Gross primary production is stimulated for *Populus* species grown under free-air CO$_2$ enrichment

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Biogeochemistry, (Schlesinger, 1997)
Gross Primary Production

- GPP = gross photosynthetic carbon assimilation
- Driving step of the global carbon cycle
- Forest trees account for large proportion of terrestrial GPP
Intergovernmental Panel on Climate Change (Houghton, 2001)
How will GPP of trees be changed in an elevated \( CO_2 \) world?
Two Problems

1. Growing trees in an elevated $CO_2$ atmosphere: OTC’s

2. Measuring GPP of $CO_2$ enriched trees: Closed Chambers
POPFACE: Poplar Free-Air CO$_2$ Enrichment

- FACE: No alteration to climate or restriction to growth
- Large scale; short-rotation intensive Populus plantation
- Enrichment of CO$_2$ to 550 ppm in 3 plots; 3 control plots
FACE Technology

Photo by Steve Bunn
FACE Technology
POPFACE: Poplar Free-Air CO$_2$ Enrichment

Rotation Cycle
1999-2001

9ha

CONTROL

ELEVATED (550ppm)
Measurements

- Photosynthetic Photon Flux Density (PPFD) - 30 min
- Temperature - 30 min
- Leaf Area Index (LAI) - biweekly
Measurements

- Gas exchange measurements
- Maximum rate of electron transport: $J_{\text{max}}$
- Maximum rate of carboxylation: $V_{c,\text{max}}$
Maximum rate of electron transport: $J_{\text{max}}$
Maximum rate of carboxylation: $V_{c,max}$

Rubisco-Limited Photosynthesis
$A/c_i$ Response Curve

Net CO$_2$ assimilation rate ($A$) mmol m$^{-2}$ s$^{-1}$

Intercellular [CO$_2$] mmol mol$^{-1}$

Rubisco Limited Photosynthesis

RuBP Limited Photosynthesis

Maximum Rubisco Activity - $V_{c,max}$

Maximum Rate of Electron Transport - $J_{max}$
From Measurements to a Model of GPP

\[ V_{c,\text{max}} \]
\[ J_{\text{max}} \]
Light
Temperature
Leaf Area Index
\[ CO_2 \]

Photosynthesis

GPP
Utilize Independent Data to Model GPP

1. Data
2. Leaf Photosynthesis
3. GPP
Utilize Independent Data to Model GPP

1. Data
2. Leaf Photosynthesis
3. GPP
Average Monthly PPFD (µmol m⁻² s⁻¹)

Average Monthly Temperature (°C)

**1999**
- PPFD
- Temperature

**2000**

**2001**

Month: MAR, APR, MAY, JUN, JUL, AUG, SEP, OCT, NOV, DEC
$P.\ nigra$

Vc,max, 25°C & Jmax, 25°C

LAI (m$^2$ m$^{-2}$)

Month

<table>
<thead>
<tr>
<th>Year</th>
<th>J$_{\text{max}}$</th>
<th>Vc$_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td></td>
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</tr>
</tbody>
</table>

- △△△triangle: Control
- ■■ ■square: Elevated
Utilize Independent Data to Model GPP

1. Data
2. Leaf Photosynthesis
3. GPP
Farquhar Model of Leaf Photosynthesis ($A_{\text{leaf}}$)

$$A_{\text{leaf}} = f(\text{PPFD, } T, \text{ CO}_2, J_{\text{MAX}}, V_{C, \text{MAX}})$$
Leaf Photosynthesis ($A_{leaf}$)

$$A_{leaf} = \left[1 - \frac{\Gamma^*}{C_i}\right] \cdot \min\{W_c, W_j\}$$

$W_c$ = Rubisco-Limited photosynthesis

$W_j$ = RuBP-Limited photosynthesis
Utilize Independent Data to Model GPP

1. Data
2. Leaf Photosynthesis
3. GPP
Mean PPFD of Sunlit Leaves → Sun Canopy Photosynthesis ($A_{sun}$)
Mean PPFD of Shaded PPFD → Shade Canopy Photosynthesis ($A_{shade}$)

Forseth & Norman, 1993; Long 1991
\[ \text{LAI}_{\text{sun}} = (1-e^{-k\text{LAI}/\cos\theta}) \times \cos\theta / k \]

\[ \text{LAI}_{\text{shade}} = \text{LAI} - \text{LAI}_{\text{sun}} \]

\[ k = \text{Foliar absorption coefficient} \]
\[ \theta = \text{solar zenith angle} \]

Forseth & Norman, 1993; Long 1991
GPP

\[ GPP = A_{sun} \cdot LAI_{sun} + A_{shade} \cdot LAI_{shade} \]
Hypotheses

1. Elevated $\text{CO}_2$ will stimulate $\text{Gross Primary Production (GPP)}$

2. Sustained stimulation of GPP throughout rotation cycle (1999-2001)
Results?
P. nigra
July, 2000
Percent Stimulation Decreased

- Absolute GPP higher in elevated plots all years
- Relative stimulation decreased with canopy closure.
GPP Validation: Net Primary Production (NPP)

- NPP = GPP - Autotrophic Respiration (Ra)

- Assuming 40% GPP lost to Ra, can calculate NPP

- Adding up biomass increments from POPFACE and making minor assumptions about litter turnover, can calculate NPP
<table>
<thead>
<tr>
<th>Species</th>
<th>GPP(1-0.4)</th>
<th></th>
<th>Biomass increments + root and leaf turnover</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Elevated</td>
<td>Control</td>
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<tr>
<td><em>P. alba</em></td>
<td>73</td>
<td>87</td>
<td>63</td>
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<td><em>P. nigra</em></td>
<td>79</td>
<td>103</td>
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<td><em>P. x euramericana</em></td>
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<td>79</td>
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<tr>
<td><strong>Average</strong></td>
<td><strong>27%</strong></td>
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<tr>
<td><strong>Stimulation</strong></td>
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</tr>
</tbody>
</table>

*Biomass increments + root and leaf turnover reproduced from Calfapietra et al. 2003 and Lukac et al. 2003*
Discussion

• The decline in relative stimulation in GPP is a function of canopy closure not acclimation
• An increasing proportion of GPP occurs in the shade: RuBP-Limited Photosynthesis
• RuBP-Limited Photosynthesis not as responsive to elevated $CO_2$ as Rubisco-Limited Photosynthesis
Conclusion

• Hypothesis 1 supported: Stimulation of GPP in elevated CO$_2$ treatments

• Hypothesis 2 not supported: Although absolute GPP was stimulated in all years, the relative magnitude of the stimulation decreased with canopy closure
Implications

• Important to understand the dynamics in tree canopies

• Sun-shade model effective at capturing these dynamics

• GPP can be effectively estimated
Future Directions

• Interacting Global Changes:
  Rising $\text{CO}_2$ + Rising $\text{O}_3$
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UIUC Environmental Council
\[ Q_{dir} = I_s \star \odot \left( \frac{P}{P_0} / \cos \theta \right) \]

\[ Q_{diff} = 0.5 \star I_s \left( 1 - \odot \left( \frac{P}{P_0} / \cos \theta \right) \right) \star \cos \theta \]

\[ Q_{scat} = 0.07 \star Q_{dir} \star (1.1 - 0.1 \star \text{LAI}) \star e^{-\cos \theta} \]

\[ Q_{shade} = Q_{diff} \star e^{-0.5 \text{LAI}^{0.7}} + Q_{scat} \]

\[ Q_{sun} = Q_{dir} \left( \frac{\cos d}{\cos \theta} \right) + Q_{shade} \]

Where: \( I_s \) = solar constant; \( \odot \) = atmospheric transmittance; 
\( d \) = angle between the leaf surface and the direct beam solar radiation; 
\( P/P_0 \) = ratio of standard and sea level atmospheric pressure