“Advanced Biotechnology”
21st Century Opportunities
for Greenhouse Gas Abatement

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“Biotechnology and Greenhouse Gas Mitigation”
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Pacific Northwest National Laboratory
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Biotech -- Major Points

• Biotechnology is cross-cutting and so will have a \textit{pervasive impact} on 21\textsuperscript{st} 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

Biology and Computing are being integrated to achieve a Predictive Understanding 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

- IS92a(1990 technology)
- IS92a
- 550 Ceiling
Potential Impact of Technology Systems (MMt C/yr)

*Systems likely to be impacted by biotechnology

<table>
<thead>
<tr>
<th>Systems</th>
<th>Global</th>
<th>United States</th>
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</thead>
<tbody>
<tr>
<td>Low-Carbon Fuels Production, Capture, &amp; Sequestration*</td>
<td>186</td>
<td>27</td>
</tr>
<tr>
<td>BioEnergy*</td>
<td>90</td>
<td>15</td>
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<tr>
<td>Soil Sequestration*</td>
<td>51</td>
<td>6</td>
</tr>
<tr>
<td>Stationary Fossil Power Capture &amp; Sequestration*</td>
<td>51</td>
<td>5</td>
</tr>
<tr>
<td>Energy Efficiency*</td>
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<td>14</td>
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<tr>
<td>Solar</td>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td>Conservation (“Doing with Less”)</td>
<td>17</td>
<td>12</td>
</tr>
<tr>
<td>Nuclear</td>
<td>13</td>
<td>0</td>
</tr>
</tbody>
</table>

![Graph showing millions of tonnes of carbon per year from 1990 to 2095.](chart.png)

- Low Carbon Fuels Production, Capture, & Seq.
- BioEnergy Production
- Soil Sequestration
- Stationary Fossil Power Capture & Seq.
- End-Use Efficiency & Conservation
- Solar
- Nuclear
- 550ppm

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Biotech – Potential Impacts

(≈ order of magnitude, Gt/century)

- Dedicated Biomass Biofuels (including H2), Biopower
- Soil Carbon Sequestration
- Direct Microbial H2 Production
- Microbial CO2 Capture
- Nitrogen Fixation
- Energy Efficiency Applications
  Waste treatment, Fossil energy biotechnology, Industrial biotechnology

Dark horses?
Biotechnology Insights from Integrated Assessment Models

Increasing general agricultural productivity increases the size of the biomass market

Primary energy (exajoules/yr), 550 ppm CO₂ 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
Biorefinery of the Future

- 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

- **AM Fungi**
- **Aggregates**
- **CO$_2$**
- **Microbes**
- **C, N, P**
- **N, P**
- **C**
- **C, N, P**
- **N, P**
- **Slow & Stable Pools C & N**
Microbial Diversity & Versatility

Photosynthetic bacteria

Filamentous fungi

Extremophiles

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 (H₂) Production

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

1. Direct Biophotolysis (simultaneous, single-cell, single stage, H₂-andO₂ production)

   \[
   \text{H}_2 \text{O} \rightarrow \text{PSII} \rightarrow \text{PSI} \rightarrow \text{Ferredoxin} \rightarrow \text{Hydrogenase}
   \]

   Green Microalgae

2. Direct Biophotolysis (with spatial separation of H₂ -andO₂ production)

   \[
   \text{H}_2 \text{O} \rightarrow \text{PSII} \rightarrow \text{PSI} \rightarrow \text{(CH}_2\text{O)}_n \rightarrow \text{(CH}_2\text{O)}_n^- \rightarrow \text{Ferredoxin} \rightarrow \text{Nitrogenase}
   \]

   \[
   \text{PSI} \rightarrow \text{ATP}
   \]

   Vegetative Cells

   Heterocysts

   Heterocystous N₂-fixing Cyanobacteria
Microbial Hydrogen (H₂) Production

3. Indirect Biophotolysis (Single cell H₂ and O₂ production, separated temporally or spatially)

\[
\begin{align*}
O_2 & \quad CO_2 \leftrightarrow (recycle) \ CO_2 \quad H_2 \\
H_2O \rightarrow & \ PSII \rightarrow \ PSI \rightarrow (CH_2O)_n \rightarrow \ (CH_2O)_{n-} \rightarrow \ PSI \rightarrow \ Hydrogenase \\
\text{First Stage} & \quad \text{Second Stage} \\
\end{align*}
\]

Green Microalgae

4. Photofermentation (Single Cell, no O₂ Production).

\[
\begin{align*}
CO_2 & \quad H_2 \\
\uparrow & \quad \uparrow \\
(CH_2O)_{n-} & \rightarrow \ Ferredoxin \rightarrow \ Nitrogenase \\
\end{align*}
\]

Photosynthetic Bacteria

Bacterial PS \rightarrow ATP \uparrow
Microbial Hydrogen (H₂) Production

5. Dark Fermentation (No O₂ Production)  Anaerobic Bacteria

5.1. Maximum H₂ Production coupled to growth

\[
\begin{align*}
2\text{CO}_2 & \uparrow & 4\text{H}_2 & \uparrow \\
(\text{CH}_2\text{O})_6 & \rightarrow \text{Ferredoxin} & \rightarrow \text{Hydrogenase} + 2 \text{CH}_3\text{COOH}
\end{align*}
\]

5.2. Maximum Stoichiometric H₂ Production

\[
\begin{align*}
6\text{CO}_2 & \uparrow & 12\text{H}_2 & \uparrow \\
(\text{CH}_2\text{O})_6 & \rightarrow \text{Ferredoxin} & \rightarrow \text{Hydrogenase}
\end{align*}
\]

6. Microbial Shift Reaction (Dark process)  Anaerobic Bacteria

\[
\text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2
\]
Microbial Fixation of CO₂ and N₂

Microalgae and Cyanobacteria

Photosynthetic Bacteria

Opportunities Include:
- CO₂ Capture: Flue Gases & Direct Atmospheric
- Waste and Wastewater Treatment
- Coupled H₂ and CH₄ 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

PARAMETRIC CHARACTERIZATION OF THE RATE OF PHOTOSYNTHESIS vs SOLAR RADIATION
VARIABLE CHLOROPHYLL: RC RATIOS

Problem: Light Saturation

Solution: Reaction Center Structural Re-engineering

Antenna Size and Photosynthetic Efficiency

Photosynthetic Electron-Transport Chain

Photosynthetic Electron-Transport Chains

Problem: Light Saturation

Solution: Reaction Center Structural Re-engineering
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