"Advanced Biotechnology"
21st Century Opportunities for Greenhouse Gas Abatement

F. Blaine Metting
Pacific Northwest National Laboratory
Richland, Washington USA

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"Biotechnology and Greenhouse Gas Mitigation"
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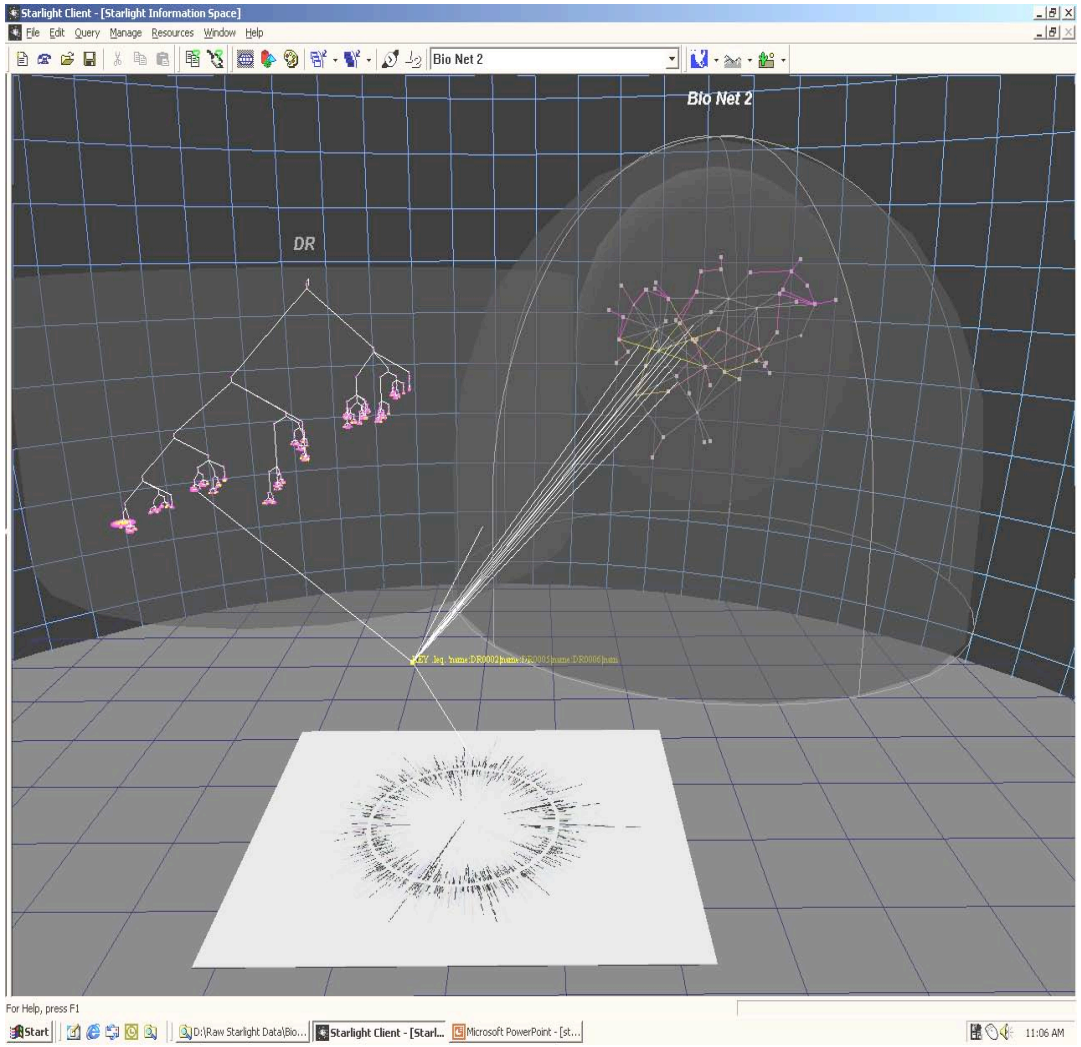
Biotech -- Major Points

- Biotechnology is cross-cutting and so will have a *pervasive impact* on 21st century energy technologies
- Greatest impact is expected to be via enhanced biological productivity and management efficiency of crop, forest and dedicated biomass production
- Microbial biodiversity is a vast, untapped opportunity that will yield currently unforeseen breakthroughs from the application of genome and post-genome science to basic understanding

A Revolution in Biology

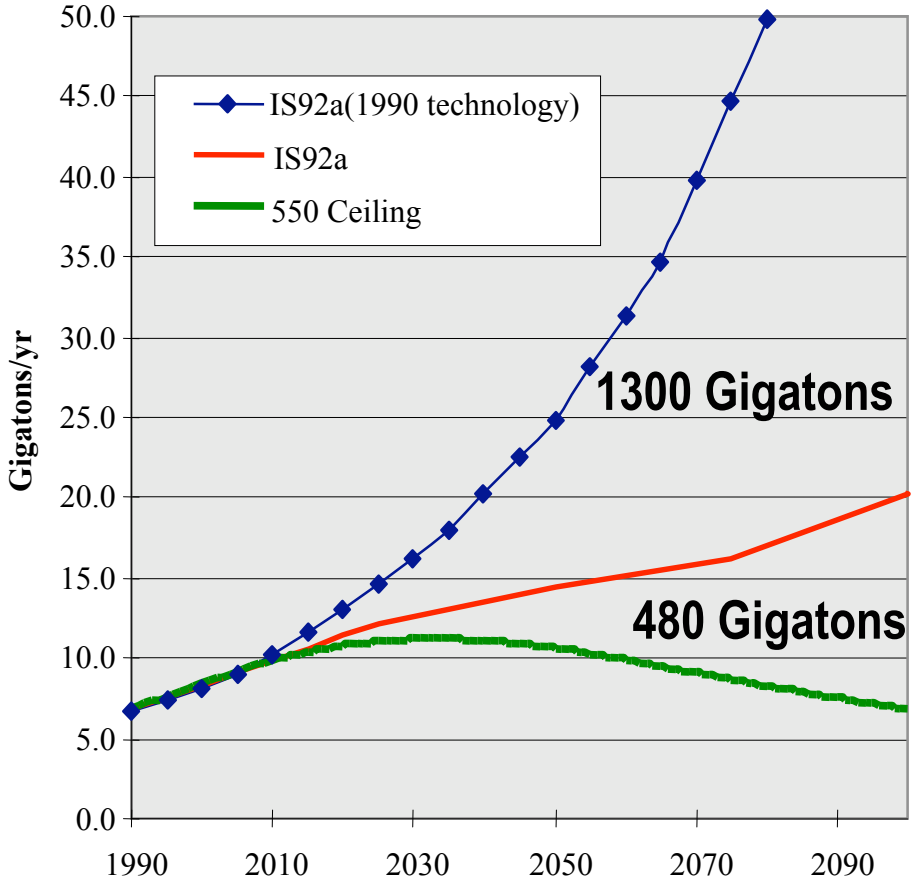
- 1953 – DNA structure
- 1970s – rDNA technology
- 1980s – Metabolic engineering
- 1990s – Genomics
- 21st Century – "Systems" biology (post-genome biology)

Biology and Computing are being integrated to achieve a <u>Predictive Understanding</u> of living systems



Global Carbon Management

Technologies in the Current R&D Pipeline Are Not Enough



Where today's technology will take us

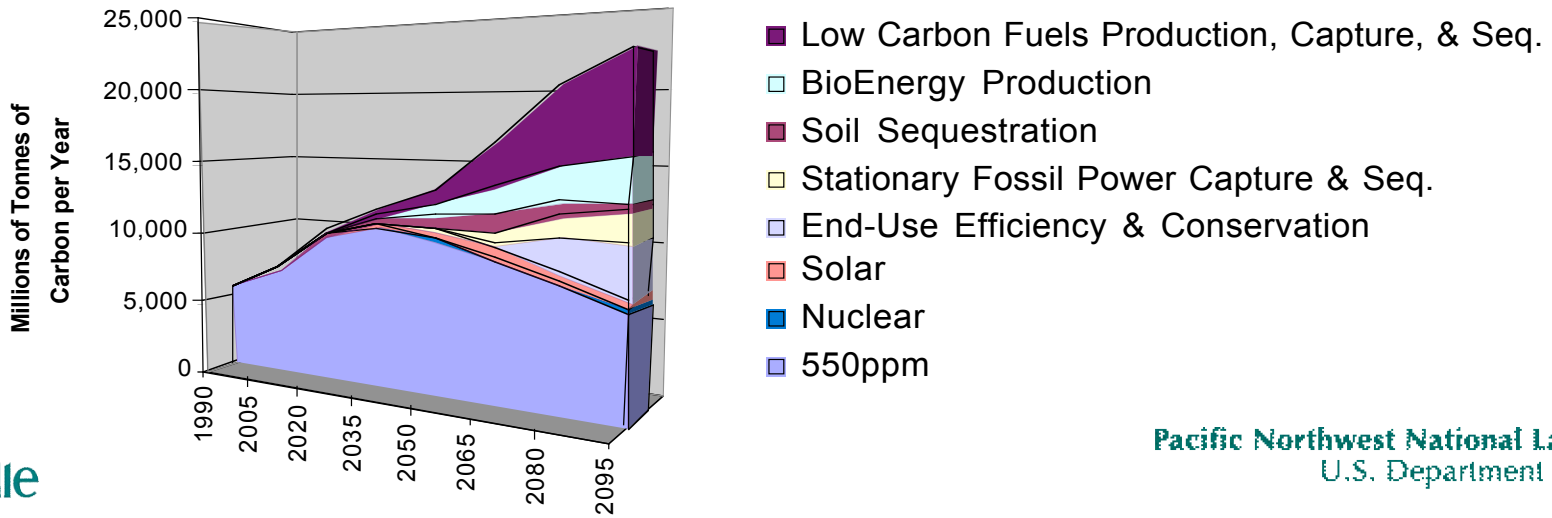
Where our current aspirations for technology will take us

Where we need to go to stabilize carbon

Potential Impact of Technology Systems (MMt C/yr)

*Systems likely to be impacted by biotechnology

	Global	United States
Low-Carbon Fuels Production, Capture, & Sequestration*	186	27
BioEnergy*	90	15
Soil Sequestration*	51	6
Stationary Fossil Power Capture & Sequestration*	51	5
Energy Efficiency*	42	14
Solar	34	0
Conservation ("Doing with Less")	17	12
Nuclear	13	0



Biotech – Potential Impacts

(~ order of magnitude, Gt/century)

100

- **Dedicated Biomass**
  Biofuels (including H_2), Biopower

- **Soil Carbon Sequestration**

10

- **Direct Microbial H_2 Production**

- **Microbial CO_2 Capture**

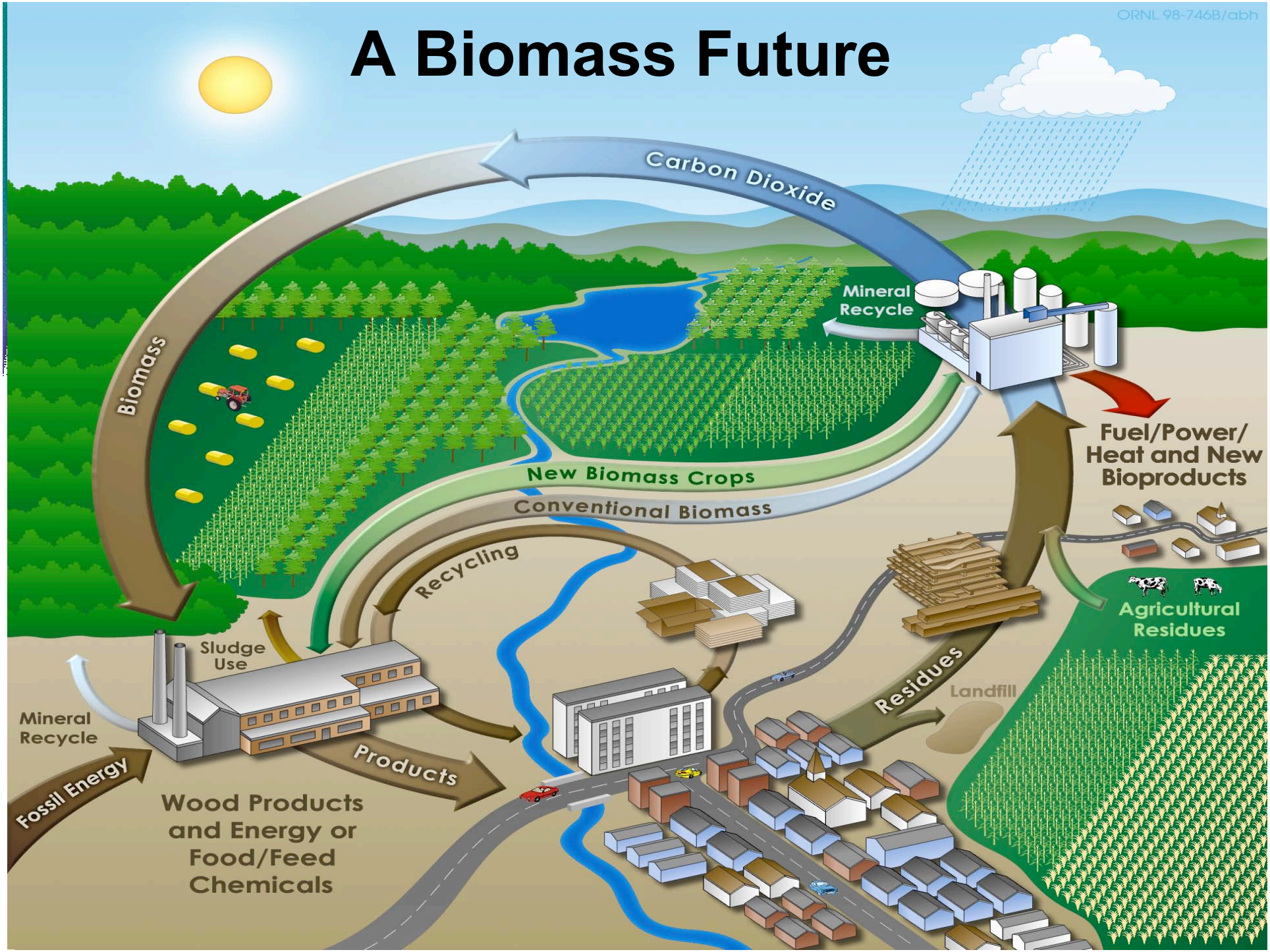
1

- **Nitrogen Fixation**

- **Energy Efficiency Applications**
  Waste treatment, Fossil energy biotechnology, Industrial biotechnology

Dark horses ?

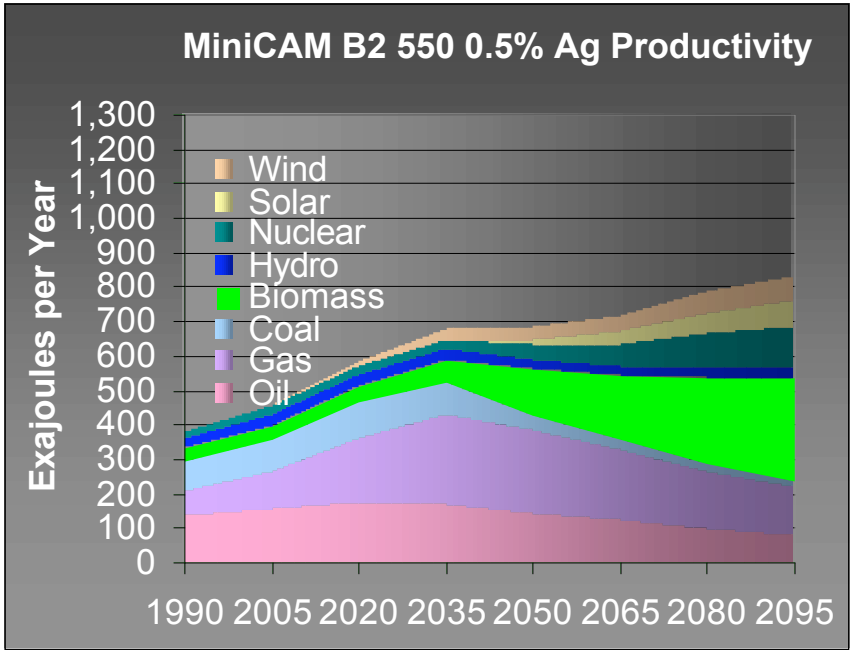
A Biomass Future

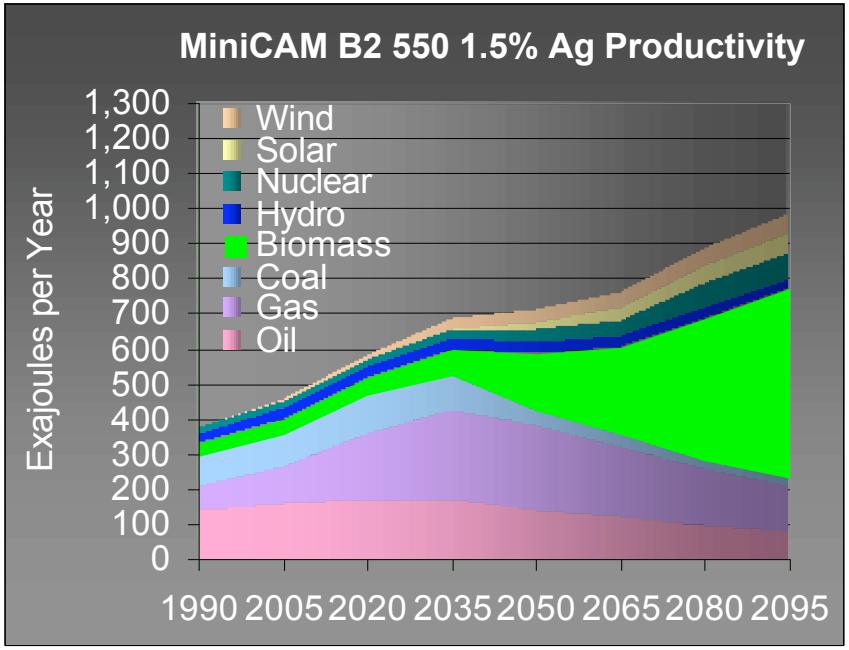


Biotechnology Insights from Integrated Assessment Models

Increasing general agricultural productivity increases the size of the biomass market

Primary energy (exajoules/yr), 550 ppm CO_2 stabilization





Biomass -Energy Crops

Biotechnology – *Accelerating the rate of domestication and acquisition of desired traits*

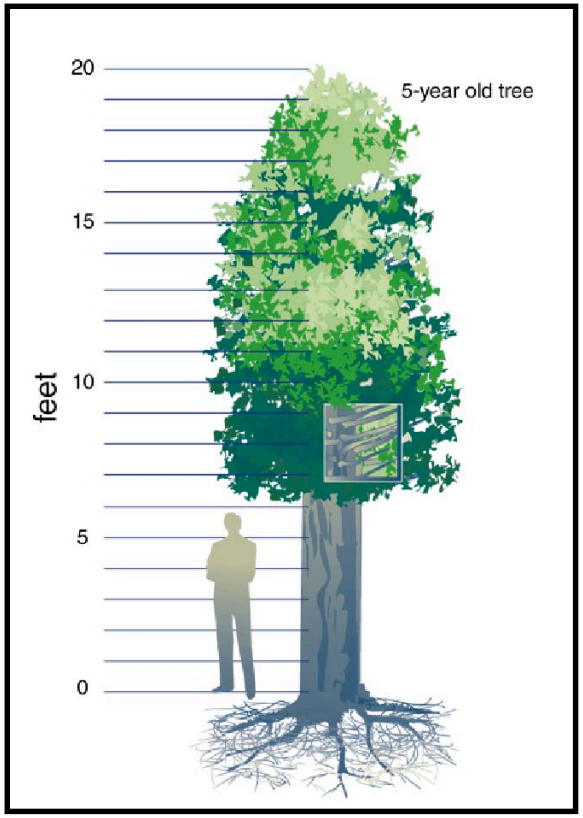
Constraints – Yields, Available Land, Geographic Distribution

Hybrid Poplar

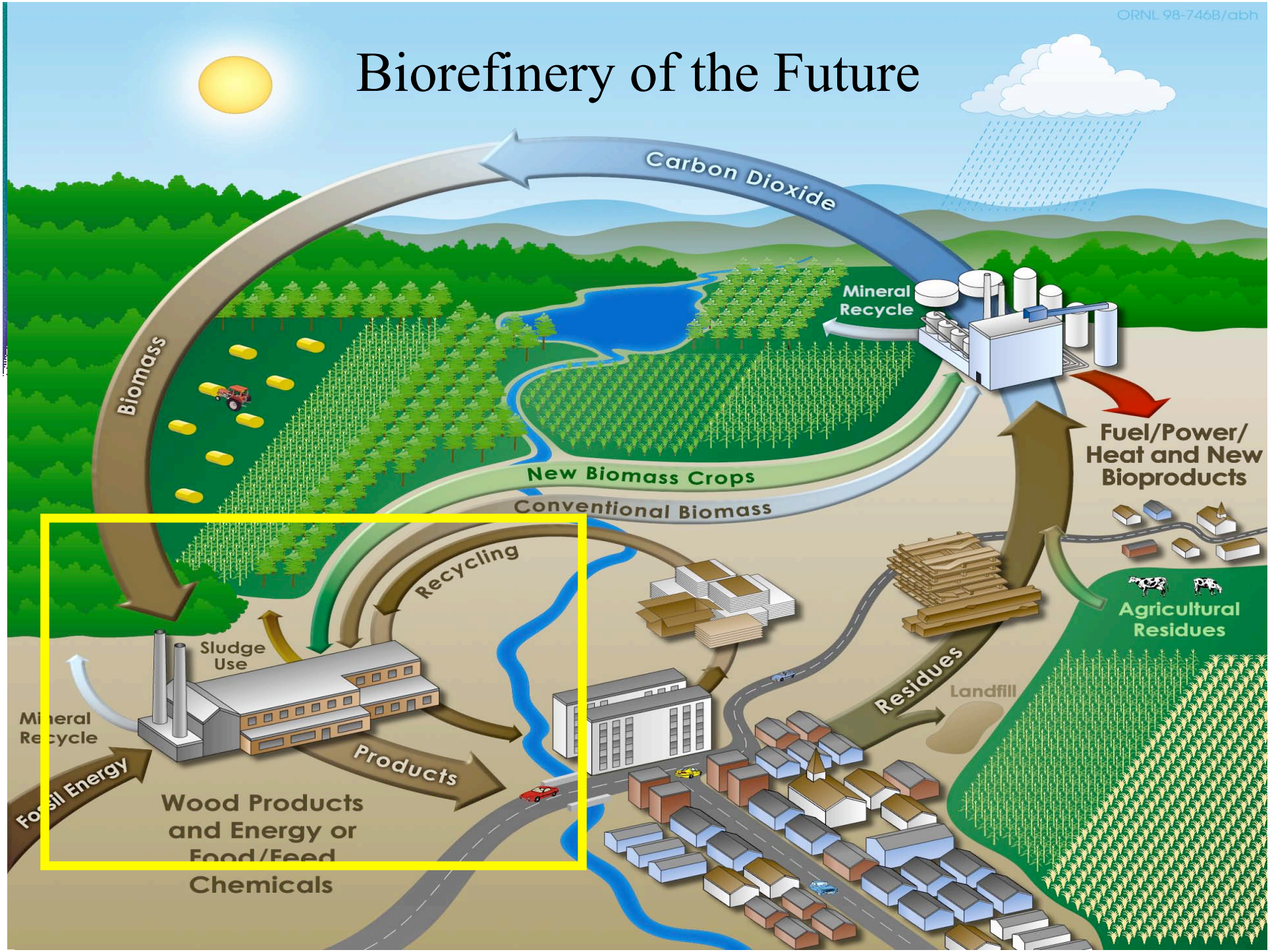
Switch Grass

Domesticated *Populus* Attributes

- Enhanced photosynthetic efficiency
- Controlled C allocation
- No response to competition
- Reduced height growth
- Less (or more) extensive root system
- Improved wood chemistry
- Pest resistance
- Optimized photoperiod response



Biorefinery of the Future



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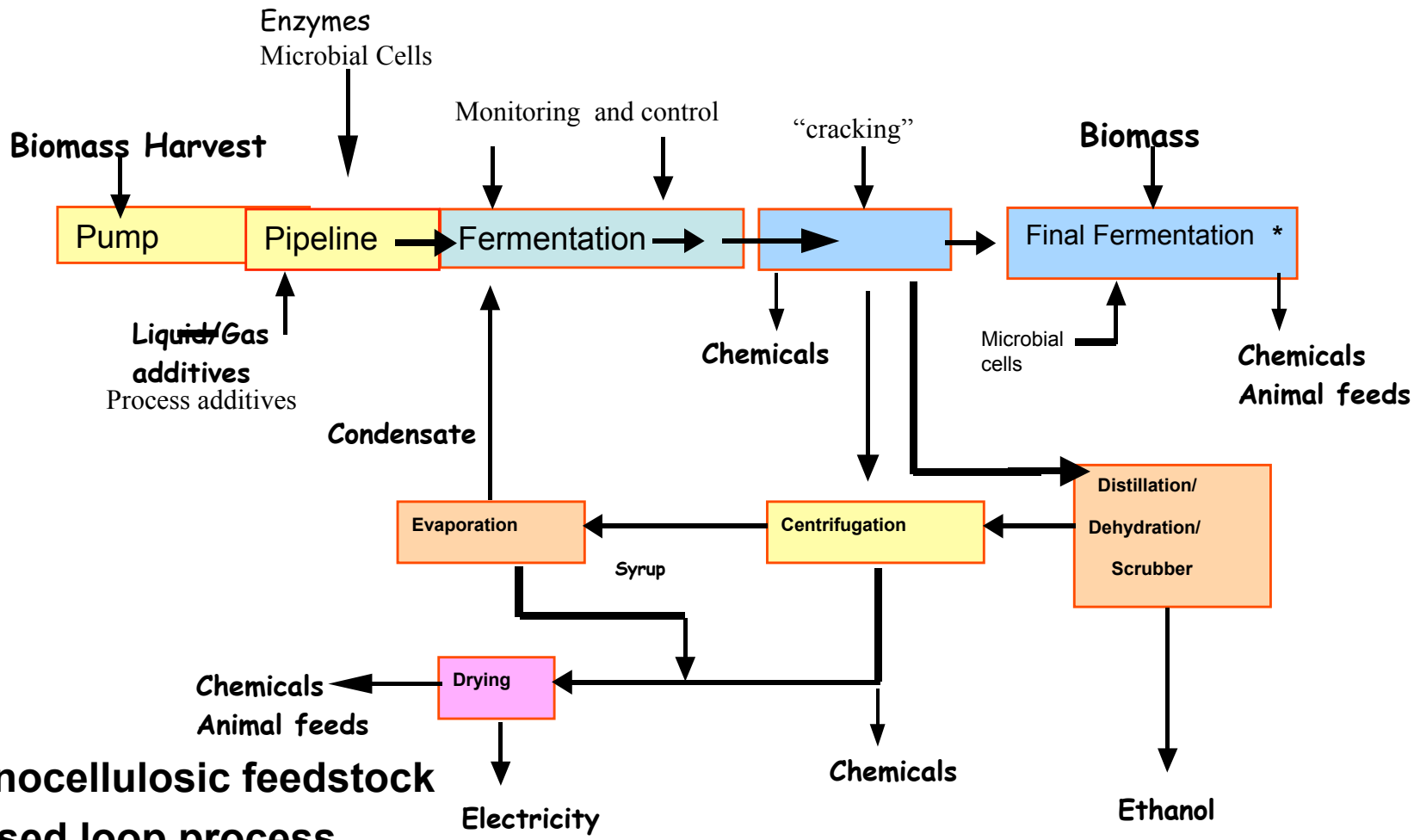
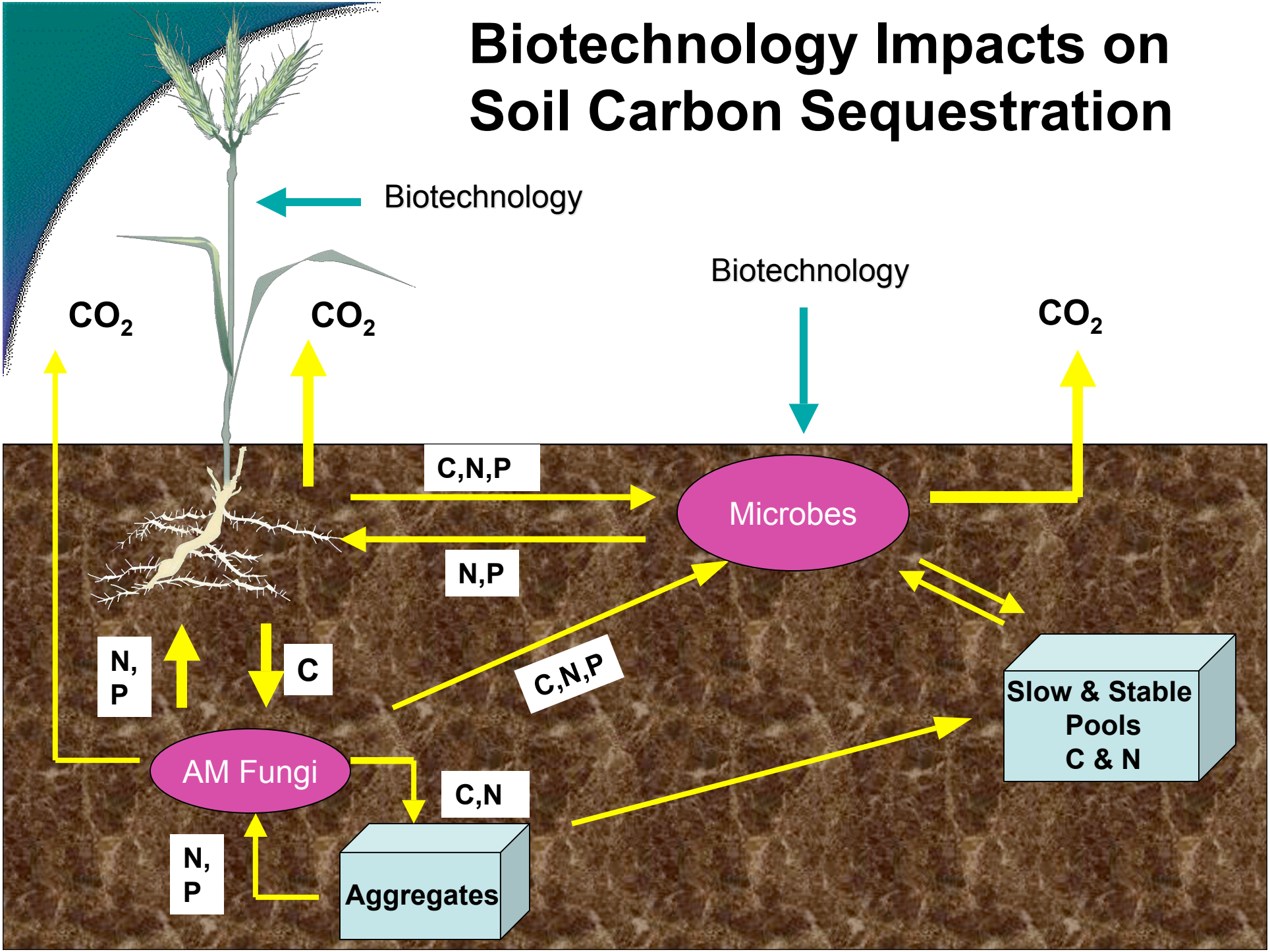


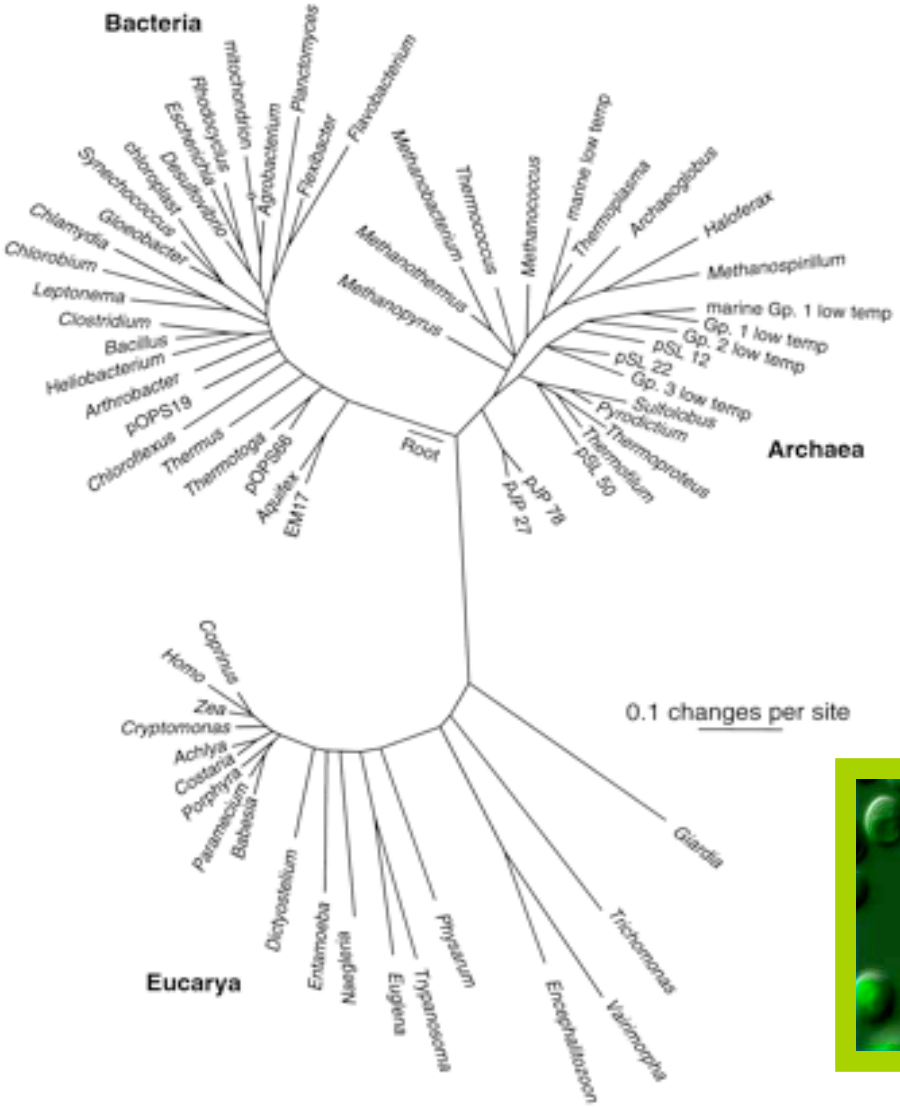
- Lignocellulosic feedstock
- Closed loop process
- Zero GHG emissions
- Use of engineered microbes
- Complete "cracking" of "crop residues" to products

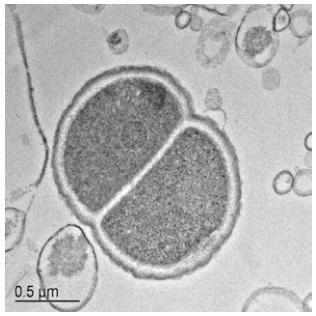
Biotechnology Impacts on Soil Carbon Sequestration



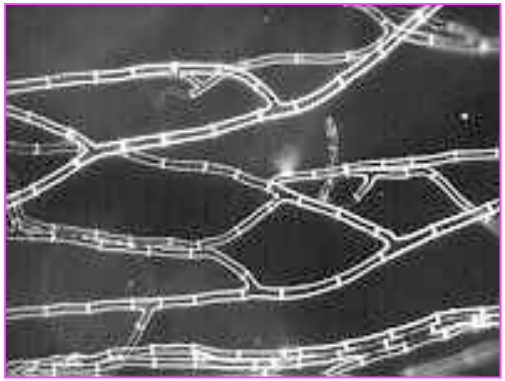
Microbial Diversity & Versatility

Photosynthetic bacteria



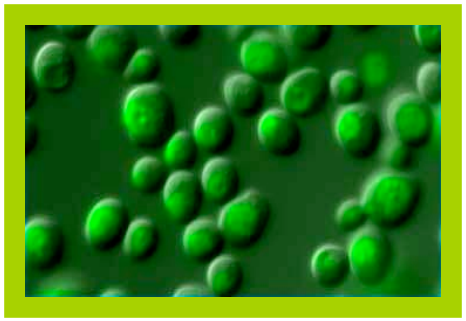


Extremophiles



Filamentous fungi

Microalgae



Microbial Biotechnology - Understanding Molecular Machines
Then putting them to work

Potential - ***Make lignocellulosics a viable energy feedstock for creating the biomass energy industry.***

Microbial Hydrogen (H_2) Production

[NOTE: These are generalized schematics. Ferredoxin also represents other electron carriers]

1. Direct Biophotolysis (simultaneous, single-cell, single stage, H_2 -andO_2 production)

O_2 ⇧ H_2 ⇧

H_2O → PSII → PSI → Ferredoxin → Hydrogenase

Green Microalgae

2. Direct Biophotolysis (with spatial separation of H_2 -andO_2 production)

O_2 ⇧ CO_2 ⇩ ← (recycle) CO_2 ⇧ H_2 ⇧

H_2O → PSII → PSI → $(CH_2O)_n$ → $(CH_2O)_{n-}$ → Ferredoxin → Nitrogenase

PSI → ATP ⇧

Vegetative Cells Heterocysts

Heterocystous N_2-fixing Cyanobacteria

Microbial Hydrogen (H_2) Production

3. **Indirect Biophotolysis** (Single cell H_2 and O_2 production, separated temporally or spatially)

O_2 $\quad$ CO_2 ← (recycle) CO_2 $\quad$ H_2

H_2O → PSII → PSI → $(CH_2O)_n$ →→ $(CH_2O)_{n-}$ → PSI → Hydrogenase

First Stage $\quad$ Second Stage

Green Microalgae

4. **Photofermentation** (Single Cell, no O_2 Production).

CO_2 $\quad$ H_2

$(CH_2O)_{n-}$ → Ferredoxin → Nitrogenase

Bacterial PS → ATP

Photosynthetic Bacteria

Microbial Hydrogen (H_2) Production

5. **Dark Fermentation** (No O_2 Production) **Anaerobic Bacteria**

5.1. Maximum H_2 Production coupled to growth

$$(CH_2O)_6\text{-} \rightarrow \underset{\uparrow\ 2CO_2}{\text{Ferredoxin}} \rightarrow \underset{\uparrow\ 4H_2}{\text{Hydrogenase}} + 2\ CH_3COOH$$

5.2. Maximum Stoichiometric H_2 Production

$$(CH_2O)_6\text{-} \rightarrow \underset{\uparrow\ 6CO_2}{\text{Ferredoxin}} \rightarrow \underset{\uparrow\ 12H_2}{\text{Hydrogenase}}$$

6. **Microbial Shift Reaction** (Dark process) **Anaerobic Bacteria**

$$CO + H_2O \rightarrow H_2 + CO_2$$

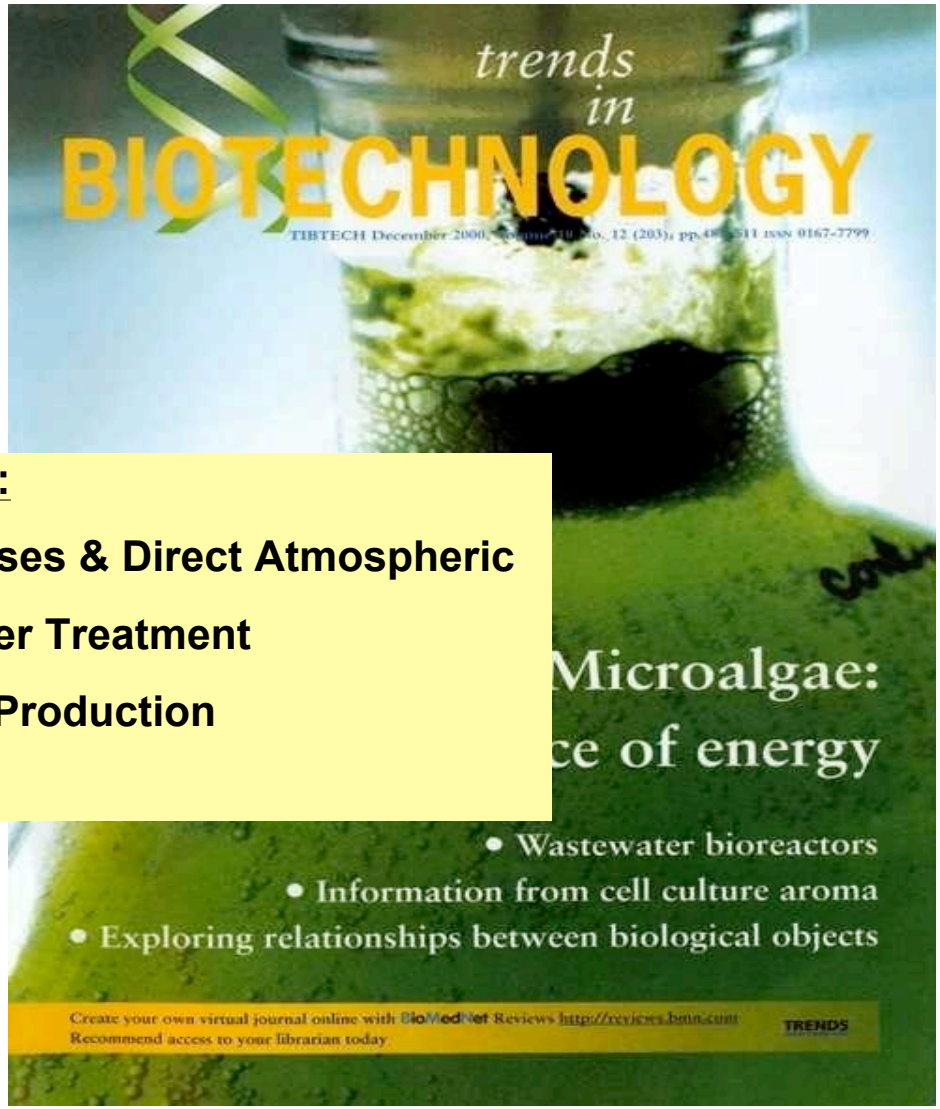
Microbial Fixation of CO_2 and N_2

Microalgae and Cyanobacteria

Photosynthetic Bacteria

Opportunities Include:

- **CO_2 Capture: Flue Gases & Direct Atmospheric**
- **Waste and Wastewater Treatment**
- **Coupled H_2 and CH_4 Production**
- **Fertilizer Production**



Impact of Biotechnology: *One Example*

Challenge: Photosynthetic Efficiency

Is 10% solar energy efficiency a realistic target?

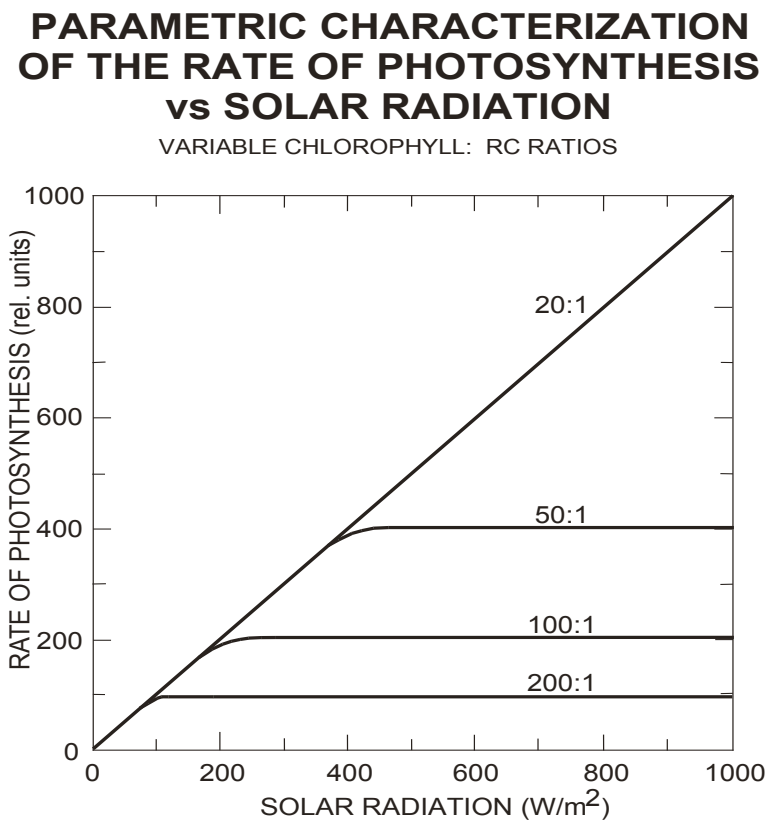
Potential Approaches:

Enhanced enzyme efficiency

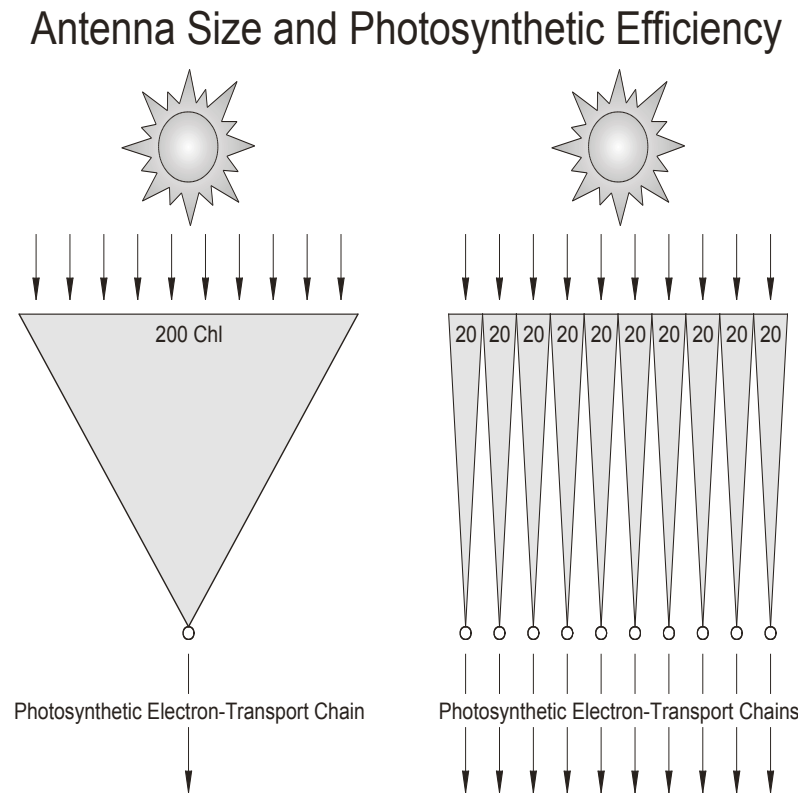
- **Directed evolution**
- **Rational redesign**

Structural Engineering – Reaction Center Complex

Biotechnology Approach to Enhance Photosynthetic Efficiency



Problem: Light Saturation



Solution: Reaction Center Structural Re-engineering

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