Technological, Climate Change and Sustainability Aspects of Future Transportation Fuels

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May 2008
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Ethanol Today:

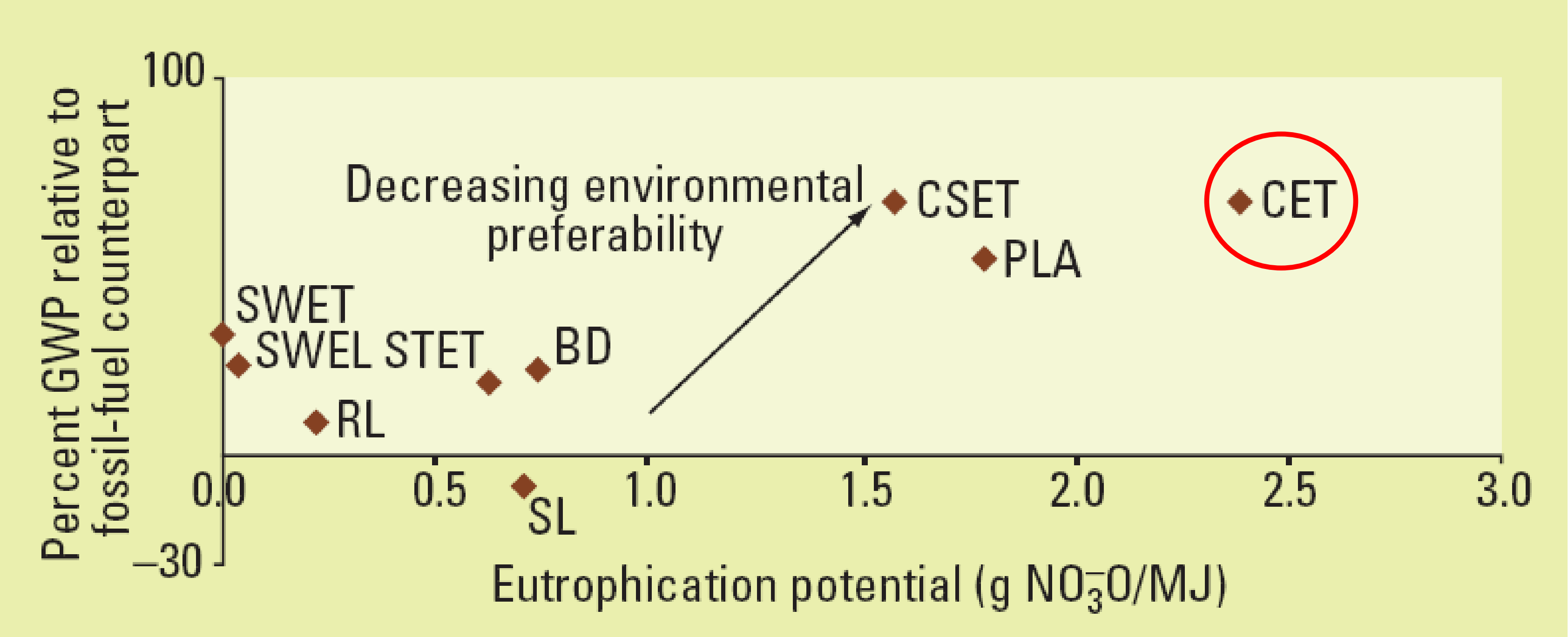
- Currently > 6 million flexible fuel vehicles (US/Can)
  - Run on up to 85% ethanol (by volume)
- Produced from corn grain, *starch*-based technology
  - Co-products key in production economics
  - US: 7.8 billion gal in 2007 (2% energy in transportation)
- Future expansion limited to 15-18 billion gal (corn)
- Policy initiatives to stimulate advanced biofuels
  - U.S. EPAct 2005; EISA, 2007: 21 billion gal cellulosic ethanol/biofuel by 2022, beginning in 2016
  - California: Low Carbon Fuel Standard

Source: F.O. Licht 2006, RFA 2008, Corn Grower's Association (2007)

Ethanol: Energy and Environment

- Over its life cycle, compared to gasoline, corn ethanol:
  - Significantly reduces petroleum use (~95%), moderately lowers (13%) fossil energy use (Farrell et al. 2006);
  - potentially **increases** overall GHG emissions due to indirect land use change (Searchinger et al., 2008)
  - GHG reduction and co-product credits (Groode and Heywood 2006)
- Only *lignocellulosic ethanol* offers large reductions in fossil energy use/GHG emissions AND large production volume (Farrell et al. 2006)
- Lignocellulosic ethanol LCAs:
  - Sheehan et al. (2004); Spatari et al. (2005); GREET (Argonne)
- Research Gaps:
  - Many ethanol conversion technologies
  - Variation in technological and "sustainability" performance
  - Uncertainty

Conflicting Sustainability Criteria



Miller et al. (2007)

Sustainability issues:

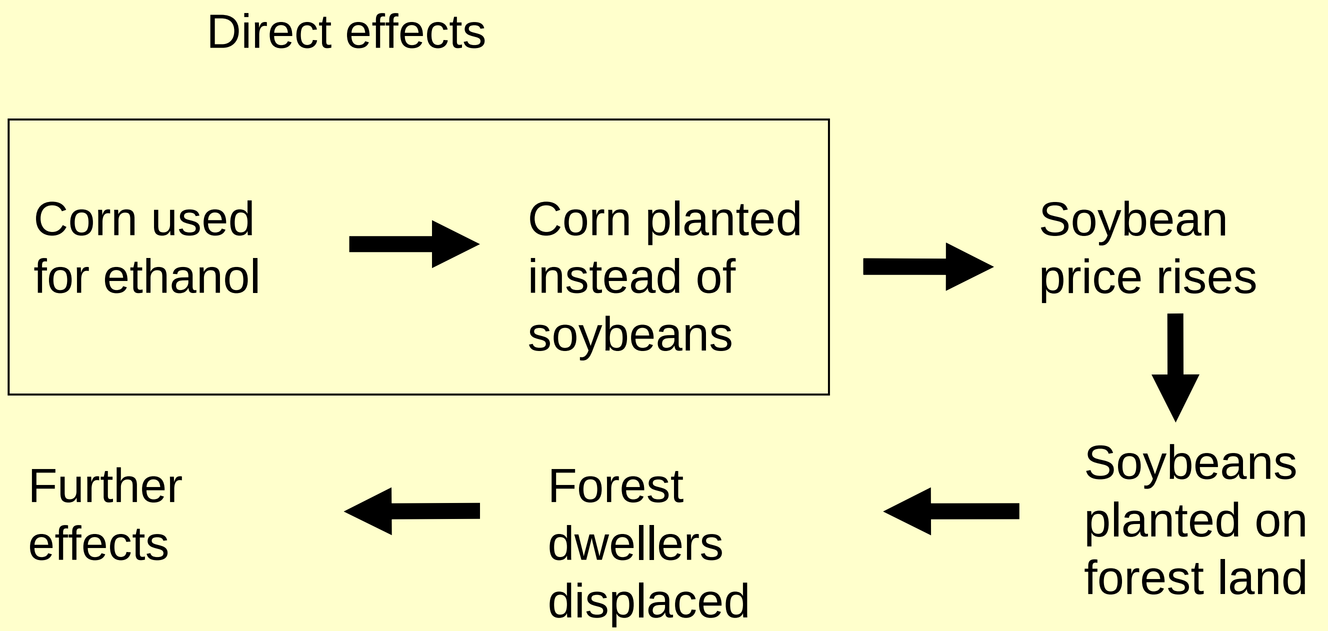
Sustainability criteria[1]	
Ecological	**Socio-economic**
Water use	Food and energy security
Water pollution	Land tenure
Organic pollutants	Net Employment
Agro-chemicals	Income distribution
Biodiversity	Wages
Soil erosion	Working conditions
Fertilizer use	Child labor
GMOs	Social responsibility
GHGs/energy input	Competitiveness
Harvesting practices	Culture - Traditional way of life

[1]Direct + Indirect

Scale: Regional, national, global

Market Mediated Effects:

- **Indirect land use change (LUC) scenario:**



- Use computational general equilibrium model (CGE) to determine indirect LUC, but this is far from actual sustainability measures

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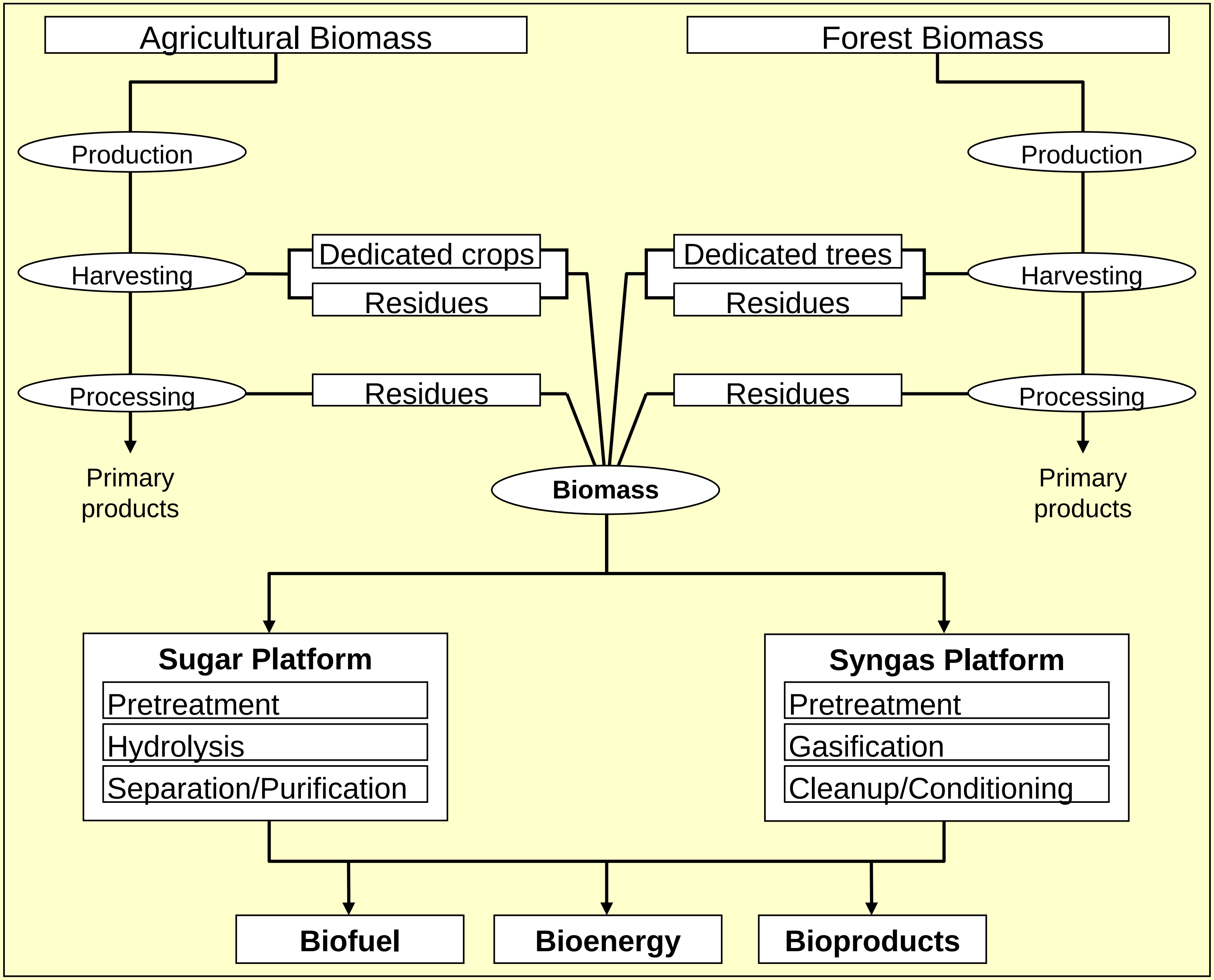
Biorefinery Production Pathways



Mabee et al., 2004

Lignocellulosic Ethanol

- Lignocellulosic feedstocks contain
  - **Cellulose**
  - **Hemicellulose**
  - **Lignin**

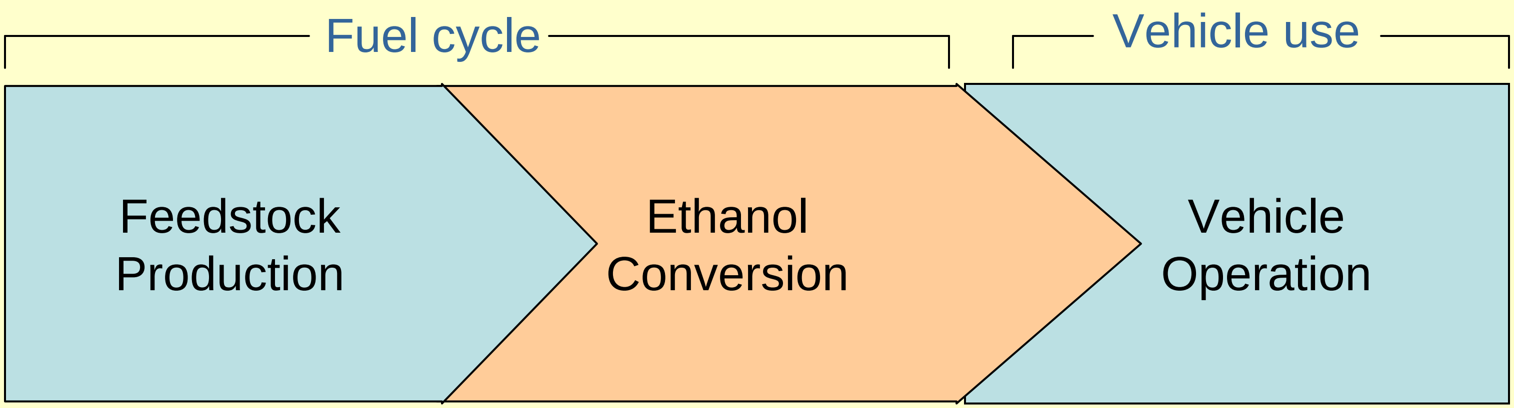
  Energy crops (e.g., switchgrass), agricultural and forest/ mill residues, municipal solid waste
- Advanced biotechnology performs hydrolysis then fermentation on cellulose/hemicellulose fraction
  - **Lignin portion of biomass utilized for energy (co-product)**
- Not yet at commercial scale

Technological Challenges

- Key challenges for R&D:
  - Overcoming the "recalcitrance" of the cellulosic feedstock (Stephanopolous, 2007)
  - Improving enzyme performance
    - Improving enzyme specific activity (FPU/g cellulase)
  - Reducing enzyme costs
  - Reducing pretreatment chemical costs (Himmel et al, 2007)
- Result in improved yields, better cost performance
- But, still much uncertainty in performance

Stephanopolous, 2007, Science. 315:801-804; Himmel et al., 2008, Science. 315:804-807

Life Cycle Model



- Fertilizer
- Herbicides
- Harvesting operations

<u>Feedstocks:</u>
- Corn stover (CS)
- Switchgrass (SG)
- Douglas fir (Df)

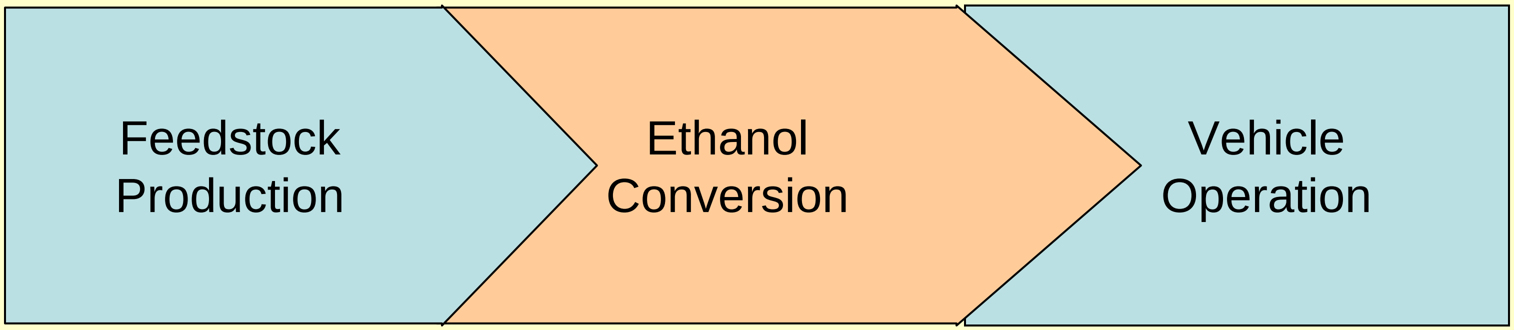
- Pretreatment chemicals
- Enzymes
- Nutrients

<u>Technologies:</u>
- Dilute acid (NREL)
- Ammonia fibre explosion (AFEX)
- Steam explosion (SE)
- Organosolv (OS)
- Enzymatic Hydrolysis
- Fermentation

- Blending with gasoline
- Vehicle operation

<u>Vehicles:</u>
- Ethanol-fueled vehicle (E85)
- Reformulate gasoline-fueled vehicle (RFG)

Life Cycle Model



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Life Cycle Model

Feedstock Production → Ethanol Conversion → Vehicle Operation

Feedstock Production
- Fertilizer
- Herbicides
- Harvesting operations

Ethanol Conversion
- Pretreatment chemicals
- Enzymes
- Nutrients

Vehicle Operation
- Blending with gasoline
- Vehicle operation

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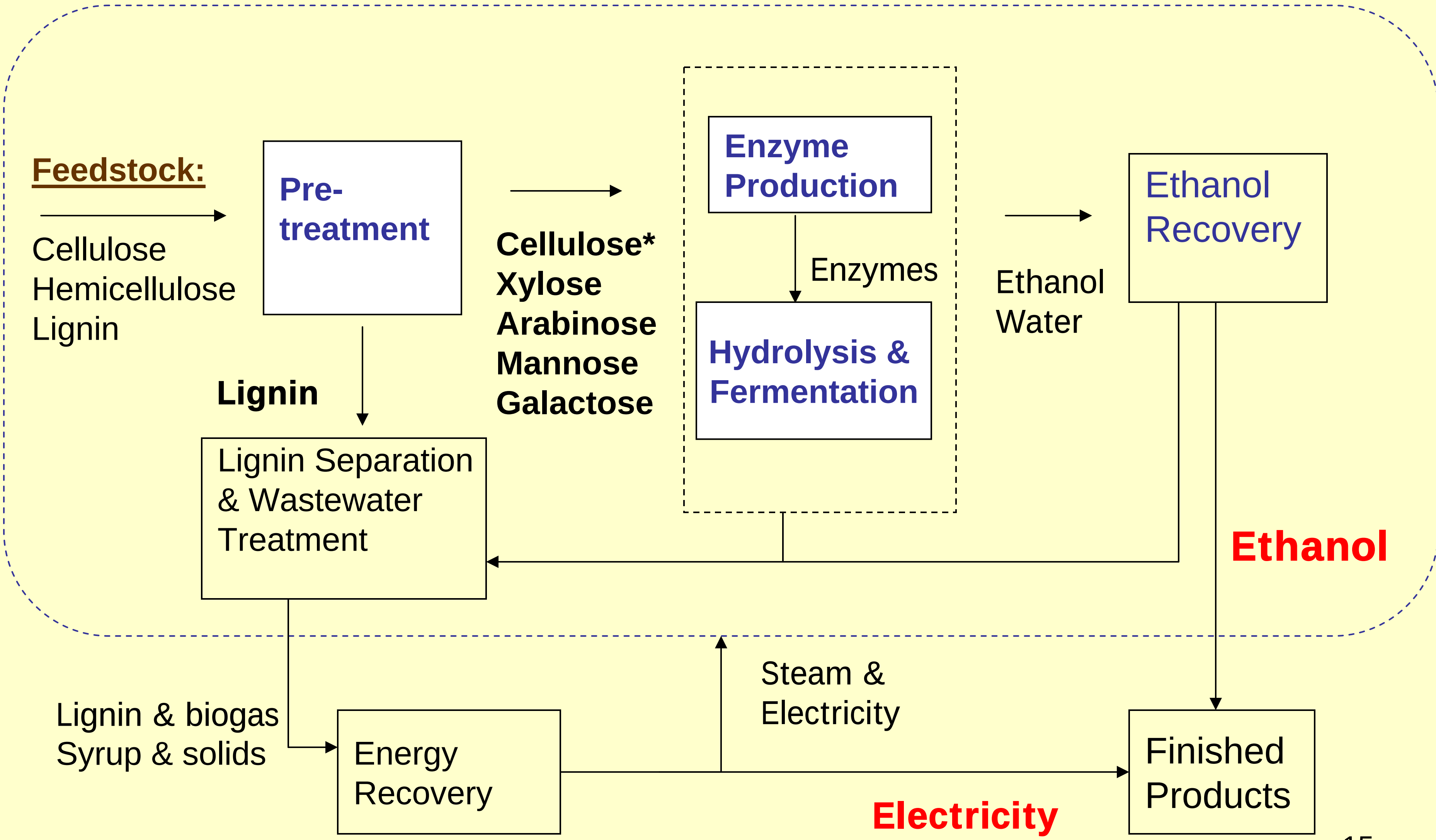
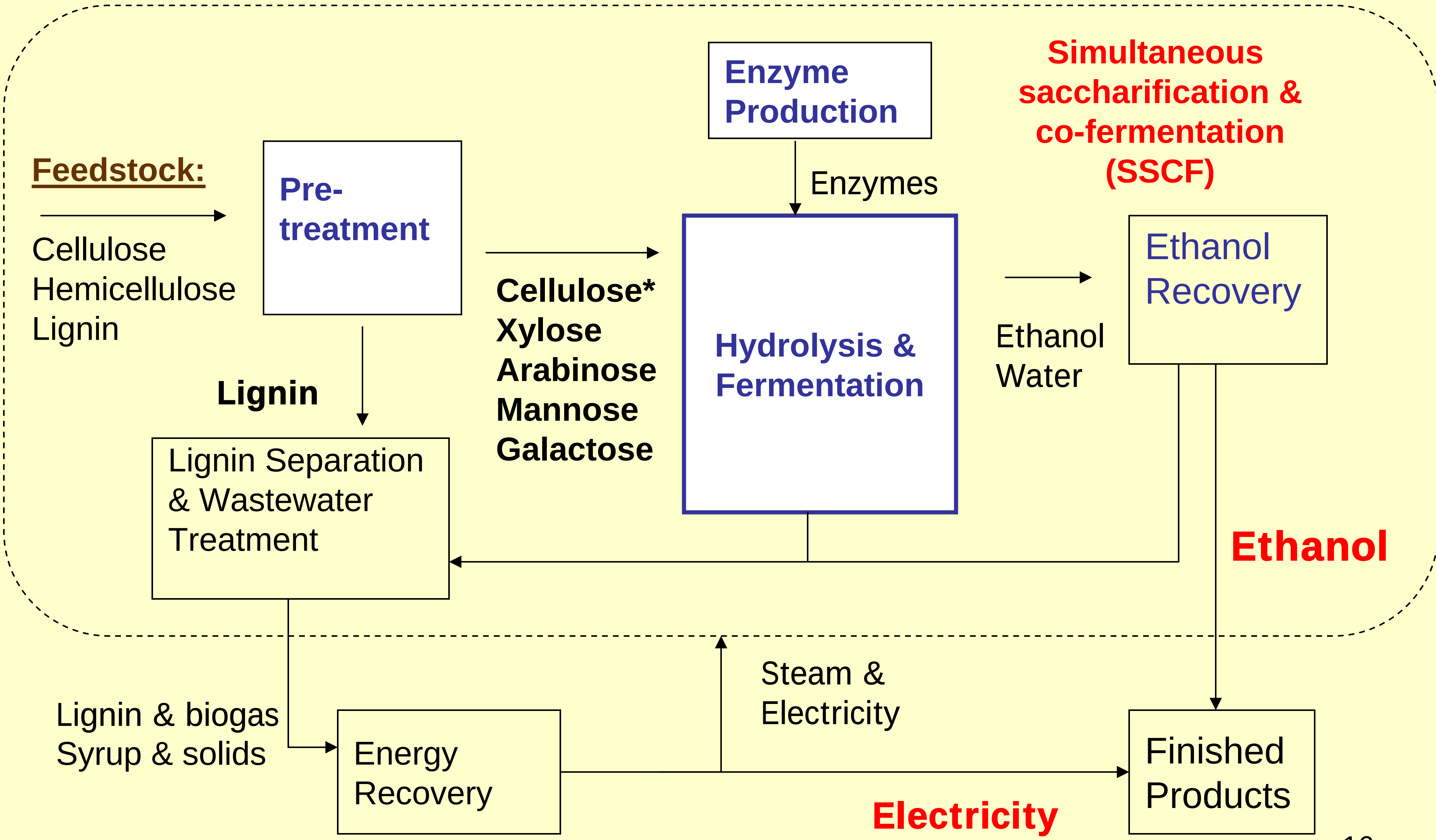
Ethanol Conversion Model



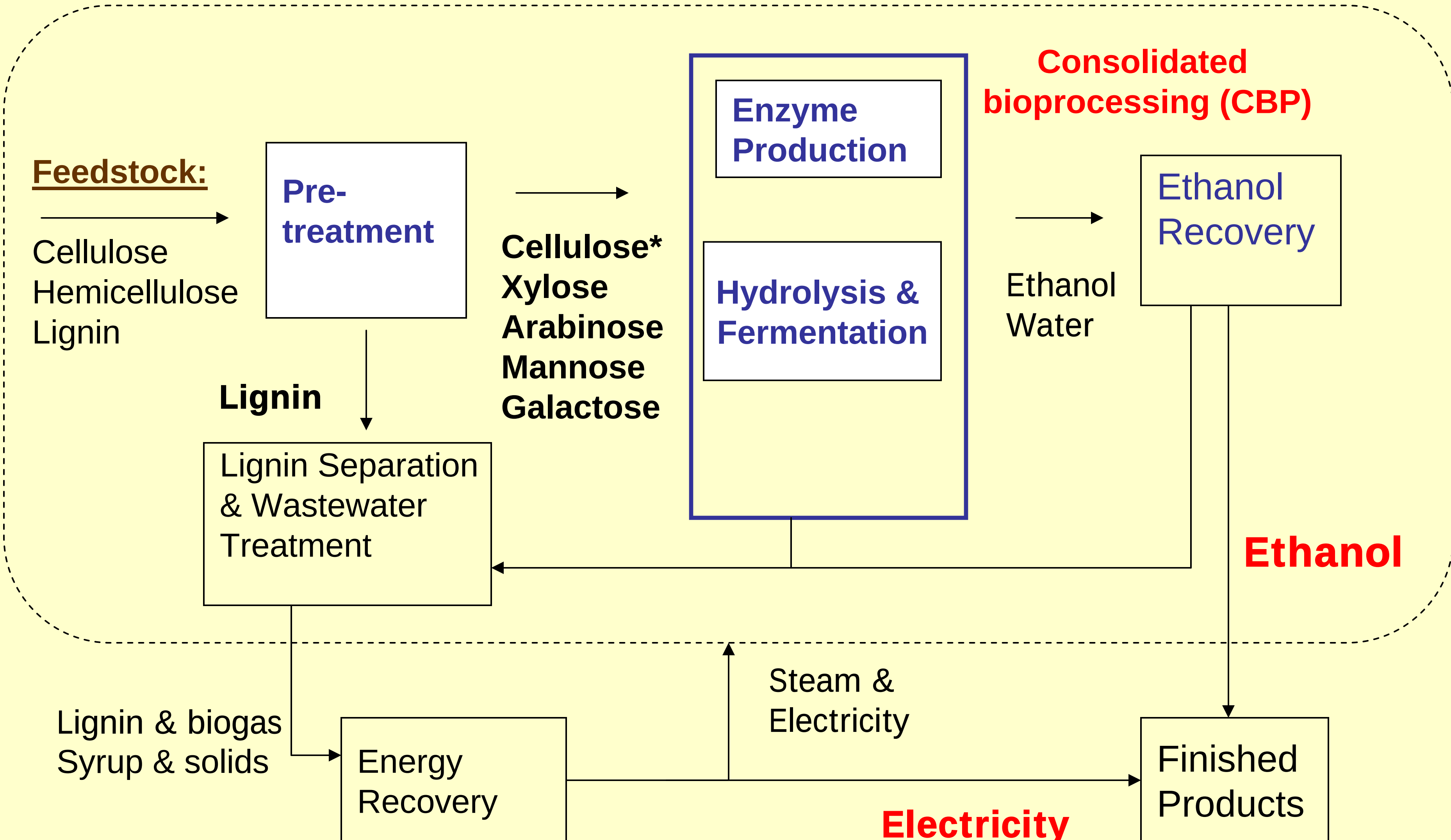
* Pre-treated cellulose

Ethanol Conversion Model: Near-term



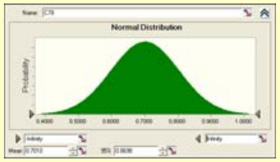
* Pre-treated cellulose

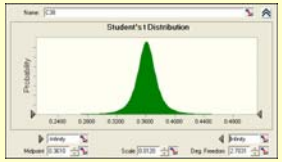
Ethanol Conversion Model: Mid-term

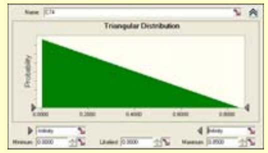


* Pre-treated cellulose

Model Equations & Variables: Performance







x_1 y_2 y_3…

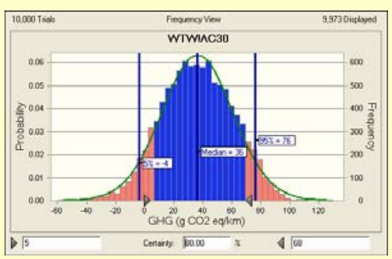
Ethanol (Y_i) = f(x_1, x_2, x_3;y_1,y_2…)

Electricity (E_b) = g(x_1, x_2, x_3; y_1 …)

→ Ethanol yield, Y_i (L/metric ton)

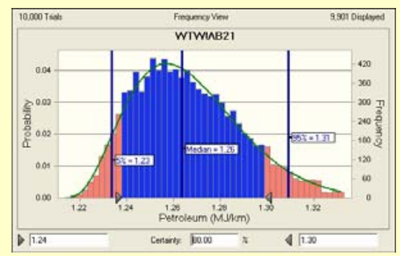
→ Electricity capacity, E_b (MW)

Sample model results



__9 ethanol conversion variables:__

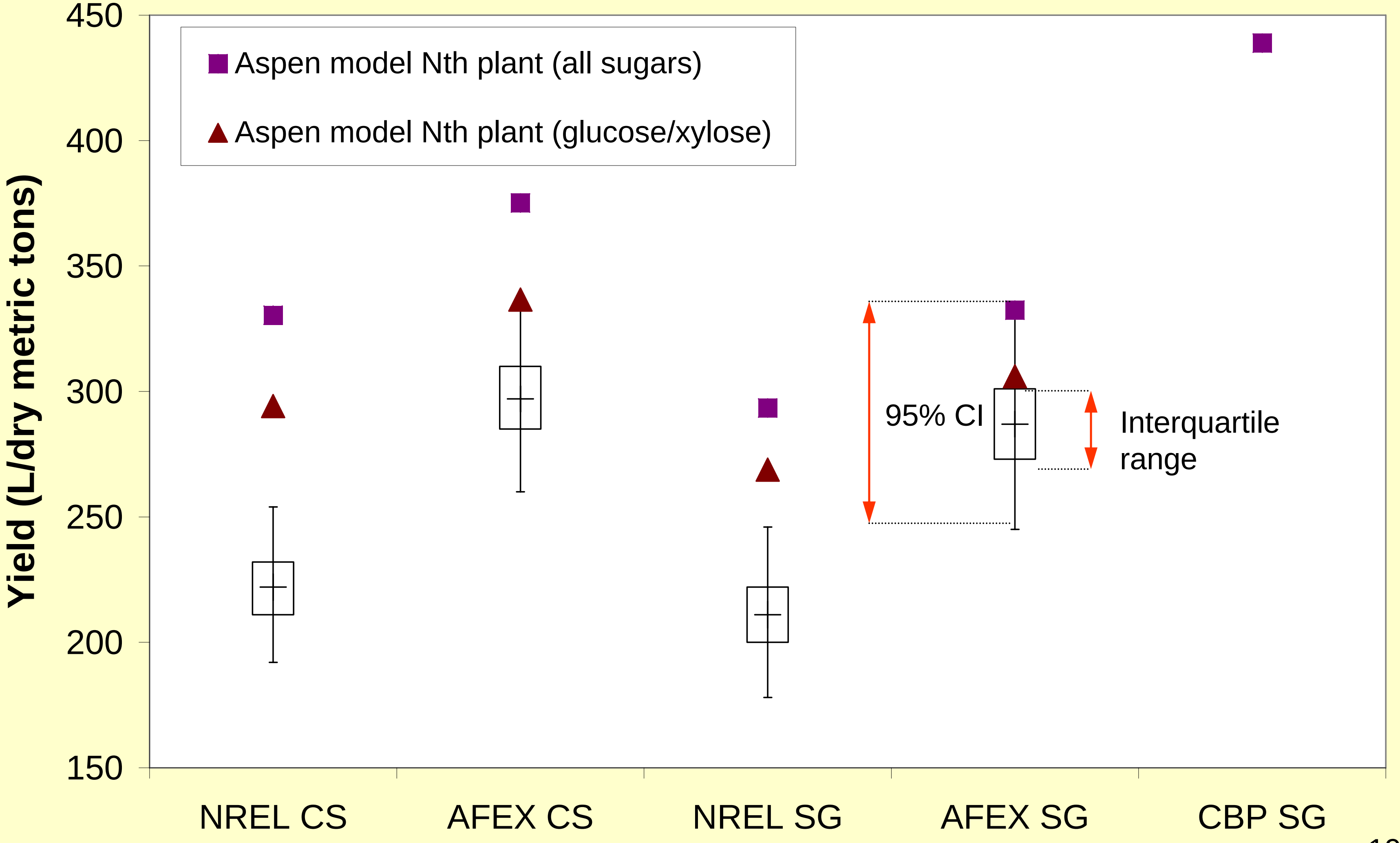
Feedstock	(2)
Pre-treatment	(1)
Hydrolysis	(1)
Fermentation	(5)



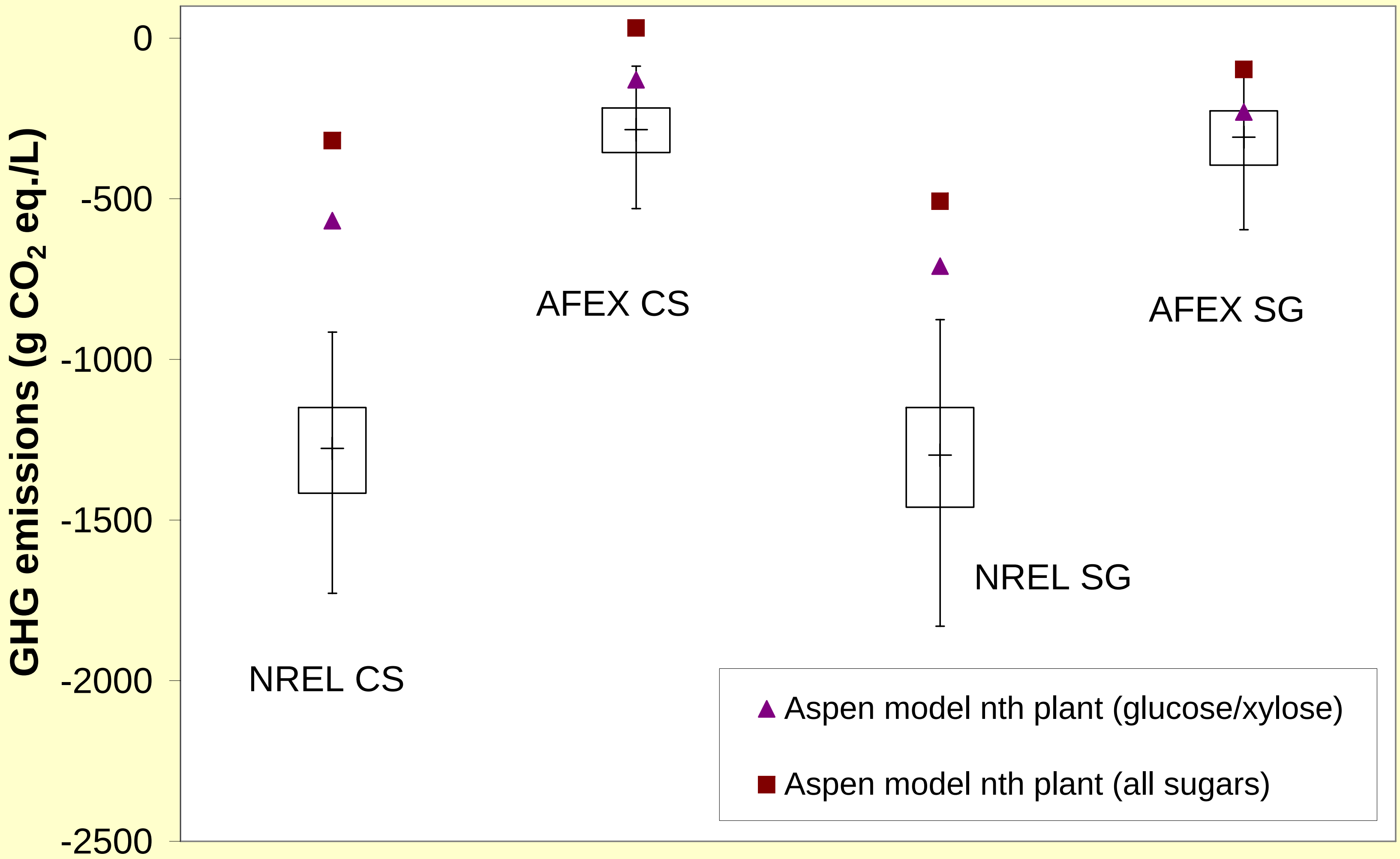
$$\mathrm{Y}_i = \sum_i \sum_j \sum_k x_i \times y_j \times \beta_k$$

$$E_\mathrm{b} = \sum_{i=1}^{n} M_i LHV_i - M_F \cdot LHV_E \sum_{i=1}^{5} Y_i$$

Performance: Ethanol Yield

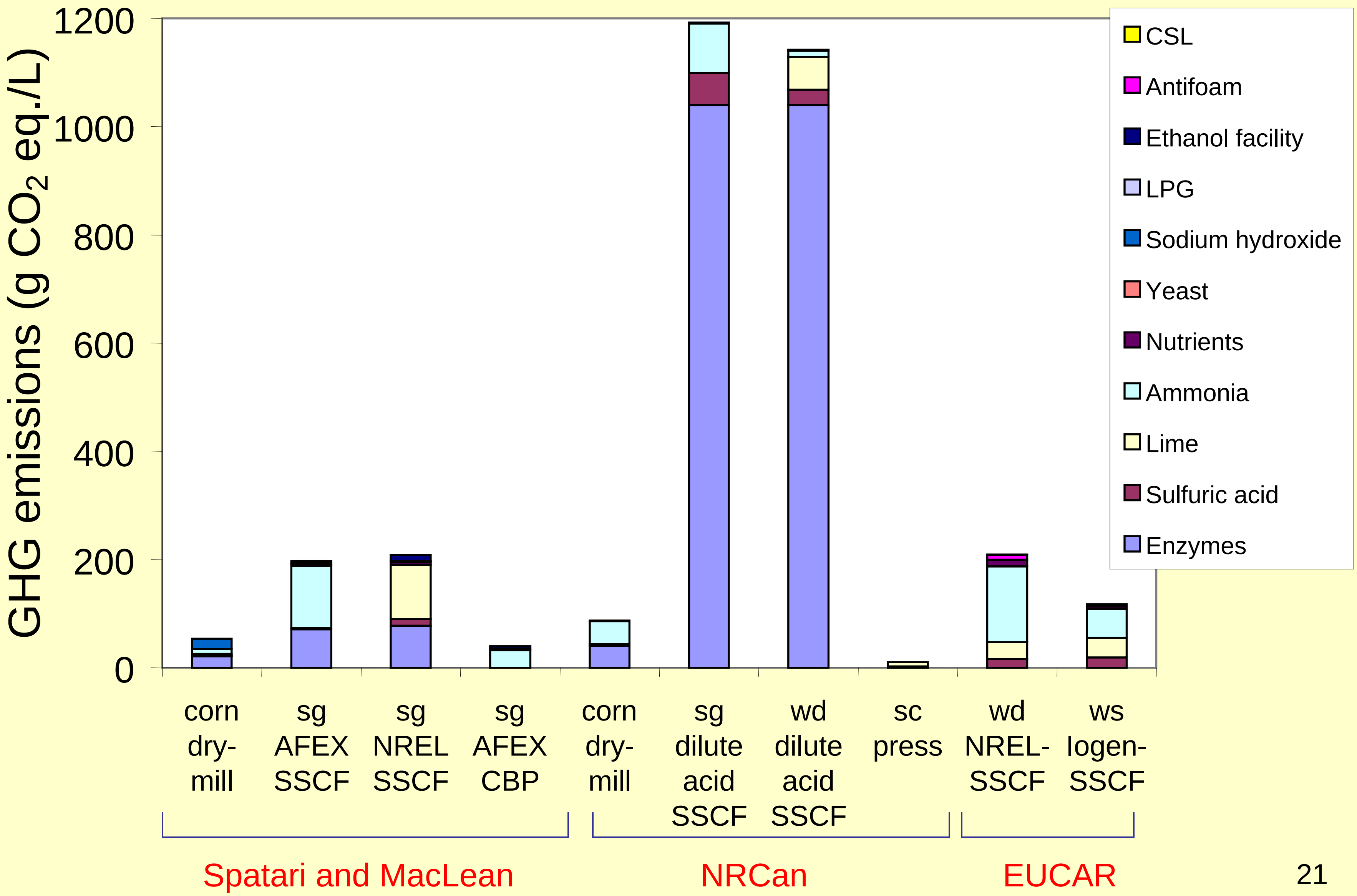


Environment: WTG GHG emissions



Electricity credit included

Ethanol Conversion: Chemicals and Enzymes



Results Depend on Input Variables!

- Change chemical or enzyme loading requirements
  - Vastly increases GHG emissions
- Case illustrated: Cellulases are still specialty products, only a few decades old, high production costs
  - Endoglucanases, exoglucanases, β-glucosidases
  - Technology still evolving
- Need for plausible probability distributions for all significant variables in any LCA model
- Important to update results with new information, with technological change
  - Bayesian updating techniques useful

How to estimate/evaluate S metrics

- Option 1: Qualitative criteria
  - Best practices = “Good”
- Option 2: Estimate a scalar sustainability (S) metric:
  - Compute all sustainability measurements in some “S” unit, social cost-benefit?
  - e.g., define 1 ha biodiversity loss = X “S” units
    - OR
  - Ranking system, ordering importance of S criteria:
    - Biodiversity = 40 units S
    - Cultural diversity loss = 20 units S

How to estimate/evaluate S metrics

- Option 3: Binary system to evaluate feedstocks/technologies:
    - “acceptable” – MSW feedstocks
    - “not acceptable” – feedstocks grown on arable land
- Option 4: Define a vector of mixed “S” criteria
    - – Set threshold levels for each S criteria
- Option 5: Combinations of all of the above
- Very difficult to define, measure, and evaluate sustainability of fuels!

Challenge to Calculating Sustainability (S)

- Treatment of uncertainty across S criteria
  - Compare stochastic model results for GWI with the point estimates and/or undefined S criteria
  - Hardly close to estimating uncertainty for S AND it is important for decision making!
  - Also important are sustainability criteria that may conflict with GWI
    - Eutrophication versus GHG reduction
- Maybe a qualitative evaluation approach is best for now
  - Encourage sustainable production practices

Acknowledgements

- Natural Sciences and Engineering Research Council of Canada (NSERC)
- Alex Farrell, Michael O’Hare, Dan Kammen, Sonia Yeh, U.C. Berkeley and Davis
- California Air Resources Board
- Heather L. MacLean, University of Toronto
- Bruce Dale, Michigan State University

Life Cycle GHG Emissions

Without electricity credit