Modeling Night-Time Ecosystem Respiration by a Constrained Source Optimization

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Introduction

- Estimating ecosystem respiration **(**Re**)** is a fundamental and practical research problem in carbon cycling.

- Quantifying Re is critical to Net Ecosystem Exchange (NEE) and Gross Primary Productivity (GPP).

Motivation

While methods are available to measure Re, they are plagued by several complications:

- *Chambers and Cuvetts*: Spatial aggregation and continuous measurements in time.
- *Eddy covariance*: when the mechanical production of turbulent kinetic energy is small (i.e. small friction velocities u_*).

New approaches to complement existing methods are needed.

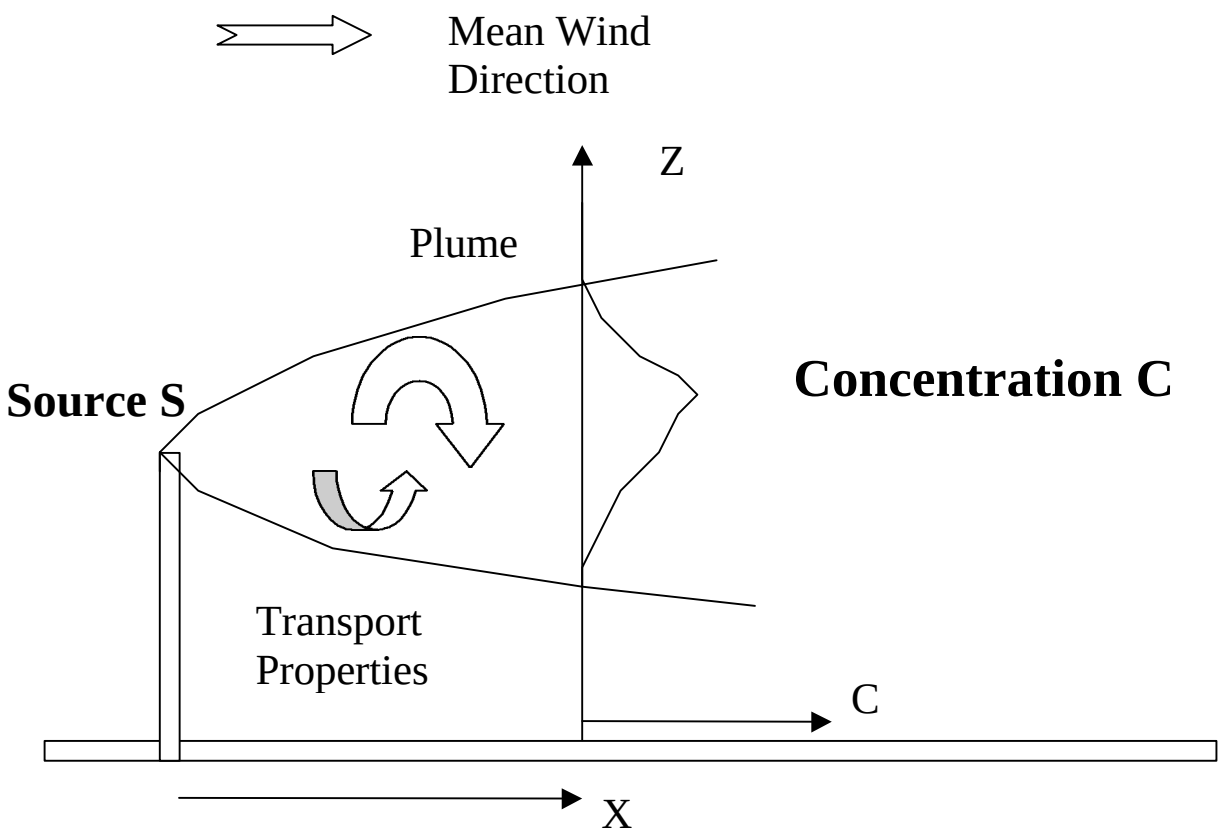
Preliminary Assessments

- Disagreements between chamber and eddy-covariance measured nighttime respiration ~ 50% (e.g., Law et al., 1999).

- Eddy-covariance nighttime corrections for low u_* can affect NEE by about **100 g C m^{-2} y^{-1}** (as evidenced by measurements at Harvard and Duke Forests).

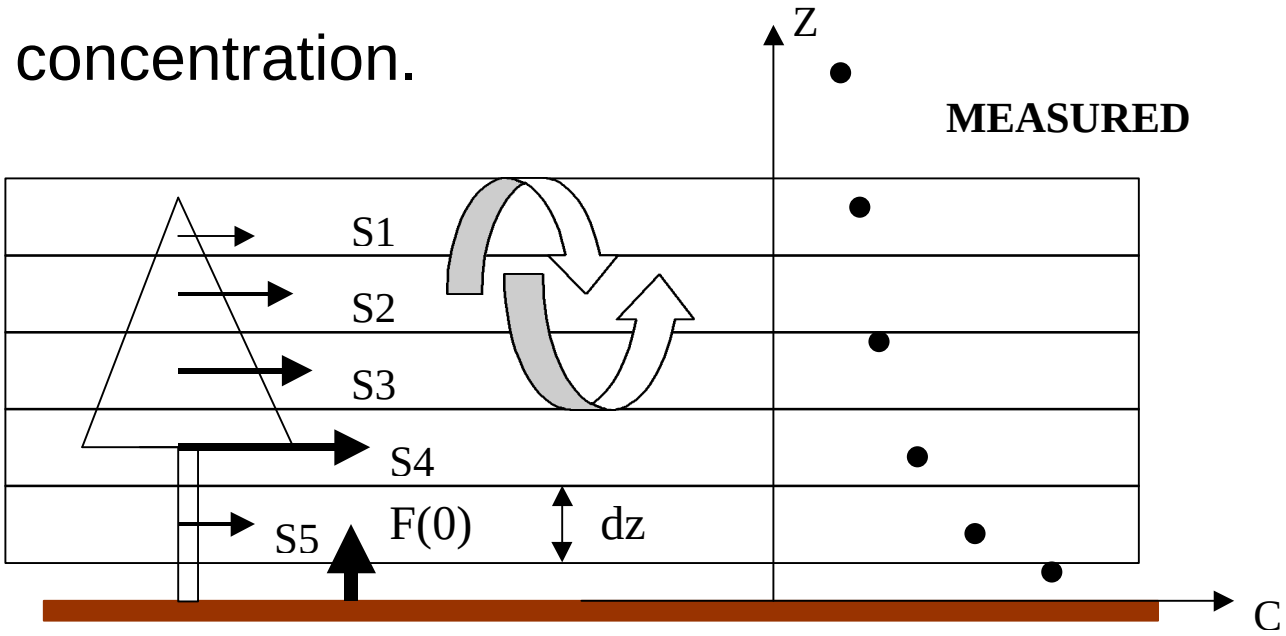
Proposed Approach

Use measured mean CO_2 concentration profiles inside canopy. Idea borrowed from air pollution:



Proposed Approach:

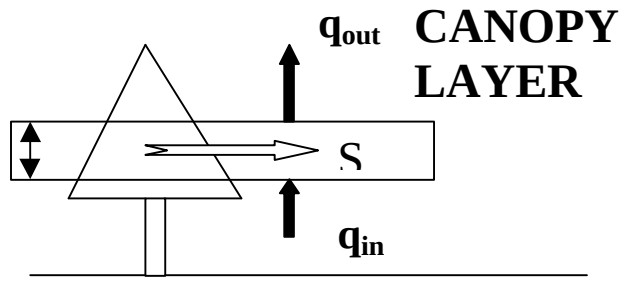
Inverse Methods – Estimate foliage CO_2 production and forest floor respiration from measured mean CO_2 concentration.



Model Formulation

Mass Balance:

$$\frac{\partial C}{\partial t} = -\frac{\partial q}{\partial z} + S$$



- $C(z,t)$ is measured – two unknowns (q,S) and one equation.
- $q \rightarrow C$ from Lagrangian Fluid Mechanics Principles.

Problem is *mathematically solvable* – though the *solution* is very *sensitive* to *measurement errors* in $C(z,t)$ (Sequeira et al., 2000; JGR, in press).

Constrained Source Optimization

Basic Idea:

Assume that plant respiration is:

$$S(z,t) = a(z,t)\ a\ V_{c\max}(T)$$

S = CO_2 production by plants (leaves+wood).

$V_{c\max}$ = Maximum Rubisco Capacity per unit leaf area.

$a(z,t) =$ Plant area density

a = Unknown constant ~ 0.01-0.015 from porometry.

Constrained Source Optimization

PROBLEM IS REDUCED TO THE FOLLOWING OPTIMIZATION PROBLEM:

What combination of forest floor flux $F(0,t)$ and a best reproduces the measured $C(z,t)$ each 30 minutes.

Degrees of freedom > 8.

Model Inputs and Outputs

Inputs:

- Measured Plant Area Density ~ every month.
- Measured C(z,t) ~ every 30 minutes at 10 levels.
- Measured Flow Statistics above the canopy ~ every 30 minutes.
- $V_{c\max}$ for pines and hardwood.

Outputs:

- Flow statistics inside canopy
- Optimized $a, F(0,t)$ ~ Above Ground and Forest Floor Respiration.
- Modeled $C(z,t)$ and root-mean squared error for concentration.

Model Testing

- Eddy-covariance measurements for high u_*?

- Forest-Floor Flux/Soil Temperature relations from chamber measurements (and literature values)?

- a consistency with literature values and porometry measurements?

- Using other measured variables (e.g., NPP, NEE), recover established dimensionless quantities (e.g. NPP/GPP)?

Model Results – 1: Flow Field

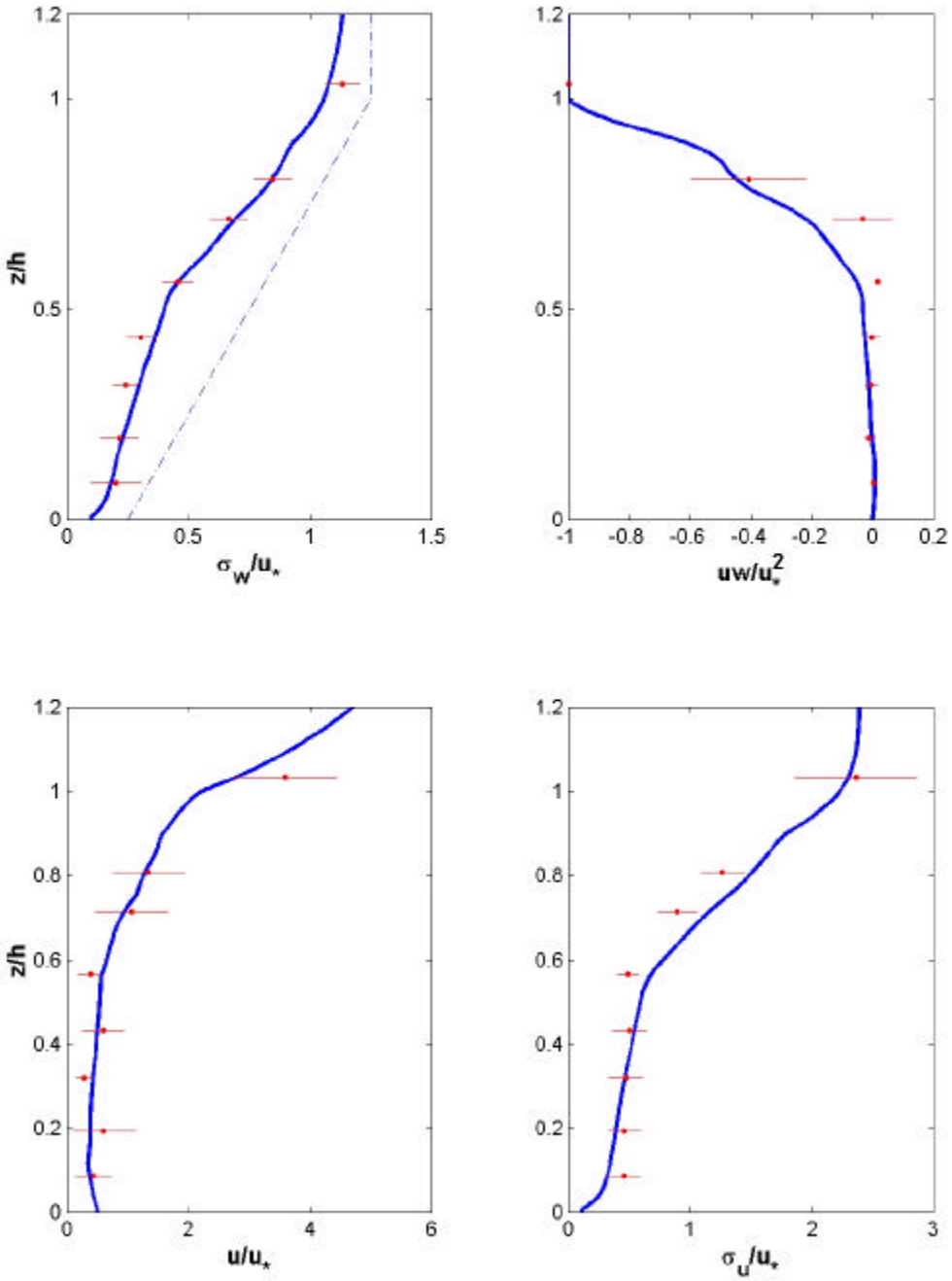
Conservation of Mean Momentum and Reynolds Stress Equations:

$$\frac{\partial < \overline{U_i} >}{\partial t} = ...$$

$$\frac{\partial < \overline{u_i' u_j'} >}{\partial t} = ...$$

- The needed velocity statistics (e.g., s_w) for linking $q \rightarrow C$ are generated from the solutions of the above system of equations.

- The model calculations agree well with experiments at the Pine Forest.

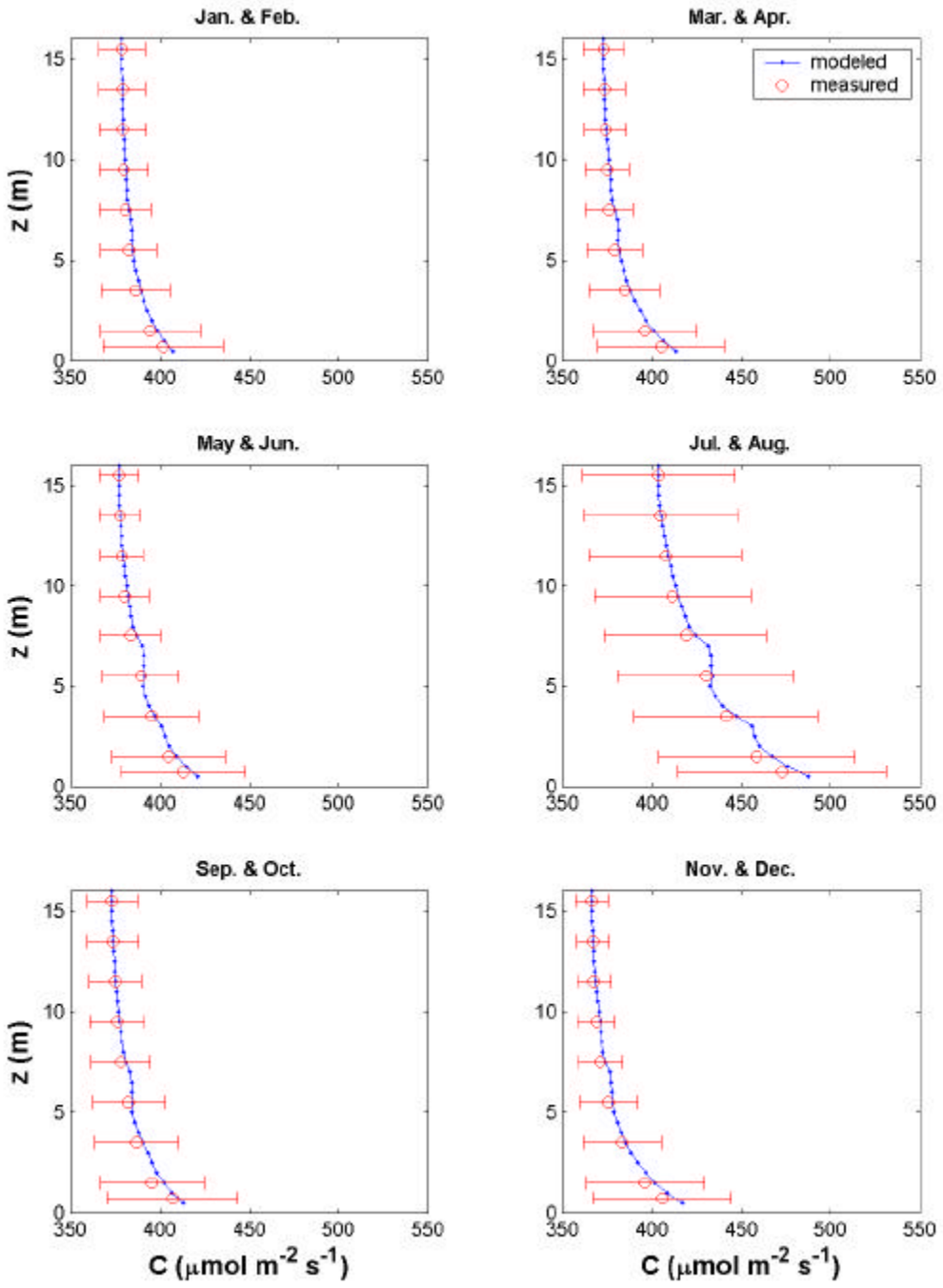


All measurements are for a wide range of stable runs.

Model Results – 2: Optimized Concentration Profiles

Computed $C(z,t)$ based on the optimized a and forest floor flux $F(0,t)$ is compared to measured $C(z,t)$.

Calculations are conducted every 30 minutes – but results are averaged every 2 months to illustrate seasonal patterns.


Jan. & Feb.
Mar. & Apr.
May & Jun.
Jul. & Aug.
Sep. & Oct.
Nov. & Dec.
modeled
measured
z (m)
C (μmol m-2 s-1)
0
5
10
15
350
400
450
500
550

Model Results – 2: Night-Time NEE

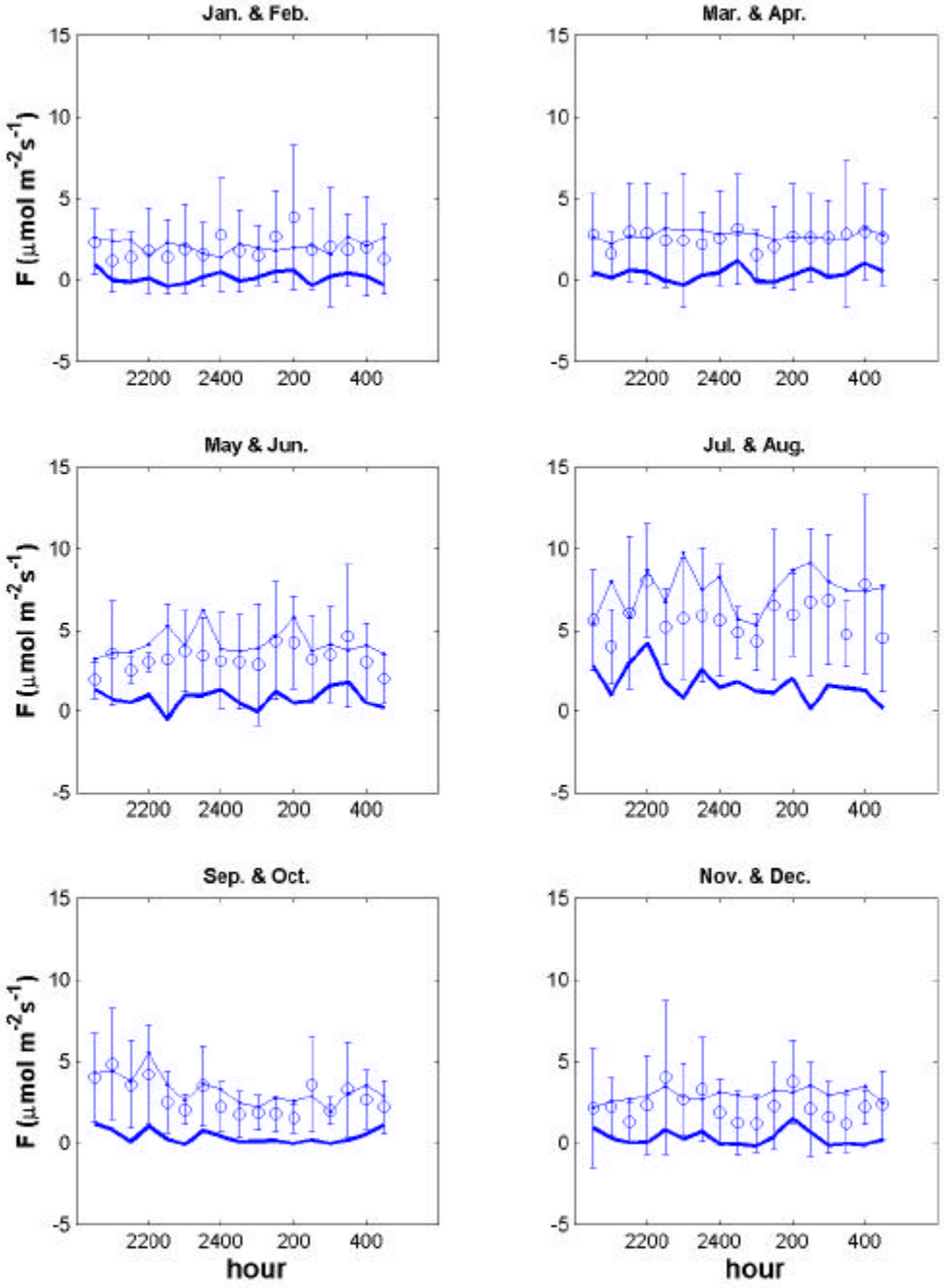
$$\int_0^h \frac{\partial C(t,z)}{\partial t}\,dz + F(t,h) = F(t,0) + \int_0^h S(z,t)\,dz$$

Left Hand Side (all measured):

Storage Flux + Eddy-Covariance Measured NEE

Right Hand Side (all modeled):

Forest Floor Respiration + Total Above Ground Respiration.


Jan. & Feb.
Mar. & Apr.
May & Jun.
Jul. & Aug.
Sep. & Oct.
Nov. & Dec.
F (μmol m-2s-1)
15
10
5
0
-5
2200
2400
200
400
hour

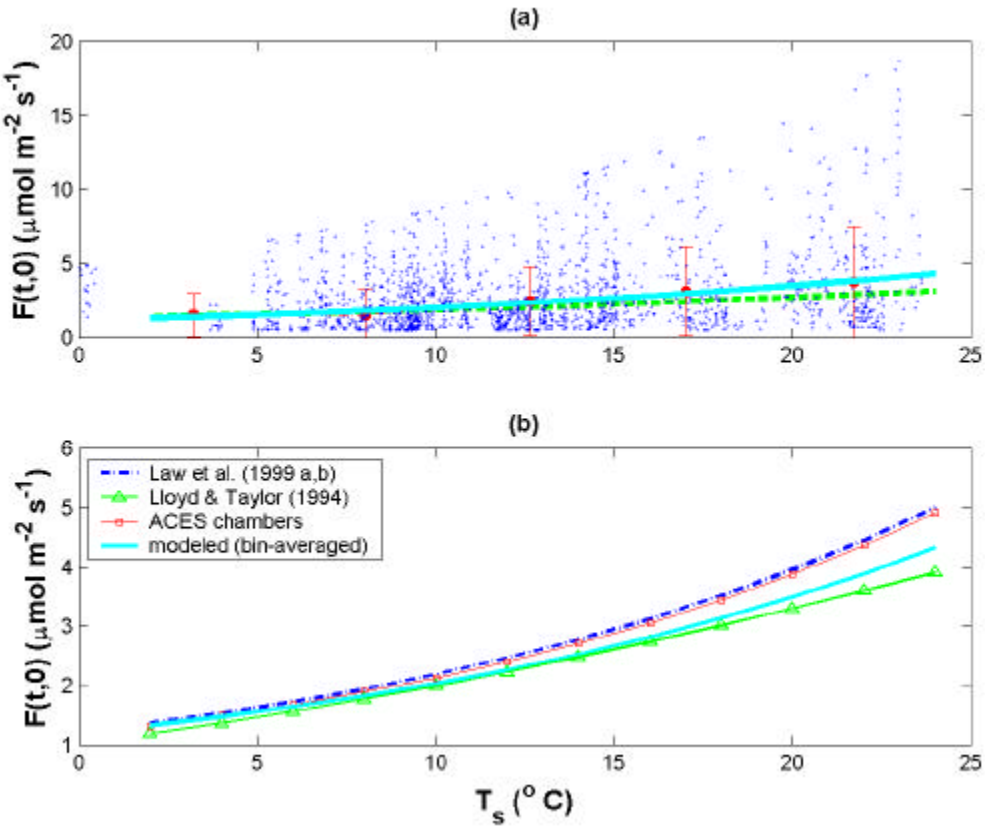
Model Results – 3: Chambers

Literature Data Sets (sample):

- Law et al. (1999) – Pine (Oregon)
- Lloyd and Taylor (1994) – Activation Energy Hypothesis

Data Sets Available at Duke Forest Site

- Butnor – US Forest Service – 15 ACES systems (April-May, 1999; 30 minutes interval)


(a)
F(t,0) (μmol m-2 s-1)
(b)
Law et al. (1999 a,b)
Lloyd & Taylor (1994)
ACES chambers
modeled (bin-averaged)
F(t,0) (μmol m-2 s-1)
Ts (° C)

Model Results – 4: Porometry

Literature Values:

Farquhar et al. (1980); $a = 0.011$

Collatz et al. (1993); $a = 0.015$

Porometry Measurements at Duke Forest:

Only an **upper Limit** on a can be derived from daytime $A - Ci$ curves. Farquhar Model is fitted to 52 daytime $A - Ci$ curves (collected around noon at 12 m in 1999).

From a regression fitting procedure, R_d and $V_{c\max}$ are determined.

- Resulting calculations: $\overline{a}$ =0.025 (± 0.07).

- Model Results: $\overline{a}$ =0.012 (± 0.05).

Model Results – 5: C-Budget

RATES ARE IN g C m^{-2} y^{-1} UNLESS STATED.

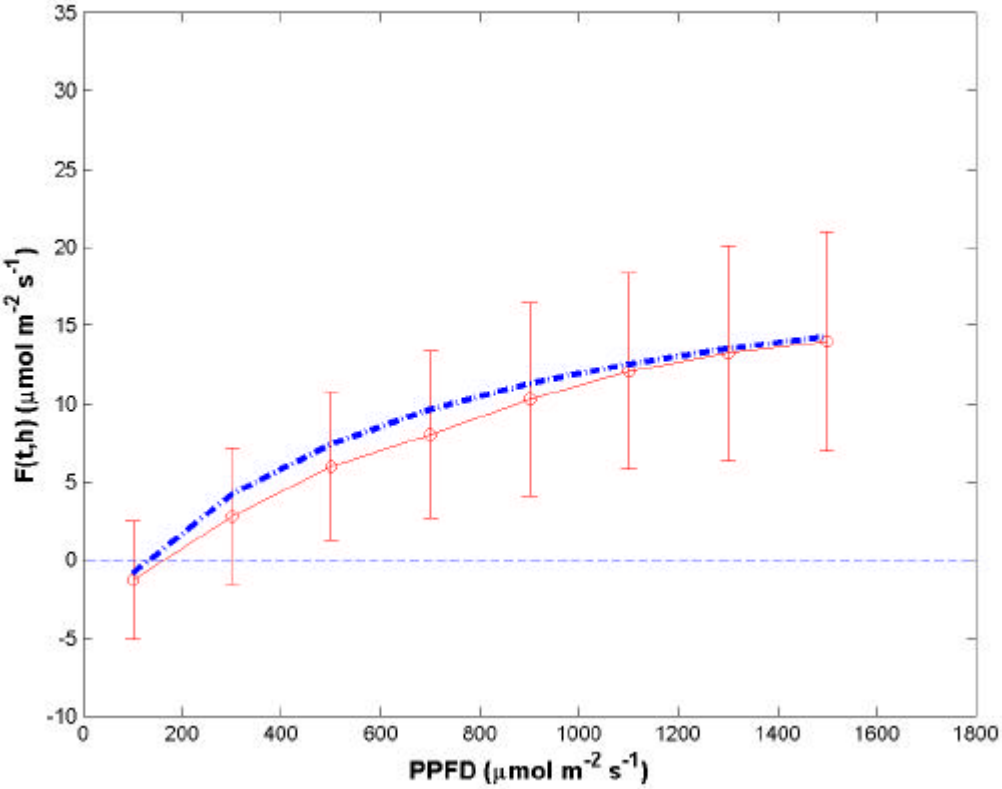
Study site	**NC. Loblolly pine**	**Fl. Slash pine**
Location	36º 2’ N, 79º8’ W	29º44’ N, 82º9’ W
Vegetation type	17-yr-old *Pinus taeda L.*	24-yr-old *Pinus elliotii* var. *elliotii*
Site Index at age 25 years	16 m	15 m
Long-term mean air temperature (ºC)	7.6 (winter) 27.2 (summer)	14 (winter) 27 (summer)
Long-term mean annual rainfall (mm)	1154	1332
Total daytime net C exchange *(estimated from F-PPFD curve)*	*1342*	*1529 (1996)* *1416 (1997)*
Total plant respiration	214	Not reported
Total forest floor respiration	989	1400
Total night time respiration	737	789 (1996) 808 (1997)
NEE =	1342-737 = 605 (630 Eddy-Corr.).	740 (1996) 608 (1997)
GPP =	214+989+605 =1808	> 2008

Comparisons with Florida Slash Pine

Daytime net CO_2 exchange for Florida Slash Pine (Clarck et al., 1999) estimated from:

$$F(t,h) = \frac{a_p \, PPFD F_{sat}}{a_p \, PPFD + F_{sat}} - R_0 \, .$$

- F-PPFD response curves for NC Loblolly and FL Slash Pines compare well.


35
30
25
20
15
10
5
0
-5
-10
0
200
400
600
800
1000
1200
1400
1600
1800
F(t,h) (μmol m-2 s-1)
PPFD (μmol m-2 s-1)

Model Results – 5: C-Budget

Consistency with two established ratios for pines:

- NPP/GPP & R_a/GPP

RATES ARE IN g C m^{-2} y^{-1} UNLESS STATED.

GPP (Model) =	1800	
NPP (DeLucia et al., 1999) =	800	
NPP/GPP =	**0.44**	**0.47**
		Waring et al. (1998)
Forest Floor Flux (Model) =	988	
Andrews et al. 55% of Forest Floor Respiration is Roots $\longrightarrow$		
Root Respiration =	543	
Above Ground Respiration (Model) =	213	
Autotrophic Respiration (R_a) =	756	
		0.33-0.63;
R_a/GPP =	**0.42**	mean = **0.49**
		(Ryan et al., 1994).
Litterfall Turnover + Fine Roots		307+100
Turnover (DeLucia et al. 1999) =		
Microbial Respiration (Model) =	**445**	**407**

Model Results – 5: C-Budget

Consistency with other indirect GPP estimates:

1. Maximum Limit from Leaf Measurements:
Using Fig. 8 in Ellsworth (2000) Tree Physiology for the annual time course of daily photosynthesis **GPP ~ 2300 g C m^{-1} yr^{-1}** assuming all days are sunny (but accounting for sunlit and shaded foliage).

2. *Simple Assimilation Model (Katul et al., 2000)*

$$A = g_c C_a (1 - \frac{C_i}{C_a})$$

Schäfer: $g_c = 70\, mmol\, m^{-2} s^{-1}$; C_a=370 ppm;

C_i / C_a=0.70 (Ellsworth 1999). GPP=**1825 g C $m^{-2}y^{-1}$**.

3. Water Use Efficiency:

Schäfer: Canopy Transpiration = 478+70 mm/year

WUE = 2.06 g C/mm H_2O (Eddy Cov., Sapflux)

Day Time Forest Floor Respiration (CSO)

= 550 g C m^{-2} y^{-1}

GPP = 2.06 ×(478+70) + 550 = **1680 g C m^{-2} y^{-1}.**

Conclusions

- **A wide range of methods employed to estimate GPP. These methods use independent measurements and model assumptions.**

- **All methods independently suggest that GPP~1700-1850 g C m^{-2} y^{-1} for 1999.**

- **GPP estimates are consistent with above and below ground carbon balance and conservative ecological dimensionless ratios.**

Broader Implications

- Contrasting the NEE from the Florida and North Carolina AmeriFlux pine sites with reported NEEs from all the EuroFlux and AmeriFlux sites (Falge et al., 2000), it appears that southeastern pine forests are among the largest atmospheric terrestrial carbon sinks.