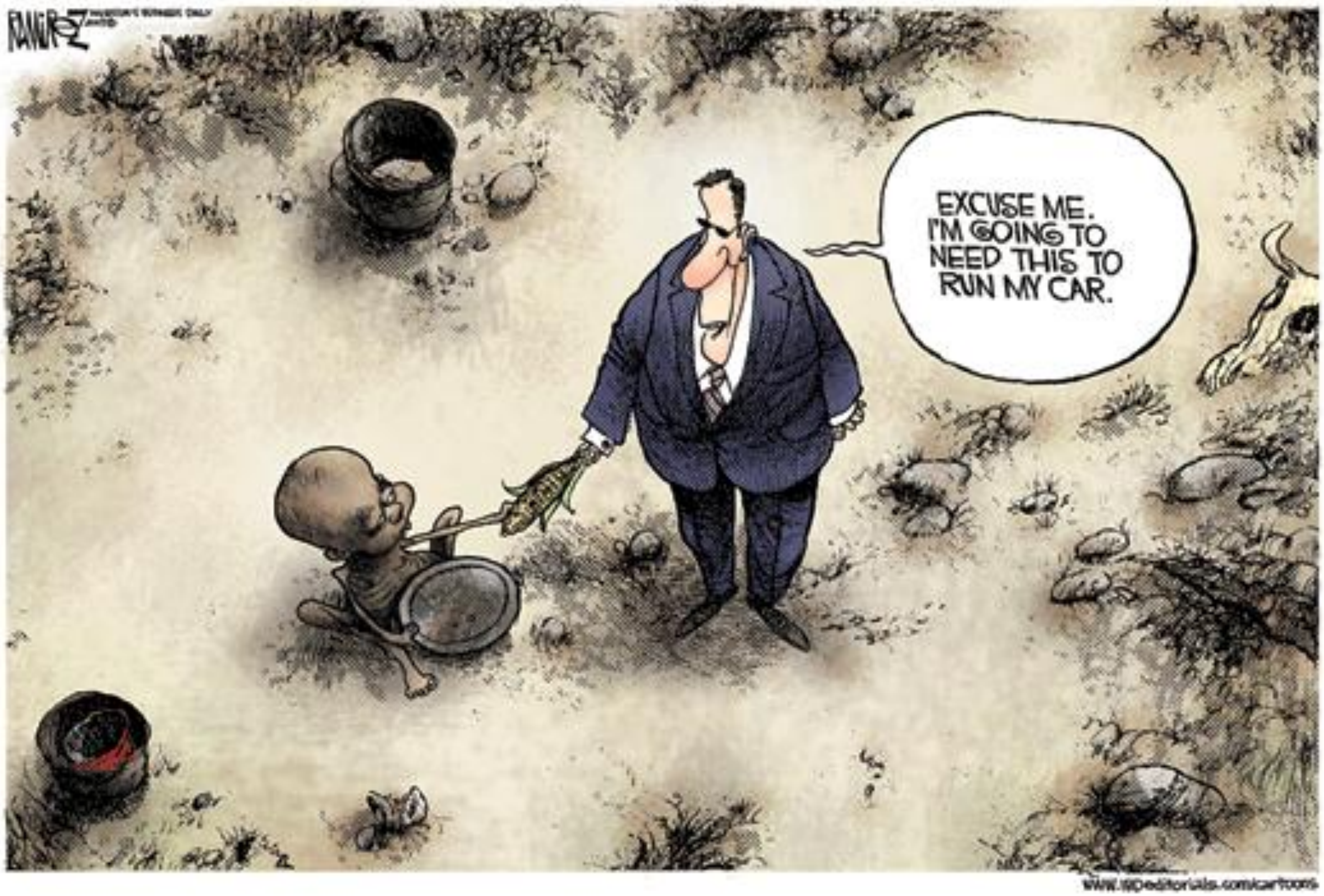
Impractically large land requirements for biomass energy production on a scale comparable to energy/petroleum use (Trainer, 1995; Kheshgi, 2000; Avery, 2006)

"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).

Strong Negative Assessments

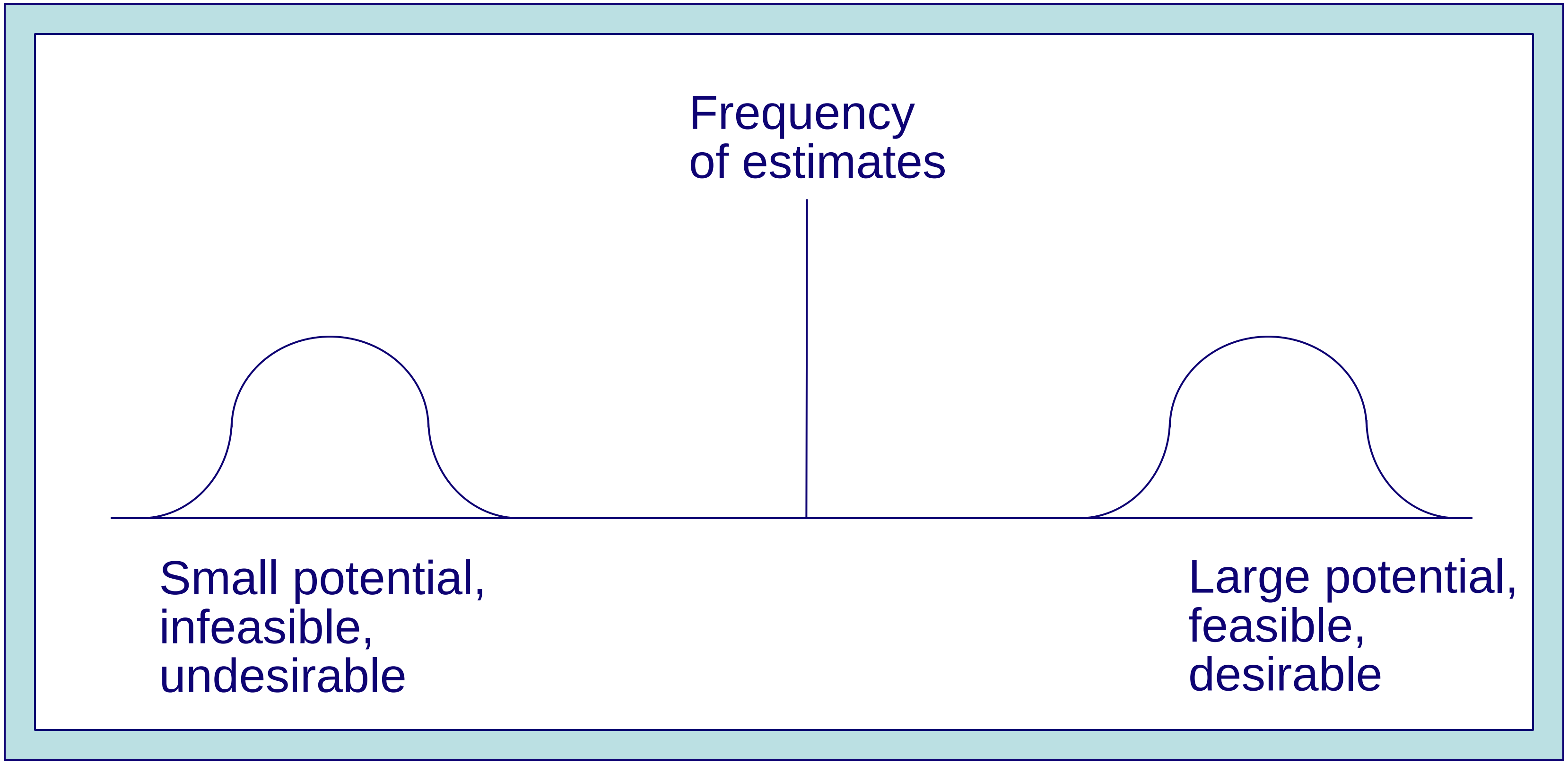
"[I]t's a crime against humanity to convert agricultural productive soil into soil… which will be burned for biofuel." (Jean Ziegler, UN Special Rapporteur, 2007)



There are also more positive assessments, considered subsequently

Sharply-Divergent Assessments of Bioenergy

Rather than clustering about a mean, estimates for the potential energy contribution of biomass exhibit a bimodal distribution with most such estimates envisioning a very small or very large energy supply role for this resource[1]



[1]Lynd et al. in Sovacol and Brown (eds.) Energy and American Society. Thirteen Energy Myths. Springer. 2007.

Sharply-Divergent Assessments of Bioenergy: Consequences

Policy makers are understandably confused

Absence of clear understanding leads to uncertainty with respect to

- Feasibility and desirability of a sustainable bioenergy-intensive future
- What should such a future look like?
- What should be done to realize it?

Strong and coherent support is difficult to motivate

We are likely

Underestimating & under-supporting meritorious options

Over-estimating & over-supporting non-meritorious options

Both – in light of the diversity of bioenergy feedstocks & processes

This is an unacceptable state of affairs in light of the urgency of the challenges inherent in the sustainability revolution

Sharply-Divergent Assessments of Bioenergy: Understanding

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

What is versus what could be. 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).

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

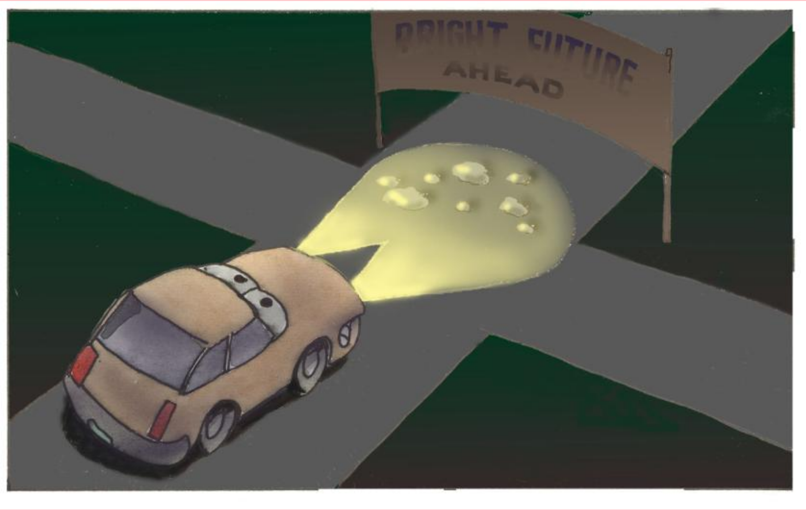
However, it is entirely unrealistic to expect to meet these challenges without both

Sharply-Divergent Assessments of Bioenergy: Understanding

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

What is versus what could be.

Low beam



High beam view

Sharply-Divergent Assessments of Bioenergy: Understanding

Many critics of bioenergy are responding to features of the substantial existing biofuels industry based on edible, 1st generation feedstocks.

Existing biofuel industries are in turn a response to government incentives motivated by a variety of objectives

- Rural economic development
- Energy security
- Balance of payments
- Large-scale sustainable energy supply

…of which the latter has seldom been the most important

Two key questions

Could we – that is, is it physically possible to – gracefully reconcile large-scale bioenergy production with feeding humanity, meeting needs from managed lands, and preserving wildlife habitat and environmental quality?

Must we produce bioenergy at large scale in order to have a reasonable expectation of achieving a sustainable world?

Prevailing view (my informal impression)

Could we? Maybe at best. See strong negative assessments.

Do we have to? Probably not. Many see bioenergy as at most an interim solution.

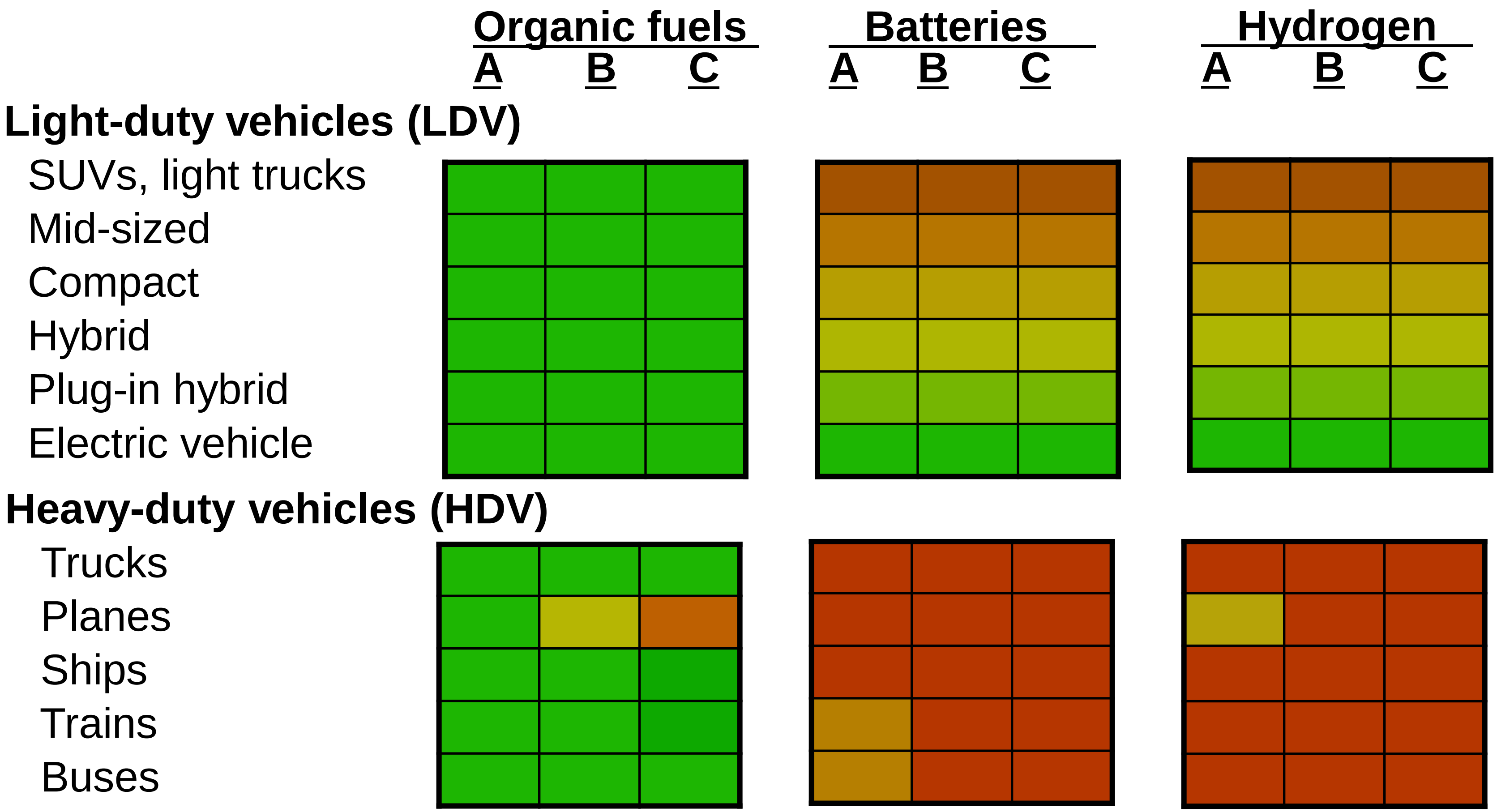
My view

Could we? Yes; Further documentation to be provided by the GSB project

Do we have to? Yes

Lynd, Bioenergy: In Search of Clarity, Submitted.

Must we produce bioenergy at large scale in order to have a reasonable expectation of achieving a sustainable world?



Electrification (batteries) impractical for planes, many heavy duty applications

With ultimate foreseeable electrification of LDVs, organic fuels still $\geq$ 50% transport energy

Hydrogen faces many challenges, particularly for HDV, low-C

Without biofuels, achieving a sustainable transportation sector is unlikely

Could we – that is, is physically possible to – gracefully reconcile large-scale bioenergy production with feeding humanity, meeting needs from managed lands, and preserving wildlife habitat and environmental quality?

Favorable indications – published studies

Biomass becomes the largest energy source supporting humankind by a factor of 2 by the middle of the 21st century (Johanssen et al., 1993)

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

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% US 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 US transport fuel demand (Perlack et al., 2005, *"Billion Tons Study"*).

30% EU transport demand by 2030 if 2nd generation lignocellulosic feedstocks grown on all areas available (REFUEL study, 2010)

Biomass the largest single energy source supporting humankind in 2050 (IEA, current "Blue Map" scenario, 50% reduction in CO_2 emissions)

Could we – that is, is physically possible to – gracefully reconcile large-scale bioenergy production with feeding humanity, meeting needs from managed lands, and preserving wildlife habitat and environmental quality?

Favorable indications – land limitation is not a show-stopper

“Most studies assume that only a small fraction of additional land is needed to feed the world’s growing population – from 6.5 billion at present to 9 billion in 2050 – and that most of the increase in food requirements will be met by an increase in agricultural productivity”. Doornbosch & Steenblik, OECD, 2007

A billion acres of abandoned agricultural land globally (Campbell et al., Env. Sci. Technol., 2008

Africa has 12 times the land area of India, similar land quality, 30% fewer people – yet India feeds itself and Africa does not. The green revolution bypassed Africa due to serious organizational and institutional weaknesses, not geographically-limited capacity (A. Temu, ICRAF)

Empirical evidence indicates that the majority – and by some credible evidence as much as three quarters - of earth's non-forest land area that is suited and available for rainfed agriculture without deforestation, lies fallow, abandoned or is underutilized due to primarily to political, socio-economic (market), and infrastructure constraints. (K. Kline, ORNL, manuscript in preparation)

Could we – that is, is physically possible to – gracefully reconcile large-scale bioenergy production with feeding humanity, meeting needs from managed lands, and preserving wildlife habitat and environmental quality?

Favorable indications – in progress analysis and sketches

Crop residues burned in China would exceed current transportation energy demand if converted to fuel (Yan et al., 2006, 2009).

Grass burned in South Africa: 21 million tons annually, biofuel potential = 7 billion liters gasoline equivalent (54% SA petrol consumption, 39% SADC petrol)

Double crops and changed animal feed rations based on leaf protein recovery

Potential exceeds 67 billion GGE (gal gasoline equivalent) in the U.S., ~50% current consumption (Bruce Dale & colleagues, Michigan State University)

Photo: A. Heggenstaller, M. Liebman, R. Anex, Iowa State University

Could we – that is, is physically possible to – gracefully reconcile large-scale bioenergy production with feeding humanity, meeting needs from managed lands, and preserving wildlife habitat and environmental quality?

Favorable indications – in progress analysis and sketches

Pasture intensification

Brazil: 200 million ha used for beef grazing now (1 animal per hectare), 4 million ha to grow sugar cane for ethanol. Doubling grazing intensity → 100 million ha → biofuel production potential ~2/3 global demand

(100 million ha) x (25 tonnes/ha) x (91 gal GGE/ton) = 228 billion gal gasoline equiv.

Global consumption (exclusive of diesel) : 330 billion gal gasoline

Estimates for the potential of Brazilian biofuel production – e.g. 5 to 10% global petrol – appear to me to be constrained by politics rather than geography

US: Biofuel production potential of similar magnitude would result from increasing the productivity of grazing lands to that of currently harvested forage in the same county, likely an underestimate of the overall potential for pasture intensification (based on analysis by Peter Vadas, US Dairy Forage Research Centre)

Global: Replacing current global petroleum use would require about 10% of pasture land with high but achievable biomass productivities and process yields (Richard Hamilton, Ceres)

Could we – that is, is physically possible to – gracefully reconcile large-scale bioenergy production with feeding humanity, meeting needs from managed lands, and preserving wildlife habitat and environmental quality?

Favorable indications – in progress analysis and sketches

Dietary change (Ethan Davis, Lee Lynd et al.)

Halving US beef consumption with replacement by poultry would make available an amount of land with biofuel potential commensurate with global gasoline consumption.

Land required per kg beef protein is ~ 50 times greater than that required per kg poultry.

Many people will likely eat higher on the food chain rather than lower. However, the kind of animal protein people eat makes considerably more difference than the amount in terms of land requirements.

Could we – that is, is physically possible to – gracefully reconcile large-scale bioenergy production with feeding humanity, meeting needs from managed lands, and preserving wildlife habitat and environmental quality?

Favorable indications – in progress analysis and sketches

Integrating bioenergy production with addressing other challenges

Decreasing the time required to regenerate fertility is a potentially powerful strategy to minimize impacts of slash-and-burn agriculture, particularly if coupled with revenues. (Peter Manang, Alternatives to Slash and Burn Agriculture Partnership)

The magnitude of soil carbon accumulation under temperate perennial grasses can be comparable to the magnitude of avoided emissions that would result from high-yield biofuel production from that grass (calculated from literature studies, Mark Laser & Lee Lynd, Dartmouth)

Improve water quality by incorporating perennial and/or double crops into the landscape (Chesapeake Bay Commission)

Alleviating causes of food insecurity

Bioenergy and Food Security

Could biofuel production be part of the solution to pressing food security and poverty alleviation challenges?

Potentially yes, more likely/extensively with 2nd generation feedstocks

Challenging, relatively underexplored, first step is to show it is possible

Problem	Solutions
African Food Insecurity	**Alleviate Poverty** • All wealthy people have access to food • All hungry people are poor

Bioenergy and Food Security

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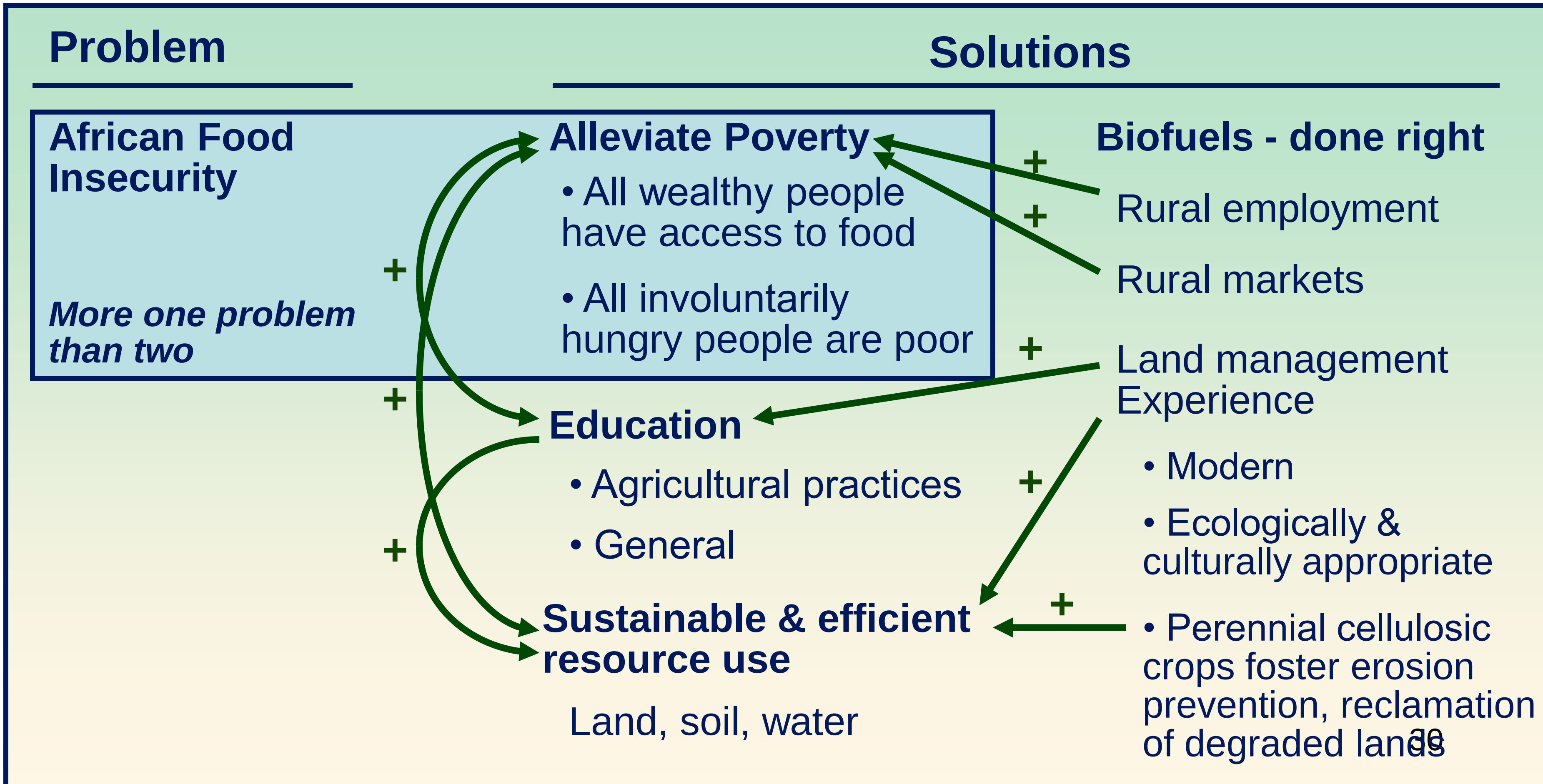
Relatively underexplored



Bioenergy and Food Security

Factors Contributing to Food Insecurity*

Food Security Impact of Biofuel Production

Cellulosic Crops

Food crops | Cropland | Non-cropland

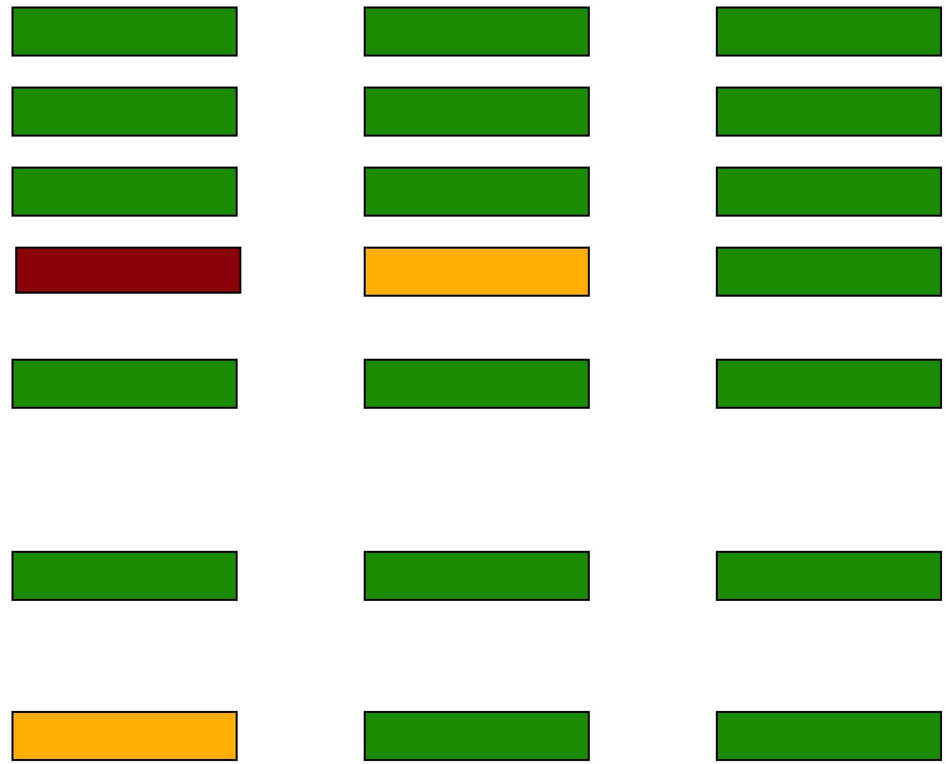
Poverty

- Rural unemployment
- Lack of marketable skills
- Low currency value
- High food prices

Local production undermined by foreign subsidies

Poorly developed ag. infrastructure (Physical, market, knowhow)

Degraded land



Bioenergy has clear potential to be developed in ways that are responsive to … [African] … challenges, including enhancing food security, but could also be developed in ways that exacerbate them." African GSB Convention

* Thurow, R, S. Kilman. Enough: Why the World's Poor Starve in an Age of Plenty. 2009. Public Affairs.

Bioenergy from Land that Can't Grow Food Crops

Example: Agave (Sisal)
5 to 10 times higher water use efficiency than most other plants due to understood mechanisms (crassulacean acid metabolism)

Although much remains to be done to evaluate (& implement If warranted), exciting potential for multiple benefits…

- Low-carbon, indigenous energy production
- Improved balance of payments and currency valuation
- Rural employment & economic development
- Land reclamation & carbon sequestration?

… in many of the world's poorest areas

Photo: Arturo Velez, The Agave Project

Could we – that is, is physically possible to – gracefully reconcile large-scale bioenergy production with feeding humanity, meeting needs from managed lands, and preserving wildlife habitat and environmental quality?

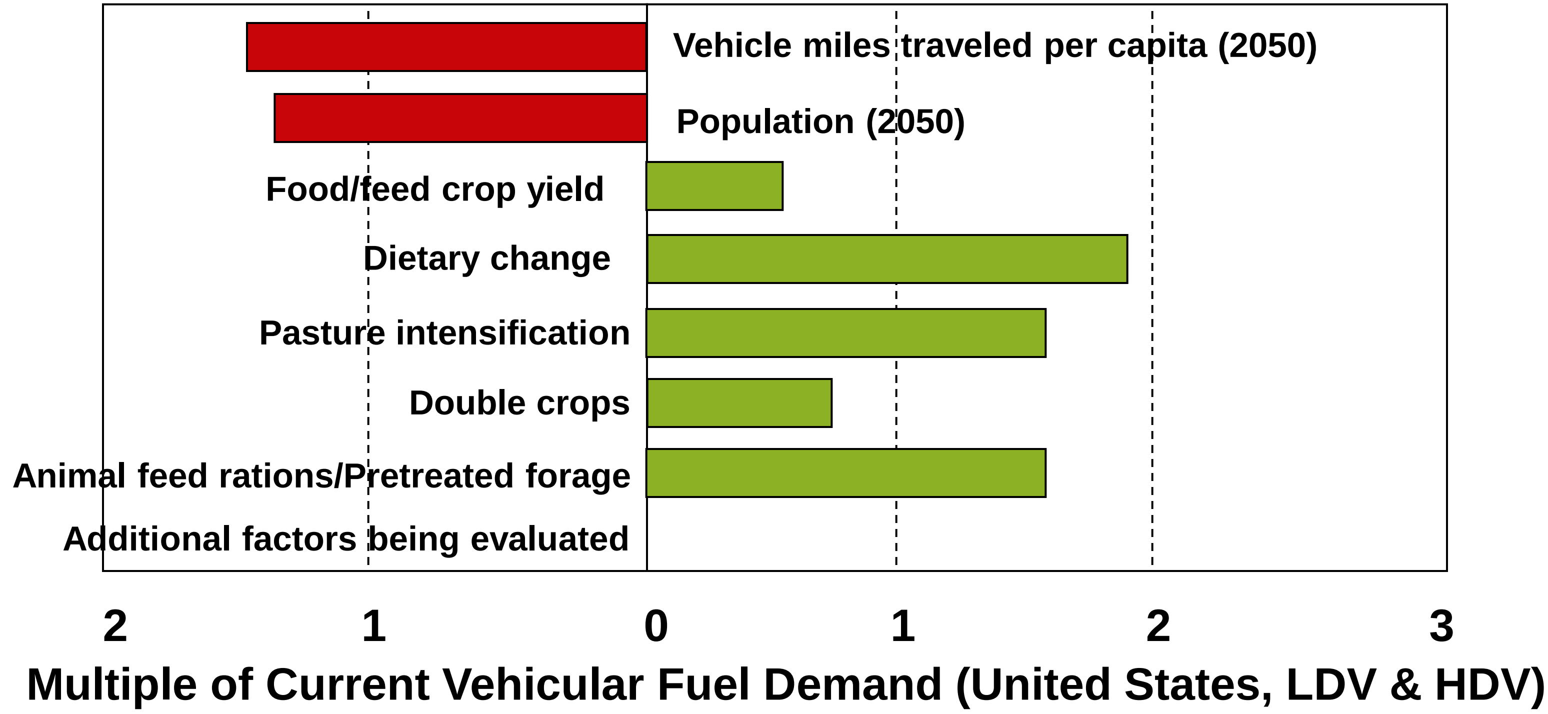
Favorable indications – in progress analysis and sketches

Factors that make satisfying mobility demand with bioenergy **more difficult**

Factors that make satisfying mobility demand with bioenergy **easier**

Current Vehicle Efficiency

Projected switchgrass productivity



Could we – that is, is physically possible to – gracefully reconcile large-scale bioenergy production with feeding humanity, meeting demands from managed lands, and preserving wildlife habitat and environmental quality?

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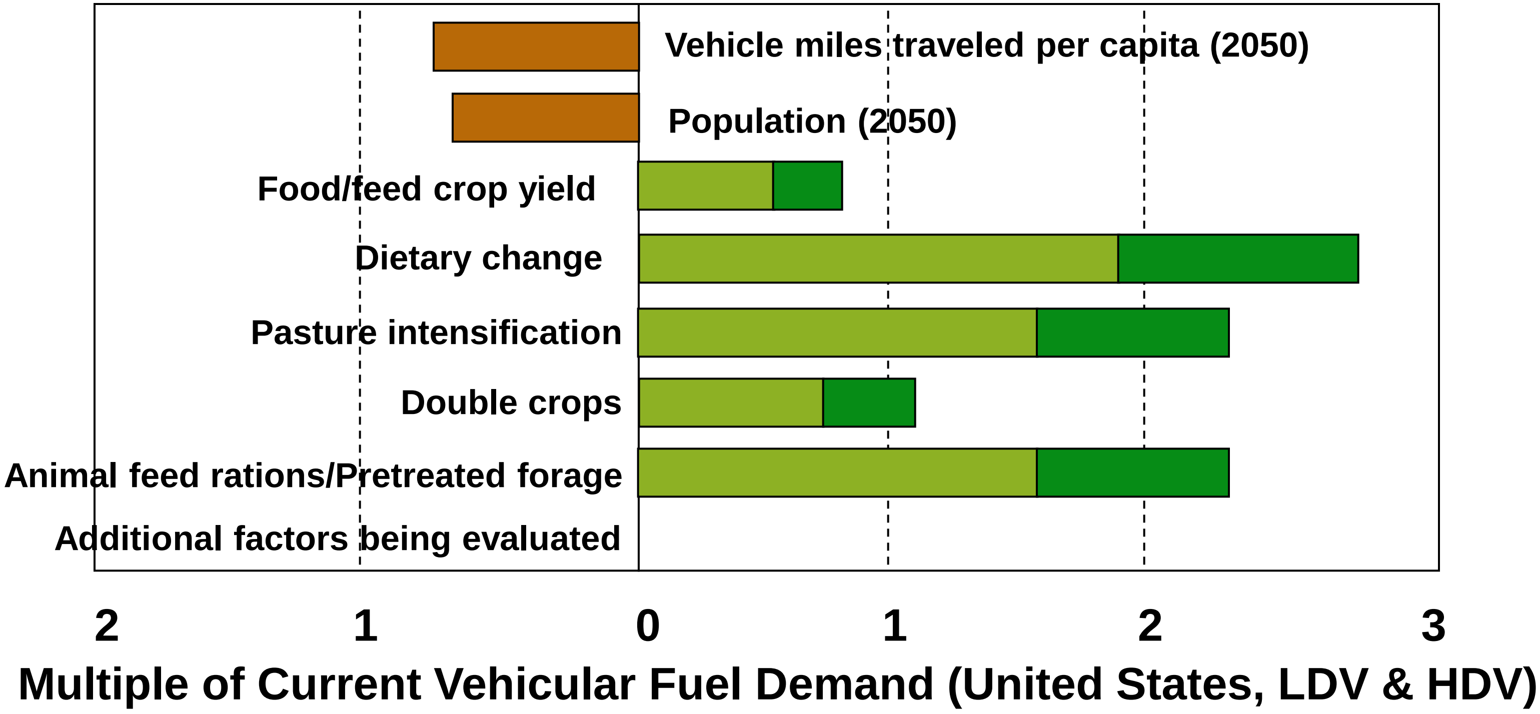
Current Vehicle Efficiency

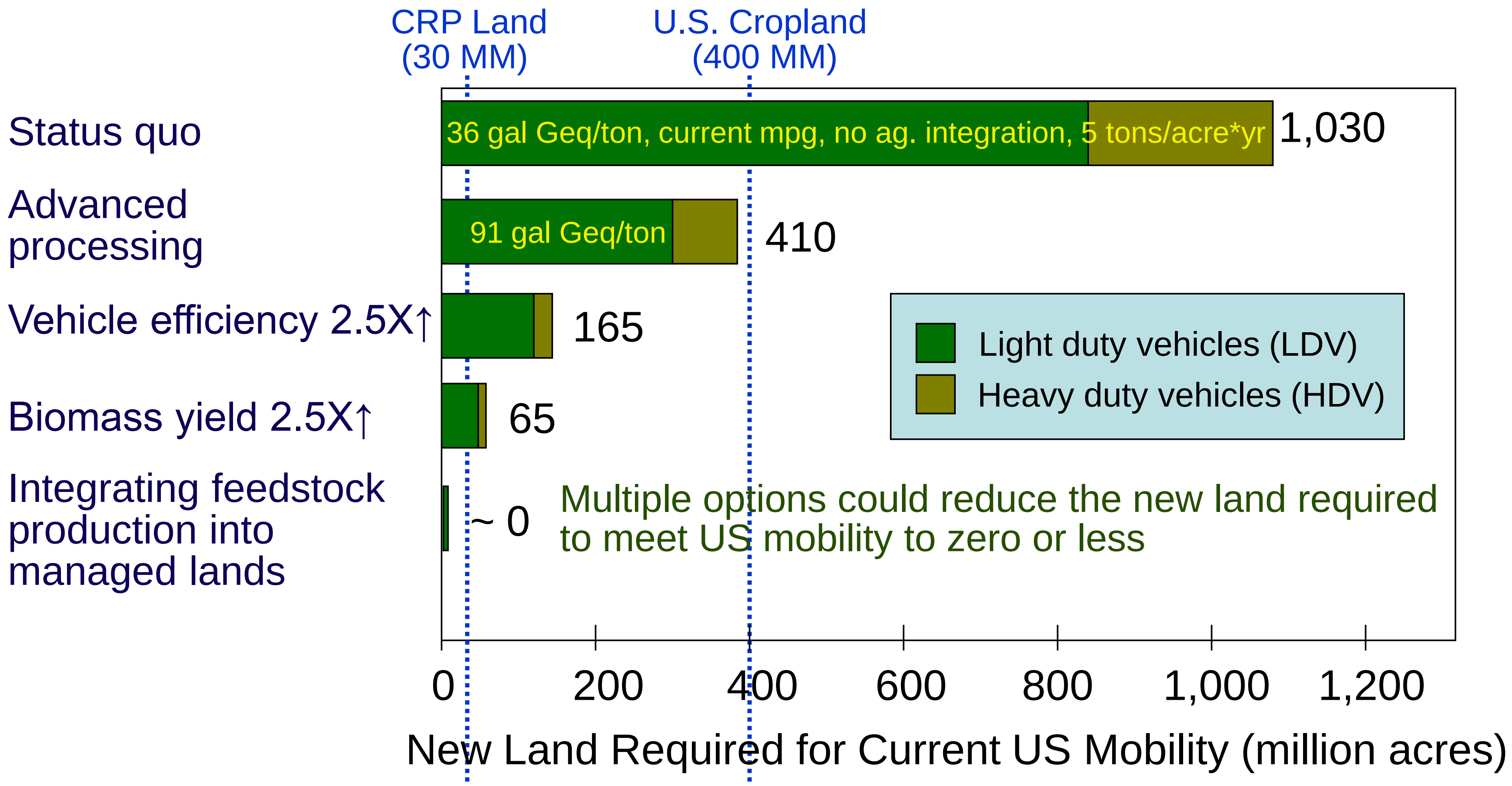
2 x Vehicle Efficiency

Projected switchgrass productivity

1.5 x projected switchgrass productivity



Multiple, complementary changes leading to a biofuel-powered transportation sector from managed lands (US)



Modified from Lynd et al., “13 Energy Myths”, Springer, 2007.

Future-Centered World View	Present-Centered World View
Business as usual	
A fantasy. The sustainability revolution is unavoidable, our responsibility to address	Basis for planning
Point of reference	
A sustainable future very different from the present - land use, economics, technology	Current reality
Analytical framework	
Systemic solutions to systemic challenges, multiple complementary changes	Marginal analysis : single changes (e.g. biofuels), extrapolate other trends
Renewable energy supply & efficiency	
Assumed, even if currently improbable, because there is no other way (footprint)	Not assumed because not currently probable
Bioenergy	
Regarded favorably because of potential for new technology and because we likely need it to achieve a sustainable world	Unfavorable: limits of current technology and practice, assumption that change to achieve graceful integration won't happen
Key criticism of the other paradigm	
Does not offer a solution	Not consistent with current reality

Future-Centered World View	Indirect Land Use Change View
Business as usual	Basis for planning
Point of reference	Current reality
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Future-Centered World View

Head in the Sand World View

“GSB” World view

(http://engineering.dartmouth.edu/gsbproject/)

Head in the Sand World View

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"GSB" World view (http://engineering.dartmouth.edu/gsbproject/)	**Head in the Sand World View**
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Which criticism is more damming?