High frequency measurements of soil carbon dioxide flux at Harvard Forest

Stephen C. Phillips
University of New Hampshire, Durham

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High frequency measurements of soil carbon dioxide flux at Harvard Forest

Abstract
Soil carbon dioxide flux was measured by automatic chambers at Harvard Forest over a four-year period, 2003-2006. The autochambers were installed along a moisture gradient from upland to wetland soils. In 2003, fluxes from the upland and mid-slope chambers exceeded the fluxes from the wetland margin. In 2004-2006, the mid-slope fluxes were significantly larger than both the upland and wetland margin chambers. The differences in flux between chamber location were most pronounced in the late summer and early fall. Residuals from a non-linear temperature regression exhibit a distinct seasonal pattern in 2003, 2004, and 2006, but not in 2005. On short time scales, the residuals are correlated with soil moisture, responding to precipitation events. The seasonal pattern of soil flux reaches a maximum later in the year than ecosystem respiration measured at the eddy covariance flux tower.

Keywords
Biogeochemistry, Agriculture, Forestry and Wildlife
HIGH FREQUENCY MEASUREMENTS OF SOIL CARBON DIOXIDE FLUX AT HARVARD FOREST

BY

STEPHEN C. PHILLIPS
BS Geology, Michigan Technological University, 2004

THESIS

Submitted to the University of New Hampshire in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Earth Sciences

May, 2007

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This thesis has been examined and approved.

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5/8/07
Date
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ABSTRACT

HIGH FREQUENCY MEASUREMENTS OF SOIL CARBON DIOXIDE FLUX
AT HARVARD FOREST

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University of New Hampshire, May, 2007

Soil carbon dioxide flux was measured by automatic chambers at Harvard Forest over a four-year period, 2003-2006. The autochambers were installed along a moisture gradient from upland to wetland soils. In 2003, fluxes from the upland and mid-slope chambers exceeded the fluxes from the wetland margin. In 2004-2006, the mid-slope fluxes were significantly larger than both the upland and wetland margin chambers. The differences in flux between chamber location were most pronounced in the late summer and early fall. Residuals from a non-linear temperature regression exhibit a distinct seasonal pattern in 2003, 2004, and 2006, but not in 2005. On short time scales, the residuals are correlated with soil moisture, responding to precipitation events. The seasonal pattern of soil flux reaches a maximum later in the year than ecosystem respiration measured at the eddy covariance flux tower.
CHAPTER I

INTRODUCTION

Exchange of carbon dioxide (CO$_2$) between forest ecosystems and the atmosphere is an important component of the global carbon cycle. Soil organic matter (SOM) composes a significant terrestrial reservoir of carbon [Post et al., 1982], that contains approximately twice the carbon present in the atmosphere. Most SOM is stored within several meters of the atmosphere [Jobbagy and Jackson, 2000], subjecting the terrestrial carbon pool to the influence of climatic and biological factors. The terrestrial biosphere can influence the atmospheric burden of CO$_2$, which in turn exerts radiative forcing on the earth's climate. Investigations into imbalances in the global carbon cycle (a.k.a. the "missing sink") suggest that terrestrial ecosystems of the northern hemisphere may be a net sink of carbon with respect to the atmosphere [Tans et al. 1990; Keeling et al., 1996; Schimel et al., 2001].

CO$_2$ enters the ecosystem through leaves via photosynthesis, or gross primary production (GPP), and returns to the atmosphere by way of autotrophic respiration (from both above-ground biomass and roots) and heterotrophic respiration of soil microbes. The balance of carbon fixation and respiration represents the system's net ecosystem exchange (NEE), ignoring episodic disturbance. Quantitative measurements of the response of these processes to
climatic factors are critical to understanding their diurnal, seasonal, and interannual variability, as well as predicting future changes to the carbon balance of an ecosystem.

Efforts to measure NEE in various ecosystems have resulted in the installation of hundreds of micrometeorological flux towers around the world [FLUXNET, see http://www-eosdis.ornl.gov/FLUXNET/]. These towers use an eddy covariance technique to calculate NEE by the net vertical flux of CO$_2$. [Wofsy et al., 1993]. These tower measurements are near-continuous, measuring year-round, however, under low-wind conditions there is insufficient turbulence to drive the vertical movement needed for measurements. Nighttime NEE measurements represent the total ecosystem respiration (ER) as there is no photosynthesis occurring. However, eddy flux tower measurements are most uncertain at night due to more frequent low-wind conditions [Goulden et al., 1996a]. These nighttime NEE values are used to partition daytime NEE measurements into GPP and ER components. ER from the night measurements extrapolated through the daytime NEE measurements using a simple model to calculate GPP by subtracting the modeled ER from NEE. In terms of interannual variability, ER, including the soil respiration (SR) component may be the primary determinant of the net carbon exchange of temperate forests [Valentini et al., 2000; Ehman et al., 2002].

More than ten years of eddy flux measurements from Harvard Forest, a temperate forest in Massachusetts suggest that this forest has been a net sink of atmospheric CO$_2$. Sums of NEE from this tower indicate a net annual uptake of
carbon, and that the amount of net uptake is controlled by climate and ecosystem factors \cite{Wofsy et al., 1993; Goulden et al., 1996b Barford et al., 2001}. Net uptake increased consistently over a time period from 1992-2004, with both GPP and ER increasing over the measurement period; however, GPP increased to a larger extent than ER, resulting in larger net uptake \cite{Urbanski et al., in press}.

Tower eddy covariance ER measurements cannot be partitioned into autotrophic and heterotrophic components, nor can they be separated into above ground and below ground components. Independent chamber measurements of SR are necessary to look at the SR component of ER.

SR is measured using chamber methods in which a chamber is closed over the soil surface and CO$_2$ builds up within the chamber headspace. The rate of change in CO$_2$ mixing ratios is measured to calculate a flux rate as the amount of carbon released per unit area per period of time, typically expressed as $\mu$mol C m$^{-2}$ s$^{-1}$ or mg C m$^{-2}$ hr$^{-1}$. Chambers may be clear, in which the flux represents NEE; or they may be opaque, where the flux is a measurement of soil efflux. Chambers may either be manually or automatically operated. Measurements of CO$_2$ flux from manual and automated chambers (autochambers) do not vary significantly \cite{Burrows et al., 2005}. Manual chambers allow for better spatial coverage than autochambers, however, autochambers provide much better temporal resolution and can make many measurements per day \cite{Savage and Davidson, 2003}. One manual chamber can be used to make measurements at many collars at a site, but since the measurements must be made in person, it is...
normally feasible to make measurements only on time intervals longer than a day, typically weekly.

Autochambers greatly increase the number of measurements that can be recorded since they open and close automatically. High resolution, semi-continuous CO$_2$ flux data, along with other concurrent data (temperature, soil moisture, weather, etc.), provide an excellent opportunity to observe changes in soil flux on shorter time-scales. Compared to manual chambers, autochambers allow for better accuracy in creating empirical models of the effects of temperature and soil moisture on soil respiration [Savage and Davidson, 2003].

Independent flux measurements from chamber systems allow for a better understanding of the soil flux component of ER. In general, comparison of chamber measurements to tower measurements have produced mixed results due to uncertainty in whether the chambers are representative of the tower's footprint [Loescher et al., 2006]. In general, chamber SR measurements comprise a large fraction (45-80%) of tower ER [Lavigne et al., 1997; Davidson et al., 2006a].

Soil flux is the diffusion of CO$_2$ from the soil surface resulting from the combined respiration of free-living soil microbes and roots including mycorrhizal symbionts. Although estimates of the root contribution to soil flux are difficult to obtain and vary greatly by site, results from various root exclusion and isotopic labeling studies indicate that root respiration (including rhizosphere activity) compose a significant fraction (10-90%) of the total SR in forest ecosystems [Hanson et al., 2000]. At Harvard Forest, the live root contribution to SR was
determined to be 33% [Bowden et al., 1993]. Changes in root respiration therefore may produce significant changes in overall soil flux. Decomposition of organic matter through heterotrophic respiration depends on a variety of climatic and soil property factors including temperature, soil moisture, carbon substrate, soil type, and nutrient availability [Davidson et al., 2000]. In the remainder of this paper, 'soil respiration' refers to total soil flux.

Increases in soil temperature are positively correlated with increases in SR [Raich and Schlesinger, 1992]. SOM turnover times decrease with increases in the long-term temperature of a site [Trumbore et al., 1996]. Warmer temperatures due to climate change may increase soil respiration rates, thus making respiration of soil organic carbon a positive feedback with respect to global warming [Houghton et al., 1998; Cox et al., 2000]. Soil warming experiments reveal that on time scales less than a decade, warmer soil temperatures increase SR, net nitrogen-mineralization rates, and plant productivity [Rustad et al., 2001]. Increases in nitrogen mineralization may increase plant growth and carbon storage, offsetting the carbon lost through increased SOM decomposition [Melillo et al., 2002]. No consensus has yet been reached over the long-term soil respiration response to temperature, due to the complexity and heterogeneity of soil organic carbon [Davidson and Janssens, 2006]. Root respiration may be more sensitive to temperature than non-rhizosphere microbial respiration, as shown by higher temperature response for soils with roots than soils without roots at Harvard Forest [Boone et al., 1998].
Increased soil fluxes have been observed during and after wetting events in New England forests [Borken et al., 2003; Lee et al., 2004]. Simulated droughts (rainfall exclusion plots) at Harvard Forest resulted in decreased soil fluxes due to lower organic horizon water content [Borken et al., 2006]. In upland locations, natural droughts reduced SR at Harvard Forest, however, SR increased in drying wetlands during the same droughts [Savage and Davidson, 2001]. Low soil moisture has been found to decrease fine root respiration [Burton et al., 1998]. Statistically separating the temperature and soil moisture effect on SR can be difficult since temperature and soil moisture covary seasonally [Davidson et al., 2003].

This paper analyzes SR data, measured by autochambers on a hill-slope at Harvard Forest, for seasonal and interannual controls, as well as the effect of chamber location. The temperature and soil moisture effects are explored, and other possible factors are discussed. The autochamber SR measurements were compared qualitatively to the eddy covariance flux tower at Harvard Forest.
CHAPTER II

METHODS

Site Description

The Harvard Forest Environmental Measurement Site (EMS) is located near Petersham, Massachusetts (42° 32' N 72° 11' W) at an elevation between 220 and 410 m. Harvard Forest is a 50-70 year old second-growth mixed forest located on abandoned agricultural land that is representative of a typical New England forest [Foster, 1992]. The dominant tree species are red oak (Quercus rubra) and red maple (Acer rubrum), with smaller numbers of white pine (Pinus strobus) and hemlock (Tsuga canadensis).

The eddy covariance flux tower is located at the EMS site in the Prospect Hill Tract at Harvard Forest and has been measuring NEE since 1990. The eddy covariance instrumentation at Harvard Forest is described by Wofsy et al. [1993] and Goulden et al. [1996a]. Additional investigations into the uncertainties of the eddy covariance method are described in Baldocchi et al. [2000], Falge et al. [2001], Hagen et al. [2006], and Loescher et al. [2006].

Instrumentation

A system of eight automatic CO₂ flux chambers was installed near the flux tower at the EMS site in April 2003. These autochambers were operated from
April through November during 2003, and April through December during the years 2004, 2005, and 2006. The autochambers exist along a moisture gradient from a beaver pond to an upland forest (Figure II.1). The bottom of the slope is characterized by poorly-drained wetland soils; soils at the top of the slope are well-drained upland soils. The system at Harvard Forest is similar to autochamber soil flux instrumentation used in a boreal forest [Goulden and Crill, 1997], a tropical agricultural soil [Crill et al., 2000], and a temperate peatland [Bubier et al., 2003].

Each aluminum opaque chamber contains a volume of 38,100 cm$^3$ (43.2 cm x 43.2 cm x 15.2 cm) and covers a soil surface area of 1866 cm$^2$. The chamber closes over a metal frame that extends 2 cm into the soil. Air from the chamber headspace is pumped through an infrared CO$_2$ gas analyzer (IRGA, Model LI-820, Li-Cor, Lincoln, Nebraska), and the air is then returned to chamber to minimize pressure effects on fluxes. Changes in pressure can disturb the natural diffusion of gas between the soil and atmosphere [Bain et al., 2005; Davidson et al., 2002], thus causing error in flux calculations.

The measurement system is controlled by a datalogger (CR10X, Campbell Scientific, Logan, UT) and 16 port relay that opens and closes the chambers according to set measurement cycle. Each measurement cycle takes 30 minutes, including time to flush the transfer tubing (10 minutes before and 12 minutes after each 8 minute measurement). Consequently, a flux is recorded at each autochamber every four hours. At each chamber there is a thermocouple measuring temperature of the air and at 2 cm soil depth. The CO$_2$
measurements are stored on the datalogger until they are downloaded onto a computer every week to two weeks. CO₂ fluxes are calculated by fitting a line, using least-squares linear regression, to the increase in CO₂ mixing ratios over time, recorded while the autochamber is closed. The resulting slope from this fit (Δppmv/min) is used to calculate the flux rate in μmol C m⁻² s⁻¹:

\[
\frac{Δppmv}{min} \times \frac{P}{RT} \times \frac{V_c}{A_c} \times \frac{min}{60 \text{ s}} = \frac{μmol}{m^2 s}
\]

where P is pressure (atm), T is temperature (°K), V_c is chamber volume (L) and A_c is soil surface area (m²), and R is the gas constant (0.082058 L atm mol⁻¹ K⁻¹).

Figure II.1 Locations of the autochambers along the moisture gradient: Vertical axis is the vertical distance of the chamber above the wetland. Horizontal axis is the horizontal distance from the wetland margin.
The ambient mixing CO\textsubscript{2} ratio (y-intercept from the fit) and the R\textsuperscript{2} is stored in addition to the flux and air/soil temperature measurements. A minimum R\textsuperscript{2} of 0.85 was set as criteria for accepting fluxes; any flux resulting from a linear fit of Δppmv/min with an R\textsuperscript{2} below this value was rejected.

Additional soil temperature and soil moisture measurements are recorded at three soil profiles along the slope (wetland margin, mid-slope, and upland soils) and at four depths at each profile. The depth and soil horizon of each measurement in the soil profiles are summarized in Table II.1. These soil and temperature profiles were installed in May 2004 and record hourly observations. Soil temperatures are measured using thermocouple probes (Type-T thermocouples, Omega Engineering, Stamford, CT) and soil moisture is recorded with time domain reflectometry probes (ECH\textsubscript{2}O probes, Decagon Devices, Inc., Pullman, WA) that are inserted at the base of each horizon.

Table II.1: Soil Profile Descriptions: Location along the soil profile, soil horizon, and depth in cm of the soil temperature and soil moisture profile data.

<table>
<thead>
<tr>
<th>Slope location</th>
<th>Soil horizon</th>
<th>Depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetland Margin</td>
<td>Litter</td>
<td>2.50</td>
</tr>
<tr>
<td></td>
<td>Organic Shallow</td>
<td>7.00</td>
</tr>
<tr>
<td></td>
<td>Organic Deep</td>
<td>18.75</td>
</tr>
<tr>
<td></td>
<td>Mineral</td>
<td>30.00</td>
</tr>
<tr>
<td>Mid-slope</td>
<td>Litter</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Organic</td>
<td>5.00</td>
</tr>
<tr>
<td></td>
<td>Mineral Shallow</td>
<td>16.25</td>
</tr>
<tr>
<td></td>
<td>Mineral Deep</td>
<td>30.00</td>
</tr>
<tr>
<td>Upland</td>
<td>Litter</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>Organic</td>
<td>5.00</td>
</tr>
<tr>
<td></td>
<td>Mineral Shallow</td>
<td>15.00</td>
</tr>
<tr>
<td></td>
<td>Mineral Deep</td>
<td>30.00</td>
</tr>
</tbody>
</table>

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Data Analysis

All data were analyzed using Matlab 7.1 (Mathworks, Natick, MA) and JMP 6.0.2 (SAS Institute, Inc., Cary, NC). The flux measurements were filtered to remove near-zero measurements that represent times when the IRGA is not operating, or negative flux values that cannot occur (CO₂ uptake is not possible in a dark chamber). A flux detection limit was created to determine the lowest flux value that could be determined by the autochamber system. Using the stated precision of the IRGA instrument of 1 µmol/mol, the minimum detectable slope that is significantly larger than zero was calculated. All fluxes below this threshold of 0.0024 µmol CO₂ m⁻² s⁻¹ were eliminated from the data.

The autochamber data were grouped into three locations according to their position along the slope. The four autochambers in the wettest soils (chambers 1, 3, 5, and 8) that are closest to the beaver pond are referred to as the “wetland margin” chambers. The two autochambers partway up the slope (chambers 4 and 6) are the “mid-slope” chambers, and the two autochambers at the top of the slope (chambers 2 and 7) in the driest soils are the “upland” autochambers.

Monthly averages of SR were compared using analysis of variance (ANOVA) and a multiple comparison method, Hsu's Method of Multiple Comparisons with the Best [Hsu, 1981], to compare the three chamber locations at a significance level of α = 0.05. ANOVA indicates whether the chamber location has a significant effect on flux, and Hsu's method compares monthly
means from each group to determine whether each is the highest or lowest. Hsu's method uses confidence intervals of each mean and the unknown maximum and minimum to detect differences. This method is less likely to produce Type I error, while maintaining good power to detect significant differences.

Time series of SR from the three locations were smoothed using a robust-spline function with a tension of 0.2. There are large gaps in the dataset that can introduce error into standard running-mean and running-median smoothing functions. Instead, data were smoothed using robust-spline smoothing, an adaptive-weighting method [Mosteller and Tukey, 1977] used to fit a natural spline function [Lancaster and Salkaukas, 1986] to the data.

Relationships relating the rate of SR to temperature were derived by plotting CO₂ efflux against soil temperature. A simple, exponential function was fit to the data using nonlinear least-squares regression to estimate the temperature sensitivity of soil respiration at each autochamber. The data were fit with an Arrhenius-type equation, the Lloyd and Taylor (L & T) function:

\[ \text{SR} = A e^{\frac{-E_o}{(T-T_o)}} \]

where SR is soil respiration, A is a scaling factor, T is the soil temperature, T₀ is a reference soil temperature, and E₀ is the activation energy-adjusted soil temperature [Lloyd and Taylor, 1994]. All temperatures are in Kelvin. Since A and E₀ have similar sensitivity [Richardson and Hollinger, 2005], E₀ was fixed to a constant value of 308 K [Lloyd and Taylor, 1994] to provide a more calculable
fit. Error in the fit parameters was estimated using a Monte Carlo method to calculate 95% confidence intervals.

In addition to the least-squares method, a 90th quantile fitting routine [Koenker, 2005] was used for estimating the highest range of temperature response; the flux-temperature relationship when all factors are ideal for respiration, and temperature is the dominant control. Regression quantiles are calculated by assigning differing weights (quantiles) to positive and negative residuals while optimizing a fit to the given weight [Koenker and Hallock, 2001]. In essence, multiple parameters can be fit to the data from the smallest to largest response [Cade and Noon, 2003]. Using regression quantiles allows for better estimates of limiting factors in ecological processes than using traditional least-squares regression [Cade et al., 1999]. Quantile regression creates an opportunity for an alternative residual analysis of the temperature fit.

The regression analysis resulted in a set of residuals that represents the fluxes not explained by temperature. The residuals were analyzed by time of year and for relationship with soil moisture.

**Gap-filling**

Gaps in the data were filled using a statistical approach involving the non-linear response of CO₂ flux to temperature. The nearby Fisher meteorological station records high resolution (hourly) 10 cm soil temperature data, and this data is used as a basis for filling the missing chamber measurements (see Discussion section). The temporally closest meteorological station soil temperature was
always within half an hour of a missing chamber measurement. Fit parameters A and $T_0$ from the L & T function were calculated individually for each chamber in each year using nonlinear regression. These parameters were used to predict a most-likely flux value for a given soil temperature. Uncertainty in the predictions of the nonlinear model were estimated using a bootstrapping technique that was used to simulate data 1000 times with random scatter created to resample residuals to test the fit of the regression model. Bootstrapping produced one standard deviation intervals as well as 95% prediction intervals for the fit of each L & T regression line.

Gap-filling of the soil fluxes was accomplished by applying the fitted regression parameters for each chamber and year to the soil temperature dataset. The predicted values from the soil temperature-soil efflux relationship were used to create the filled flux values, and the 95% prediction intervals were used to estimate the uncertainty of each filled value. The gap-filled dataset was used to create annual sums of respiration. Uncertainty from the gap-filling was maintained in the summation process and applied to the annual sums.
CHAPTER III

RESULTS

Data

The chamber measurements resulted in a large number of relatively continuous measurements with some gaps, usually due to power or compressor failure. Failure due to mechanical issues resulted in simultaneous gaps in all eight chambers. Removal of near-zero or negative fluxes using the flux detection limit created additional gaps in the data, however, this generally affected the chambers individually. Many of these removed fluxes correspond to times when the system was not operating properly, based on notes logged in field books. A higher percentage of fluxes were removed in data from the years 2005 and 2006 (Table III.1). The fewest gaps occurred in 2004 (Tables III.2 and III.3), with all gaps shorter than 4.2 days. Longer gaps occurred in the years 2003, 2005, and 2006, with gaps of up to 20.5, 27.6, and 16.4 days respectively.

Table III.1: Percent of flux measurements below flux detection limit: Detection limit calculated as 0.0024 μmol m$^{-2}$ s$^{-1}$. Near-zero fluxes occurred most frequently in 2005 and 2006

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>1.7</td>
<td>6.0</td>
<td>3.5</td>
<td>0.9</td>
<td>1.0</td>
<td>0.4</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>2004</td>
<td>0.2</td>
<td>1.0</td>
<td>3.0</td>
<td>0.5</td>
<td>0.4</td>
<td>1.3</td>
<td>1.2</td>
<td>0.0</td>
</tr>
<tr>
<td>2005</td>
<td>11.6</td>
<td>9.8</td>
<td>7.4</td>
<td>6.8</td>
<td>6.4</td>
<td>14.2</td>
<td>16.2</td>
<td>22.0</td>
</tr>
<tr>
<td>2006</td>
<td>13.9</td>
<td>19.3</td>
<td>44.3</td>
<td>14.5</td>
<td>12.6</td>
<td>13.6</td>
<td>13.5</td>
<td>30.2</td>
</tr>
</tbody>
</table>
Table III.2 Percent Gaps During Measurement Period: A gap is determined by a missing measurement, based on the nominal measurement interval of every four hours. Gaps here include removed data below flux detection limit.

<table>
<thead>
<tr>
<th>Year</th>
<th>Chamber 1</th>
<th>Chamber 2</th>
<th>Chamber 3</th>
<th>Chamber 4</th>
<th>Chamber 5</th>
<th>Chamber 6</th>
<th>Chamber 7</th>
<th>Chamber 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>29.9</td>
<td>35.2</td>
<td>32.3</td>
<td>28.8</td>
<td>29.2</td>
<td>28.5</td>
<td>28.8</td>
<td>28.8</td>
</tr>
<tr>
<td>2004</td>
<td>10.0</td>
<td>11.4</td>
<td>13.9</td>
<td>10.6</td>
<td>10.3</td>
<td>11.4</td>
<td>11.6</td>
<td>9.8</td>
</tr>
<tr>
<td>2005</td>
<td>34.6</td>
<td>34.0</td>
<td>30.1</td>
<td>28.9</td>
<td>29.2</td>
<td>31.8</td>
<td>31.6</td>
<td>39.4</td>
</tr>
<tr>
<td>2006</td>
<td>17.8</td>
<td>26.9</td>
<td>62.1</td>
<td>17.7</td>
<td>14.5</td>
<td>16.7</td>
<td>16.1</td>
<td>37.9</td>
</tr>
</tbody>
</table>

Table III.3 Number of Full Days Missing During Measurement Period: These are days in which there are zero flux measurements.

<table>
<thead>
<tr>
<th>Year</th>
<th>Chamber 1</th>
<th>Chamber 2</th>
<th>Chamber 3</th>
<th>Chamber 4</th>
<th>Chamber 5</th>
<th>Chamber 6</th>
<th>Chamber 7</th>
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<td>31</td>
<td>30</td>
<td>30</td>
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34,461 total flux measurements were used in this analysis (Figure III.4).

SR statistics for each chamber and chamber grouping are summarized in Table III.4. The highest average fluxes were recorded at the mid-slope chambers, and the lowest fluxes from the wetland margin. The differences between the chamber groupings are more pronounced in the years 2004, 2005, and 2006. There is more scatter in the flux data during the years 2004 and 2005, as demonstrated by larger standard deviations and higher maximum and upper quartile fluxes.
Comparison by Slope Location

Time series of the flux data illustrates the seasonal variation in SR and variation between autochamber locations (Figure III.1). Calculating daily SR averages and smoothing with a robust-spline smoothing (tension 0.2) shows the seasonal trend and differences between hillslope locations more clearly than the raw data (Figure III.2). In 2003, the upland and mid-slope chambers had similar SR magnitudes that are higher than the wetland margin. In 2004, 2005, and 2006, the mid-slope SR was higher than the upland or wetland margin.

When monthly average fluxes were compared between chamber locations, the differences in SR were significant at an $\alpha = 0.05$ significance level during the late summer and early fall months. ANOVA demonstrates that chamber location has a significant effect on SR in most months (all but April 2003 and April 2004). Hsu's method shows that the average mid-slope SR was significantly higher than the upland or wetland margin average SR in July-September of the years 2004, 2005, 2006 (Table III.5). In the same period of 2003, monthly average fluxes from the mid-slope and upland chambers were significantly higher than wetland margin SR.

Nonlinear Regression

Results of the nonlinear least-squares fitting of SR and 10 cm soil temperature data using the L & T function resulted in different best-fit A and $T_0$ parameters with 95% confidence intervals calculated from Monte Carlo simulations, and a set of residuals (Figure III.3). The goodness-of-fit ($R^2$) varied by chamber and year,
and ranged from 0.37-0.77. Nonlinear 90th quantile regression also resulted in $A$ and $T_0$ values and residuals. Based on the 95% confidence intervals, many of the L & T fit parameters were significantly different between chambers and chamber groupings (Table III.6). Larger $A$ parameters cause a steeper temperature response, while larger values of $T_0$ tend to cause a flatter response.

Table III.4 Summary Statistics: Includes mean flux, 95% confidence intervals (C.I.) of the mean, maximum flux, upper quartile, 95th percentile, and total number of measurements.

<table>
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<th>Autochamber</th>
<th>Year</th>
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<th>+/- 95% C.I.</th>
<th>Standard Deviation</th>
<th>Maximum Flux</th>
<th>Upper Quartile</th>
<th>0.95 Quantile</th>
<th>Number of measurements</th>
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Figure III.1 All Flux Measurements from the Years 2003-2006: Wetland margin fluxes are shown in red, mid-slope in blue, and upland in green.
Figure III.2 Smoothed Daily Mean Fluxes from the Years 2003-2006. Averages are smoothed using a robust-spline function with a tension of 0.2. Wetland margin fluxes are shown in red, mid-slope in blue, and upland in green.
Table III.5 Results of ANOVA and Hsu’s Multiple Comparison Method: Results at α = 0.05, indicating that in 2004-2006 monthly average SR from the mid-slope were significantly higher than the wetland and upland SR in the late summer/early fall. Upland and mid slope SR were significantly higher than wetland margin SR during these months.

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Wetland Margin Soil flux (umol m^-2 s^-1)</th>
<th>Mid Slope</th>
<th>Upland</th>
<th>ANOVA p-value</th>
<th>Hsu’s method</th>
<th>Wetland margin vs. Max p-value</th>
<th>Mid slope vs. Min p-value</th>
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Autochamber fluxes

Least-squares fit

90th quantile fit

\[ R = 1813e^{\frac{-308}{T + 273 - 237}} \]

\[ R = 1073e^{\frac{-308}{T + 273 - 236}} \]

**Figure III.3 Soil Flux Response to Temperature:** Derived by fitting data with an Arrhenius-type equation. Nonlinear fitting using least-squares (in red) and a 90th quantile regression (In blue) were used. Data from mid-slope chambers during 2004 are shown.

Regression results with a larger A, tend to have a larger \( T_0 \) (Figure III.4) but the increases of \( T_0 \) become lessened at larger values of A.

**Residuals**

SR residuals from the soil temperature regression demonstrate a distinct seasonal pattern with more negative residuals in the spring/early summer and more positive residuals in the late/summer early fall (Figure III.5). The seasonality of the residuals varies by chamber location. In each year, the mid-slope chambers demonstrated more extreme seasonal variation (lower negative
residuals and higher positive residuals) than the upland or wetland margin chambers. The pattern of residuals shows interannual variability. 2003 shows a small seasonal trend in which the upland and mid-slope residuals follow a similar pattern, and the wetland margin residuals have a smaller seasonal trend. There is a strong seasonality to the residuals during 2004 and 2006, in which the mid-slope has the largest seasonality, the upland has an intermediate response, and the wetland margin has the smallest residuals. 2005 shows little seasonal variation in any of the hillslope locations.

The seasonal pattern is also apparent when plotting monthly average fluxes against monthly average 10 cm soil temperature (Figure III.6). These graphs reveal a hysteresis effect, in which a soil at a given temperature in the fall has a larger SR than in the spring. The hysteresis loops, when separated by autochamber grouping, follow a pattern similar to the residual time series. In 2003, the mid-slope and upland have similarly large seasonal patterns, while the wetland margin exhibited a smaller pattern. In 2004-2006, the mid-slope demonstrated a much larger seasonal trend than either the upland or wetland margin.
Table III.6 Nonlinear Regression Parameters: L & T fit of SR with 10 cm temperature for both least-squares regression (includes $R^2$, and 95% confidence intervals from Monte Carlo simulations) and 90th quantile regression.

<table>
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<th>Autochamber</th>
<th>Year</th>
<th>$R^2$</th>
<th>Wetland Margin 1, 3, 5, 8</th>
<th>Upland 2, 7</th>
<th>Mid-slope 4, 6</th>
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Wetland Margin 1, 3, 5, 8

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Figure III.4 The fitted L & T parameters, A and T₀: Calculated from nonlinear least-squares regression tend to increase simultaneously, however the increases in T₀ are lessened at larger values of A. The relationship between the two parameters is best described by a natural logarithmic function.

On shorter time scales residuals are correlated with precipitation events and soil moisture. Short-term positive residuals occur within one or two days of rain and decreases with declining soil moisture (Figure III.7). Direct relationships between the SR residuals and soil moisture were not quantifiable over the entire measurement period due to the larger seasonal pattern. Residuals also followed a diurnal pattern in which the residuals are higher during nighttime than in the daytime (Figure III.7). For a given 10 cm soil temperature, SR is at a maximum during the late evening to early morning hours and at a minimum during midday.
Figure III.5 Smoothed Daily Average Residuals: Residuals from the least-squares regression were averaged for each day and smoothed using robust-spline smoothing (tension 0.2). Mid-slope chambers (blue) show a stronger seasonal trend in the residuals than Daily average residuals smoothed using robust-spline smoothing (tension 0.2). Mid-slope chambers (blue) show a stronger seasonal trend in the residuals than the upland (green) or wetland margin (red).
Figure III.6 Monthly Average Soil Temperature versus Monthly Average Soil Efflux: Demonstrates a hysteresis effect with higher fluxes for a given temperature in the fall than in the spring/early summer.

Figure III.7 Residuals and Soil Moisture: Time series of residuals (individual measurements and daily averages) and 5 cm organic horizon soil moisture over a 16-day period.
**Tower Comparison**

Qualitative comparisons of the SR data to the eddy flux tower data from the years 2003 and 2004 show a difference in the seasonal patterns of SR and ER (Figure III.8). ER reaches a peak early in the summer, while SR is at a maximum later in the summer. Likewise, SR comprises a higher fraction of ER during the late summer/early fall. High SR/ER ratios correspond to periods in which there are positive residuals (Figure III.9).

---

**Figure III.8 Tower and Autochamber Time Series**: Flux tower gap-filled ER measurements from 2003 and 2004 were compared to SR from all three hill-slope groupings, expressed as daily averages and smoothed with robust-spline smoothing (tension 0.2). SR comprises a large fraction of, or exceeds, ER, except early and late in the growing season.
Residuals and SR/ER Ratio: Daily average residuals from mid-slope chambers (black) show a similar pattern to the soil flux/ecosystem respiration ratio. Red line is 1:1 SR/ER and black line is zero residual.

Seasonal hysteresis in the tower ER data is approximately the reverse of the hysteresis of the SR (Figure III.10). For a given soil temperature, ER is higher in the spring than in the fall.

Figure III.10: Monthly average soil temperature vs. monthly average gapfilled eddy covariance tower ER.
**Gap-filling and Annual Sums**

Gap-filling resulted in predicted values inserted at four hour intervals (same as sampling interval) into the dataset in times of missing data (Figure III.11) and uncertainty of the predicted values from 95% prediction intervals from the bootstrapping technique.

![Figure III.11 Gap-filled Time Series](image)

*Figure III.11 Gap-filled Time Series: Daily average fluxes (solid line) and daily averages of gap-filled values (dashed line) from the three chamber locations, smoothed with a robust-spline function.*

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Uncertainty in each filled value was quite high (sometimes 100% of the filled value), but the uncertainty decreased when the gap-filled datasets were summed to calculate annual respiration rates (Table III.7). Annual sums were calculated for each chamber grouping and all chambers combined (Figure III.12). The annual flux calculated using all chambers did not vary significantly between years. Overall SR in 2006 was lower than the previous three years, but not outside the range of uncertainties. Annual SR from the wetland margin and upland chambers were each lower in 2006 than the same chambers in 2003-2005. There were significant differences between chamber locations. Annual flux of the wetland margin chambers was lower than the upland and mid-slope chambers in 2003. In 2004-2006, the wetland margin and upland flux were similar, and significantly lower than the mid-slope chambers. Ignoring uncertainties associated with each annual sum, the wetland margin and upland fluxes decreased over the four-year period, while the mid-slope fluxes increased. However, the uncertainties with each annual sum is so large that increases and decreases between years are not significantly significant.

Table III.7 Annual Flux: Annual sums of soil flux (kg of carbon per square meter per year) with uncertainties calculated from 95% prediction intervals in gap-filling.

<table>
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<th>Year</th>
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<th>Mid-slope</th>
<th>Upland</th>
<th>All chambers</th>
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<td>0.80 ± 0.05</td>
<td>0.78 ± 0.05</td>
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<td>0.61 ± 0.07</td>
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<td>2005</td>
<td>0.64 ± 0.09</td>
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<td>2006</td>
<td>0.56 ± 0.05</td>
<td>0.91 ± 0.05</td>
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</table>

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Figure III.12 Annual Flux Sums: Annual sums of soil flux (grams of carbon per square meter per year) for each chamber location and all chambers combined, with error bars from uncertainty derived from the gap-filling process.
CHAPTER IV

DISCUSSION

SR measurements from this dataset cover a large enough sampling period to capture seasonal and interannual variability, and are at a sufficient resolution to resolve diurnal and weather patterns. Gaps in the data prevent analyses of some short-term events, but seasonal trends are quite apparent. The large number of measurements allow for a good empirical representation of the SR temperature response, and a large set of residuals from the temperature regression.

Filtering by removing low-fluxes (below the 0.0024 µmol m² s⁻¹ detection limit) may introduce some bias into the data. It is possible that some of the low fluxes may actually be zero fluxes, and not an inaccurate measurement. Since most of the growing season is measuring fluxes significantly larger than zero, a near-zero flux is a good indication of a malfunctioning system or other reason to remove a flux. However, in certain times of the year there are actual low or zero fluxes that may have been removed by the filtering process (Table IV.1). In 2003 and 2004, there is little seasonal variation in the percent fluxes removed by month. In 2005, a very high percentage of measurements from November and December were removed. 2006 contains little seasonal bias, but a large
percentage of removed measurements associated with instrumentation problems.

Table IV.1 Percentage SR Measurements Removed by Month: Percentage of SR measurements in each month that were below the flux detection limit of 0.0024 μmol m⁻² s⁻¹.

| Year | Location       | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|------|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 2003 | Wetland Margin | 2   | 1   | 2   | 1   | 0   | 1   | 6   | -   | -   | -   |
|      | Mid-slope      | 0   | 0   | 1   | 1   | 0   | 1   | 0   | 2   | -   | -   |
|      | Upland         | 7   | 3   | 3   | 1   | 0   | 2   | 8   | 7   | 1   | -   |
| 2004 | Wetland Margin | 2   | 1   | 0   | 0   | 0   | 5   | 1   | 0   | 1   | -   |
|      | Mid-slope      | 0   | 0   | 2   | 2   | 0   | 0   | 0   | 0   | 4   | -   |
|      | Upland         | 0   | 0   | 3   | 0   | 0   | 0   | 1   | 3   | 3   | -   |
| 2005 | Wetland Margin | 0   | 0   | 0   | 0   | 1   | 3   | 8   | 79  | 72  | -   |
|      | Mid-slope      | 0   | 0   | 0   | 0   | 0   | 0   | 2   | 83  | 64  | -   |
|      | Upland         | 4   | 0   | 0   | 1   | 1   | 3   | 6   | 84  | 97  | -   |
| 2006 | Wetland Margin | 15  | 32  | 85  | 38  | 17  | 17  | 61  | 37  | 15  | -   |
|      | Mid-slope      | 4   | 4   | 51  | 29  | 0   | 0   | 40  | 30  | 3   | -   |
|      | Upland         | 6   | 10  | 55  | 32  | 3   | 1   | 40  | 39  | 4   | -   |

Fluxes measured by these autochambers are similar to fluxes measured by other automatic and manual systems at Harvard Forest, with some differences depending on year and chamber location. SR from late June to late August in 2002 as measured by both manual and autochambers resulted in mean fluxes of 4.56 ± 0.32 and 4.61 ± 0.49 μmol m⁻² s⁻¹ respectively [Savage and Davidson, 2003]. Our mean fluxes for all chambers during 2003, 2004, and 2006 during the same June to August measurement period are lower (4.08 ± 0.05, 4.32 ± 0.06, and 4.02 ± 0.07 μmol m⁻² s⁻¹) than those from 2002 reported by Savage and Davidson [2003], and these differences are significantly different (5% confidence level) in 2006. In 2005, fluxes are significantly larger (5.47± 0.10 μmol m⁻² s⁻¹), however, a substantial percentage of the time period is missing in 2005 and this may bias the mean SR towards larger values. This comparison demonstrates that interannual variability in one set of chambers is large, which presents
difficulties when comparing flux measurements from different years and different methods.

Spatial heterogeneity of soils also presents a challenge in comparing different sets of SR measurements. When comparing each chamber grouping separately to the 2002 chamber measurements by Savage and Davidson [2003], SR from the upland chambers, averaged over 2003-2006 during the same time period, was most similar ($4.24 \pm 0.07 \mu\text{mol m}^2 \text{s}^{-1}$), the mid-slope was significantly higher ($5.43 \pm 0.08 \mu\text{mol m}^2 \text{s}^{-1}$), and the wetland was significantly lower ($4.03 \pm 0.04 \mu\text{mol m}^2 \text{s}^{-1}$). There is a large amount of variability between locations, which should be considered when SR measurements are compared, even within the same site.

The annual SR rates measured by the autochambers from 2003-2006 are in a similar range as values from 1995-1999 reported by Savage and Davidson [2001]. Annual SR from manual measurements at Harvard Forest ranged from 0.44 to 0.99 kg C m$^2$ yr$^{-1}$ on well-drained soils, 0.41 to 0.81 on moderately-drained soils, and 0.37 to 0.55 on poorly-drained soils. Annual sums from the autochambers 2003-2006 ranged from 0.54 to 0.78 kg C m$^2$ yr$^{-1}$ on the upland soils, 0.80 to 0.99 on the mid-slope soils, and 0.56 to 0.67 on the wetland margin soils. Both sets of data demonstrate large interannual variability.

**Slope Differences**

Differences in SR between the chamber groupings are largely unexplained. One would expect the wetland margin chambers to consistently
measure the lowest fluxes since they are located on the wettest soils where \( O_2 \) diffusion may be limiting respiration. Wetland margin chambers measure the lowest fluxes in the years 2003 and 2004, but in 2005 and 2006, the wetland margin SR is similar to that measured by the upland chambers. This indicates that another factor besides temperature and soil moisture is affecting fluxes.

SR measured by the mid-slope chambers is consistently higher than the upland and wetland margin chambers during the late summer months in 2004-2006. The soils of the mid-slope and upland are quite similar in terms of vertical structure and vegetation. Both the upland and mid-slope soil profiles have a shallow base of the litter (1.25 and 1.0 cm) and organic layers (15 and 16.25 cm), when compared to the wetland margin (2.5 cm litter, 18.75 organic). The vegetation in the upland and mid-slope is similar with mainly mature trees and little understory vegetation. One would expect both the upland and mid-slope to have SOM turnover rates and long-term SR rates that are higher than the wetland margin.

There are no identifiable differences in soil type between the upland and mid-slope that provides an explanation of why the mid-slope SR is significantly higher than the upland. Too little soil moisture data was recorded to determine if the long-term soil moisture in the mid-slope soils was significantly different than in the upland soils. No soil moisture data was recorded in 2003 and due to equipment issues, an insufficient fraction of the 2005 and 2006 data was recorded. Soil moisture data recorded in 2004 indicated that there are no significant differences in average soil moisture or soil temperatures at any depth...
between the upland and mid-slope; however, time series of water content show that the mid-slope drains faster than the upland (Figure IV.1). The mid-slope soils are better drained, which suggests that these soils might have an optimum soil moisture for SR. Wetland margin soil temperatures are more variable, and soil water content at these chambers is much higher than further up the slope.

![Figure IV.1 Soil Moisture and Soil Temperature along Slope](image)

**Figure IV.1 Soil Moisture and Soil Temperature along Slope:** Water content (top panel), and soil temperature (bottom panel) at 5 cm for the wetland margin (red), mid-slope (blue), and upland (green) chambers.

**Temperature Model**

The choice of soil temperature is important to fitting the temperature model correctly. Although 2 cm soil (litter) temperature is measured at each autochamber, it was determined that this shallow temperature was not representative of the soil horizons contributing to the flux. During mid-day
measurements the surface of the soil warms up much more than most of the organic horizon, resulting in a 2 cm soil temperature that is warmer than much of the SOM is actually experiencing. Fitting the L & T function to SR using the 2 cm temperature, resulted in very different temperature regression parameters at different times of the day, specifically, there is a lower response in the mid-day versus the nighttime. The daytime temperature response was underestimated by the higher litter temperatures.

The 5 - 7 cm temperature at the three soil profiles provided a much more consistent SR response to soil temperature, which showed less variation throughout the day. This is consistent which studies that partition the sources of CO₂ in the soil, where both the O-horizon (40 - 48%) [Davidson et al., 2006b] and litter layer (0 – 42 % depending on moisture conditions) [Cisneros-Dozal, 2006] contribute a significant fraction to SR.

The 5 - 7 cm soil temperatures were only recorded during 2004, and small portions of 2005, and 2006. However, these temperatures are very similar to the 10 cm soil temperature measured at the Fisher meteorological station (always within 1 to 2 degrees) and follow closely on diurnal and seasonal timescales without lags. Since the 10 cm soil temperature record at the meteorological station is so similar and virtually complete, it was used for the basis of all the temperature regressions.

Residuals

Residuals from the regression show variation on a variety of scales from diurnal to seasonal. Seasonal variation of the residuals is the largest when
compared to those on a diurnal or weather pattern scale. One possibility is that root respiration and photosynthate transport to the roots varies on a seasonal scale, and is influencing SR. If root respiration varies over the course of the growing season but is not directly proportional to soil temperature, it could create a considerable effect in the residuals. Since the availability of readily decomposed carbon is one factor affecting SR, an increase in exudation of carbohydrates from roots to the rhizosphere may increase SR. Like most soil processes that are poorly understood, there is little information on the phenology of downward photosynthate transport or production of root exudates.

Other studies have shown that photosynthesis has a strong effect on SR. A tree girdling experiment in Sweden revealed that cutting off the supply of photosynthate to the roots and mycorrhizal fungi reduced SR by 54%, with the decrease apparent in less than 5 days [Högberg et al., 2001]. In a study of European flux tower sites, GPP was determined to be the most significant factor in determining SR and ER, explained by the influence of photosynthate exudation and leaf litter and fine root production [Janssens et al., 2001]. However, studies that have measured the contribution of root respiration to SR over the duration of a growing season in a Japanese forest [Lee et al., 2003] and a Tennessee forest [Cisneros-Dozal et al., 2006] do not see much variation in root respiration relative to SR.

The seasonal transition of the residuals occurs around late July to early August. If the seasonal pattern of the residuals is controlled by autotrophic factors, a change in evapotranspiration could trigger a change in belowground
respiration. Since the late summer is a time of warm temperatures and lower precipitation, drought induced changes to the plants, such as stomatal closure, could be a factor influencing the residuals. A further look at the seasonal pattern of evapotranspiration or the phenology of the plants may present a possible mechanism.

SR residuals are correlated with soil moisture only on short time scales. Individual rain events of the mid-to-late summer produce an easily recognizable spike in the residual shortly after the rain event that subsides with soil moisture. Residuals from an entire measurement season from these chambers cannot be explained by soil water content as others have done at Harvard Forest [Savage and Davidson, 2001; Borken et al., 2003; Savage and Davidson, 2003]. The seasonal trend in the residuals overwhelms the influence of soil moisture, and no year-long quantifiable correlation between residuals and soil moisture or precipitation can be found.

Interannual variability in climate (air temperature, precipitation, and photosynthetically active radiation (PAR) measured at the Fisher meteorological station did not explain why 2005 does not show the seasonal variation in the SR residuals (Table IV.2). Annual averages in temperature were increasing in each year, but not significantly. Precipitation totals were highest in 2005, but it was nearly as high in 2003. Average daytime PAR was lower in 2005, compared to 2004 or 2005, which could be a possible explanation. PAR measured at the eddy flux tower was even lower in 2003; however, PAR from the tower was much lower in 2004 than measured at the meteorological station. When the tower
data, including PAR, from 2005 are available it can be determined if PAR in 2005 was anomalous compared to the previous years.

### Table IV.2 Annual Climate Averages and Sums

Average annual air temperature, precipitation totals, and average daytime PAR measured at the Fisher meteorological station. Too few measurements of PAR were made at the meteorological station in 2003 and data from the EMS tower were used.

<table>
<thead>
<tr>
<th>Year</th>
<th>Air Temperature (°C)</th>
<th>Precipitation (cm)</th>
<th>PAR (µmol m⁻² sec⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>9.7 ± 0.8</td>
<td>101</td>
<td>541 ± 14*</td>
</tr>
<tr>
<td>2004</td>
<td>9.6 ± 0.8</td>
<td>98.3</td>
<td>609 ± 15</td>
</tr>
<tr>
<td>2005</td>
<td>9.9 ± 0.9</td>
<td>111</td>
<td>571 ± 7.4</td>
</tr>
<tr>
<td>2006</td>
<td>10.4 ± 0.7</td>
<td>93.6</td>
<td>589 ± 7.6</td>
</tr>
</tbody>
</table>

*measured at EMS tower- insufficient measurements at meteorological station

### Gap-filling

Gap-filling is a necessary process to create annual respiration rates. The gaps associated with system failures and time periods outside the measurement period are much too large to be interpolated without using an involved statistical process, described in the methods section. Since temperature is the strongest factor controlling diurnal and seasonal variation in SR, it is the best predictor of SR to be used to fill the gaps with a best-estimate. However, since any SR measurement is heavily influenced by the seasonal hysteresis and soil moisture, the error in the temperature fit is not a simple, random uncertainty around the best fit line. As a result, gap-filling results in an overestimation of fluxes earlier in the growing season. Uncertainties were still calculated using this assumption of normally distributed error. Improved gap-filling and uncertainties could be
created using a more complex statistical model that incorporates temperature, day of year, and soil moisture.

Gap-filling using the temperature response creates a large uncertainty in individual filled values; however, for sums or averages on annual scales the uncertainty is less. The uncertainty in any individual filled value is too large to use in an analysis, however, as the values are summed over longer time intervals, especially those containing actual measurements, the uncertainty decreases considerably, similar to Hagen et al. [2006]. The uncertainties of the annual sums are low enough (6-15% of the total flux) to be useful estimates of annual SR.

**Tower Comparison**

Comparing soil flux measurements to nighttime tower NEE directly was deterred by the few numbers of actual measurements that occurred close to simultaneously (within one hour). In 2003 and 2004, due to gaps in both datasets the number of instances in which the tower and autochambers measured a flux within the same hour was very low (less than 20% of potential measurements in each growing season). If the data was filtered by wind direction (northwest) to maximize the possibility of the chambers being within the tower's footprint, the amount of data was reduced by another 1/3. Not enough data remained after filtering to make meaningful comparisons. In addition, uncertainty in the tower's footprint raises questions as to whether the chambers are representative of the area actually measured by the tower. However, with
three locations along the gradient and a large number of measurements, chamber SR can be compared qualitatively to the gap-filled ER from the tower.

Time series of both the ER and SR show that fluxes resulting from below-ground processes are occurring on a different seasonal pattern than fluxes from the combined above and below-ground processes. ER reaches a maximum earlier in the summer (May-June) than SR, which peaks later in the summer (July-August). The seasonal hysteresis of the tower is roughly the reverse of SR.

The opposite hysteresis of the tower-measured ER and chamber measured SR may be due to different responses of the above-ground and below ground biomass to temperature and soil moisture. In the spring above-ground respiration may increase quickly due to the addition of foliar biomass to the trees, while the soils are still cool, and heterotrophic SR has not yet had a chance to increase. As the summer progresses, SR ‘catches up’ to ER as the soils continue to warm increasing both heterotrophic SR and below-ground autotrophic respiration, while above-ground respiration remains constant. For reasons still unexplained (see Residuals) when more SR is measured for a given temperature later in the summer, this effect further increases the SR/ER ratio. In the fall, as senescence increases litter inputs to the soil, which may increase the contribution of SR, while decreasing above-ground respiration. Secondly, in the fall, the soils remain warmer while the air temperatures decrease.

The higher SR/ER ratio in the fall is similar to results by Davidson et al. [2006] in a Maine spruce forest; however, our Harvard Forest measurements compared to the flux tower reach a high SR/ER ratio earlier in the season. The
increase in the ratio at Harvard Forest cannot be entirely explained by litterfall and temperature lags, as higher SR/ER occurs before senescence or seasonal scale decreases in air temperature.

The difference in hysteresis between the flux tower and chambers is largely driven by the seasonal changes in non-temperature driven respiration documented by the change of negative residuals in spring and early summer, to positive residuals in late summer and fall. The cause of this seasonal pattern is still unexplained, with possible influences of below ground changes in root respiration.
CHAPTER V

CONCLUSIONS

Four years of high-frequency measurements of SR at Harvard Forest reveal large interannual and seasonal variability. Autochambers measured SR along a moisture gradient from upland soils to soils along a wetland margin. Chambers were aggregated by slope location into wetland margin, mid-slope, and upland chambers. Variation varied significantly along the hillslope, with the mid-slope and upland chambers measuring higher SR than the wetland margin in 2003. In 2004 through 2006, the mid-slope chambers recorded higher fluxes than either the wetland margin or upland chambers. Annual sums of SR during 2003-2006 ranged from 0.54 to 0.78 kg C m\(^2\) yr\(^{-1}\) on the upland soils, 0.80 to 0.99 on the mid-slope soils, and 0.56 to 0.67 on the wetland margin soils. There is significant interannual variation within each chamber group, but also significant variation between the chamber groups in the same years.

The differences in SR between locations along the slope were most apparent in the late summer and early fall. Plotting monthly average temperature vs. monthly average flux showed that at a given soil temperature in the fall there is more flux than at the same temperature in the spring.

The temperature response to soil temperature was quantified using a 10 cm soil temperature and an Arrhenius-type equation. The temperature response
varied by chamber and chamber grouping, and resulted in a set of residuals from
the temperature fit. Residuals from the temperature fit demonstrated a distinct
seasonal trend with negative residuals early in the year, and positive residuals
later in the year.

The seasonal pattern in the residuals varied by chamber location and
year. The mid-slope chambers demonstrated a much higher seasonality than
either the upland or wetland margin chambers. This seasonal pattern differed
interannually with a strong seasonal trend in 2003, 2004, and 2006. There was
little to no seasonal pattern to the residuals in 2005. Short term trends in the
residuals are correlated with soil moisture increases in flux occurring after rain
events and declining with decreasing soil moisture.

Comparison with the flux tower demonstrated that ER measured by the
flux tower followed a different seasonal pattern than SR measured by the
autochambers. SR peaks later than the year than ER. SR comprises a higher
fraction or exceeds ER during the late summer and early fall. When plotting
monthly average soil temperature vs. ER, the tower ER measurements follow a
reverse pattern than that of SR. For a given soil temperature, ER is higher in the
spring than in the fall.

The cause of the seasonal pattern of the residuals, the hysteresis pattern,
and high mid-slope fluxes is unexplained, with a possible cause due to changes
in root or photosynthetic activity. Further work documenting the proximity of
each chamber to trees and tree and understory species, as well as soil profiles
and carbon content near each chamber can be used to explore possible answers for the unanswered questions.
LIST OF REFERENCES


exchange in a mid-latitude deciduous forest. *Global Change Biology* 8, 575-589.


APPENDIX

COMPUTER ROUTINES IN MATLAB

%processAll.m

% Load flux data
HF03ch1=load('HF03ch1.txt.');
HF03ch2=load('HF03ch2.txt.');
HF03ch3=load('HF03ch3.txt.');
HF03ch4=load('HF03ch4.txt.');
HF03ch5=load('HF03ch5.txt.');
HF03ch6=load('HF03ch6.txt.');
HF03ch7=load('HF03ch7.txt.');
HF03ch8=load('HF03ch8.txt.');

HF04ch1=load('HF04ch1.txt.');
HF04ch2=load('HF04ch2.txt.');
HF04ch3=load('HF04ch3.txt.');
HF04ch4=load('HF04ch4.txt.');
HF04ch5=load('HF04ch5.txt.');
HF04ch6=load('HF04ch6.txt.');
HF04ch7=load('HF04ch7.txt.');
HF04ch8=load('HF04ch8.txt.');

HF05ch1=load('HF05ch1.txt.');
HF05ch2=load('HF05ch2.txt.');
HF05ch3=load('HF05ch3.txt.');
HF05ch4=load('HF05ch4.txt.');
HF05ch5=load('HF05ch5.txt.');
HF05ch6=load('HF05ch6.txt.');
HF05ch7=load('HF05ch7.txt.');
HF05ch8=load('HF05ch8.txt.');

HF06ch1=load('HF06ch1.txt.');
HF06ch2=load('HF06ch2.txt.');
HF06ch3=load('HF06ch3.txt.');
HF06ch4=load('HF06ch4.txt.');
HF06ch5=load('HF06ch5.txt.');
HF06ch6=load('HF06ch6.txt.');
HF06ch7=load('HF06ch7.txt.');
HF06ch8=load('HF06ch8.txt.');

% Replace -9999's with NaN
HF03ch1=makenans(HF03ch1);
HF03ch2=makenans(HF03ch2);
HF03ch3=makenans(HF03ch3);
HF03ch4=makenans(HF03ch4);
HF03ch5=makenans(HF03ch5);
HF03ch6=makenans(HF03ch6);
HF03ch7=makenans(HF03ch7);
HF03chl = makenans(HF03chl);
HF03ch2 = makenans(HF03ch2);
HF03ch3 = makenans(HF03ch3);
HF03ch4 = makenans(HF03ch4);
HF03ch5 = makenans(HF03ch5);
HF03ch6 = makenans(HF03ch6);
HF03ch7 = makenans(HF03ch7);
HF03ch8 = makenans(HF03ch8);

HF04chl = filterZeroFlux(HF04chl);
HF04ch2 = filterZeroFlux(HF04ch2);
HF04ch3 = filterZeroFlux(HF04ch3);
HF04ch4 = filterZeroFlux(HF04ch4);
HF04ch5 = filterZeroFlux(HF04ch5);
HF04ch6 = filterZeroFlux(HF04ch6);
HF04ch7 = filterZeroFlux(HF04ch7);
HF04ch8 = filterZeroFlux(HF04ch8);

% Remove values below detection limit
[HF03chl pR03chl] = filterZeroFlux(HF03chl);
[HF03ch2 pR03ch2] = filterZeroFlux(HF03ch2);
[HF03ch3 pR03ch3] = filterZeroFlux(HF03ch3);
[HF03ch4 pR03ch4] = filterZeroFlux(HF03ch4);
[HF03ch5 pR03ch5] = filterZeroFlux(HF03ch5);
[HF03ch6 pR03ch6] = filterZeroFlux(HF03ch6);
[HF03ch7 pR03ch7] = filterZeroFlux(HF03ch7);
[HF03ch8 pR03ch8] = filterZeroFlux(HF03ch8);

[HF04ch1 pR04ch1] = filterZeroFlux(HF04ch1);
[HF04ch2 pR04ch2] = filterZeroFlux(HF04ch2);
[HF04ch3 pR04ch3] = filterZeroFlux(HF04ch3);
[HF04ch4 pR04ch4] = filterZeroFlux(HF04ch4);
[HF04ch5 pR04ch5] = filterZeroFlux(HF04ch5);
[HF04ch6 pR04ch6] = filterZeroFlux(HF04ch6);
[HF04ch7 pR04ch7] = filterZeroFlux(HF04ch7);
[HF04ch8 pR04ch8] = filterZeroFlux(HF04ch8);

[HF05chl pR05chl] = filterZeroFlux(HF05chl);
[HF05ch2 pR05ch2] = filterZeroFlux(HF05ch2);
[HF05ch3 pR05ch3] = filterZeroFlux(HF05ch3);
[HF05ch4 pR05ch4] = filterZeroFlux(HF05ch4);
[HF05ch5 pR05ch5] = filterZeroFlux(HF05ch5);
[HF05ch6 pR05ch6] = filterZeroFlux(HF05ch6);
[HF05ch7 pR05ch7] = filterZeroFlux(HF05ch7);
[HF05ch8 pR05ch8] = filterZeroFlux(HF05ch8);
[HF06ch1 pR06ch1] = filterZeroFlux(HF06ch1);
[HF06ch2 pR06ch2] = filterZeroFlux(HF06ch2);
[HF06ch3 pR06ch3] = filterZeroFlux(HF06ch3);
[HF06ch4 pR06ch4] = filterZeroFlux(HF06ch4);
[HF06ch5 pR06ch5] = filterZeroFlux(HF06ch5);
[HF06ch6 pR06ch6] = filterZeroFlux(HF06ch6);
[HF06ch7 pR06ch7] = filterZeroFlux(HF06ch7);
[HF06ch8 pR06ch8] = filterZeroFlux(HF06ch8);

% Group by location
wet_marg03 = vertcat(HF03chl,HF03ch3,HF03ch5,HF03ch8);
mid_slope03 = vertcat(HF03ch4,HF03ch6);
upland03 = vertcat(HF03ch2,HF03ch7);

wet_marg04 = vertcat(HF04chl,HF04ch3,HF04ch5,HF04ch8);
mid_slope04 = vertcat(HF04ch4,HF04ch6);
upland04 = vertcat(HF04ch2,HF04ch7);

wet_marg05 = vertcat(HF05chl,HF05ch3,HF05ch5,HF05ch8);
mid_slope05 = vertcat(HF05ch4,HF05ch6);
upland05 = vertcat(HF05ch2,HF05ch7);

wet_marg06 = vertcat(HF06chl,HF06ch3,HF06ch5,HF06ch8);
mid_slope06 = vertcat(HF06ch4,HF06ch6);
upland06 = vertcat(HF06ch2,HF06ch7);

% Load met station data
met03 = load('met03.txt');
met04 = load('met04.txt');
met05 = load('met05.txt');
met06 = load('met06.txt');

% Replace -9999's with NaN
met03 = makenans(met03);
met04 = makenans(met04);
met05 = makenans(met05);
met06 = makenans(met06);

% Get closest met. station temperature
T03chl = closestMetT(HF03chl, met03);
T03ch2 = closestMetT(HF03ch2, met03);
T03ch3 = closestMetT(HF03ch3, met03);
T03ch4 = closestMetT(HF03ch4, met03);
T03ch5 = closestMetT(HF03ch5, met03);
T03ch6 = closestMetT(HF03ch6, met03);
T03ch7 = closestMetT(HF03ch7, met03);
T03ch8 = closestMetT(HF03ch8, met03);
T04chl = closestMetT(HF04chl, met04);
T04ch2 = closestMetT(HF04ch2, met04);
T04ch3 = closestMetT(HF04ch3, met04);
T04ch4 = closestMetT(HF04ch4, met04);
T04ch5 = closestMetT(HF04ch5, met04);
T04ch6=closestMetT(HF04ch6,met04);
T04ch7=closestMetT(HF04ch7,met04);
T04ch8=closestMetT(HF04ch8,met04);

T05ch1=closestMetT(HF05ch1,met05);
T05ch2=closestMetT(HF05ch2,met05);
T05ch3=closestMetT(HF05ch3,met05);
T05ch4=closestMetT(HF05ch4,met05);
T05ch5=closestMetT(HF05ch5,met05);
T05ch6=closestMetT(HF05ch6,met05);
T05ch7=closestMetT(HF05ch7,met05);
T05ch8=closestMetT(HF05ch8,met05);

T06ch1=closestMetT(HF06ch1,met06);
T06ch2=closestMetT(HF06ch2,met06);
T06ch3=closestMetT(HF06ch3,met06);
T06ch4=closestMetT(HF06ch4,met06);
T06ch5=closestMetT(HF06ch5,met06);
T06ch6=closestMetT(HF06ch6,met06);
T06ch7=closestMetT(HF06ch7,met06);
T06ch8=closestMetT(HF06ch8,met06);

T03wm=closestMetT(wet_marg03,met03);
T04wm=closestMetT(wet_marg04,met04);
T05wm=closestMetT(wet_marg05,met05);
T06wm=closestMetT(wet_marg06,met06);

T03ms=closestMetT(mid_slope03,met03);
T04ms=closestMetT(mid_slope04,met04);
T05ms=closestMetT(mid_slope05,met05);
T06ms=closestMetT(mid_slope06,met06);

T03up=closestMetT(upland03,met03);
T04up=closestMetT(upland04,met04);
T05up=closestMetT(upland05,met05);
T06up=closestMetT(upland06,met06);

% Calculate fit parameters and residuals
[beta03ch1, resid03ch1, J03ch1]=nlinfit(T03ch1, HF03ch1(:,14), @LT2, p0);
[beta03ch2, resid03ch2, J03ch2]=nlinfit(T03ch2, HF03ch2(:,14), @LT2, p0);
[beta03ch3, resid03ch3, J03ch3]=nlinfit(T03ch3, HF03ch3(:,14), @LT2, p0);
[beta03ch4, resid03ch4, J03ch4]=nlinfit(T03ch4, HF03ch4(:,14), @LT2, p0);
[beta03ch5, resid03ch5, J03ch5]=nlinfit(T03ch5, HF03ch5(:,14), @LT2, p0);
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[beta03ch7, resid03ch7, J03ch7]=nlinfit(T03ch7, HF03ch7(:,14), @LT2, p0);
[beta03ch8, resid03ch8, J03ch8]=nlinfit(T03ch8, HF03ch8(:,14), @LT2, p0);

[beta04ch1, resid04ch1, J04ch1]=nlinfit(T04ch1, HF04ch1(:,14), @LT2, p0);
[beta04ch2, resid04ch2, J04ch2]=nlinfit(T04ch2, HF04ch2(:,14), @LT2, p0);
[beta04ch3, resid04ch3, J04ch3]=nlinfit(T04ch3, HF04ch3(:,14), @LT2, p0);
[beta04ch4, resid04ch4, J04ch4]=nlinfit(T04ch4, HF04ch4(:,14), @LT2, p0);
[beta04ch5, resid04ch5, J04ch5]=nlinfit(T04ch5, HF04ch5(:,14), @LT2, p0);
[beta04ch6, resid04ch6, J04ch6]=nlinfit(T04ch6, HF04ch6(:,14), @LT2, p0);
[beta04ch7, resid04ch7, J04ch7]=nlinfit(T04ch7, HF04ch7(:,14), @LT2, p0);
[beta04ch8, resid04ch8, J04ch8]=nlinfit(T04ch8, HF04ch8(:,14), @LT2, p0);
% beta05chl, resid05chl, J05chl = nlinfit(T05chl, HP05chl(:,14),@LT2, p0);
% beta05ch2, resid05ch2, J05ch2 = nlinfit(T05ch2, HP05ch2(:,14),@LT2, p0);
% beta05ch3, resid05ch3, J05ch3 = nlinfit(T05ch3, HP05ch3(:,14),@LT2, p0);
% beta05ch4, resid05ch4, J05ch4 = nlinfit(T05ch4, HP05ch4(:,14),@LT2, p0);
% beta05ch5, resid05ch5, J05ch5 = nlinfit(T05ch5, HP05ch5(:,14),@LT2, p0);
% beta05ch6, resid05ch6, J05ch6 = nlinfit(T05ch6, HP05ch6(:,14),@LT2, p0);
% beta05ch7, resid05ch7, J05ch7 = nlinfit(T05ch7, HP05ch7(:,14),@LT2, p0);
% beta05ch8, resid05ch8, J05ch8 = nlinfit(T05ch8, HP05ch8(:,14),@LT2, p0);
% beta06chl, resid06chl, J06chl = nlinfit(T06chl, HP06chl(:,14),@LT2, p0);
% beta06ch2, resid06ch2, J06ch2 = nlinfit(T06ch2, HP06ch2(:,14),@LT2, p0);
% beta06ch3, resid06ch3, J06ch3 = nlinfit(T06ch3, HP06ch3(:,14),@LT2, p0);
% beta06ch4, resid06ch4, J06ch4 = nlinfit(T06ch4, HP06ch4(:,14),@LT2, p0);
% beta06ch5, resid06ch5, J06ch5 = nlinfit(T06ch5, HP06ch5(:,14),@LT2, p0);
% beta06ch6, resid06ch6, J06ch6 = nlinfit(T06ch6, HP06ch6(:,14),@LT2, p0);
% beta06ch7, resid06ch7, J06ch7 = nlinfit(T06ch7, HP06ch7(:,14),@LT2, p0);
% beta06ch8, resid06ch8, J06ch8 = nlinfit(T06ch8, HP06ch8(:,14),@LT2, p0);
% beta03wm, resid03wm, J03wm = nlinfit(T03wm, wet_marg03(:,14),@LT2, p0);
% beta03ms, resid03ms, J03ms = nlinfit(T03ms, mid_slope03(:,14),@LT2, p0);
% beta04up, resid04up, J04up = nlinfit(T04up, upland04(:,14),@LT2, p0);
% beta04wm, resid04wm, J04wm = nlinfit(T04wm, wet_marg04(:,14),@LT2, p0);
% beta04ms, resid04ms, J04ms = nlinfit(T04ms, mid_slope04(:,14),@LT2, p0);
% beta05up, resid05up, J05up = nlinfit(T05up, upland05(:,14),@LT2, p0);
% beta05wm, resid05wm, J05wm = nlinfit(T05wm, wet_marg05(:,14),@LT2, p0);
% beta05ms, resid05ms, J05ms = nlinfit(T05ms, mid_slope05(:,14),@LT2, p0);
% beta06up, resid06up, J06up = nlinfit(T06up, upland06(:,14),@LT2, p0);
% beta06wm, resid06wm, J06wm = nlinfit(T06wm, wet_marg06(:,14),@LT2, p0);
% beta06ms, resid06ms, J06ms = nlinfit(T06ms, mid_slope06(:,14),@LT2, p0);
% beta03chl, resid03chl, J03chl = fitFlux(HF03chl(:,14), TO3chl, p0(1), p0(2), 0, '1', '1');
% beta03ch2, resid03ch2, J03ch2 = fitFlux(HF03ch2(:,14), TO3ch2, p0(1), p0(2), 0, '1', '1');
% beta03ch3, resid03ch3, J03ch3 = fitFlux(HF03ch3(:,14), TO3ch3, p0(1), p0(2), 0, '1', '1');
% beta03ch4, resid03ch4, J03ch4 = fitFlux(HF03ch4(:,14), TO3ch4, p0(1), p0(2), 0, '1', '1');
% beta03ch5, resid03ch5, J03ch5 = fitFlux(HF03ch5(:,14), TO3ch5, p0(1), p0(2), 0, '1', '1');
% beta03ch6, resid03ch6, J03ch6 = fitFlux(HF03ch6(:,14), TO3ch6, p0(1), p0(2), 0, '1', '1');
% beta03ch7, resid03ch7, J03ch7 = fitFlux(HF03ch7(:,14), TO3ch7, p0(1), p0(2), 0, '1', '1');
% beta03ch8, resid03ch8, J03ch8 = fitFlux(HF03ch8(:,14), TO3ch8, p0(1), p0(2), 0, '1', '1');
% beta04chl, resid04chl, J04chl = fitFlux(HF04chl(:,14), TO4chl, p0(1), p0(2), 0, '1', '1');
% beta04ch2, resid04ch2, J04ch2 = fitFlux(HF04ch2(:,14), TO4ch2, p0(1), p0(2), 0, '1', '1');
% beta04ch3, resid04ch3, J04ch3 = fitFlux(HF04ch3(:,14), TO4ch3, p0(1), p0(2), 0, '1', '1');
% beta04ch4, resid04ch4, J04ch4 = fitFlux(HF04ch4(:,14), TO4ch4, p0(1), p0(2), 0, '1', '1');
% beta04ch5, resid04ch5, J04ch5 = fitFlux(HF04ch5(:,14), TO4ch5, p0(1), p0(2), 0, '1', '1');
% beta04ch6, resid04ch6, J04ch6 = fitFlux(HF04ch6(:,14), TO4ch6, p0(1), p0(2), 0, '1', '1');
% beta04ch7, resid04ch7, J04ch7 = fitFlux(HF04ch7(:,14), TO4ch7, p0(1), p0(2), 0, '1', '1');
% beta04ch8, resid04ch8, J04ch8 = fitFlux(HF04ch8(:,14), TO4ch8, p0(1), p0(2), 0, '1', '1');
% beta05chl, resid05chl, J05chl = fitFlux(HF05chl(:,14), TO5chl, p0(1), p0(2), 0, '1', '1');
% beta05ch2, resid05ch2, J05ch2 = fitFlux(HF05ch2(:,14), TO5ch2, p0(1), p0(2), 0, '1', '1');
[A05ch3, T005ch3] = fitFlux(HF05ch3(:,14), T05ch3, p0(1), p0(2), 0, ' ', ');  
[A05ch4, T005ch4] = fitFlux(HF05ch4(:,14), T05ch4, p0(1), p0(2), 0, ' ', ');  
[A05ch5, T005ch5] = fitFlux(HF05ch5(:,14), T05ch5, p0(1), p0(2), 0, ' ', ');  
[A05ch6, T005ch6] = fitFlux(HF05ch6(:,14), T05ch6, p0(1), p0(2), 0, ' ', ');  
[A05ch7, T005ch7] = fitFlux(HF05ch7(:,14), T05ch7, p0(1), p0(2), 0, ' ', ');  
[A05ch8, T005ch8] = fitFlux(HF05ch8(:,14), T05ch8, p0(1), p0(2), 0, ' ', ');  

[A06ch1, T006ch1] = fitFlux(HF06ch1(:,14), T06ch1, p0(1), p0(2), 0, ' ', ');  
[A06ch2, T006ch2] = fitFlux(HF06ch2(:,14), T06ch2, p0(1), p0(2), 0, ' ', ');  
[A06ch3, T006ch3] = fitFlux(HF06ch3(:,14), T06ch3, p0(1), p0(2), 0, ' ', ');  
[A06ch4, T006ch4] = fitFlux(HF06ch4(:,14), T06ch4, p0(1), p0(2), 0, ' ', ');  
[A06ch5, T006ch5] = fitFlux(HF06ch5(:,14), T06ch5, p0(1), p0(2), 0, ' ', ');  
[A06ch6, T006ch6] = fitFlux(HF06ch6(:,14), T06ch6, p0(1), p0(2), 0, ' ', ');  
[A06ch7, T006ch7] = fitFlux(HF06ch7(:,14), T06ch7, p0(1), p0(2), 0, ' ', ');  
[A06ch8, T006ch8] = fitFlux(HF06ch8(:,14), T06ch8, p0(1), p0(2), 0, ' ', ');  

[A03wm, T003wm] = fitFlux(wet_marg03(:,14), T03wm, p0(1), p0(2), 0, ' ', ');  
[A04wm, T004wm] = fitFlux(wet_marg04(:,14), T04wm, p0(1), p0(2), 0, ' ', ');  
[A05wm, T005wm] = fitFlux(wet_marg05(:,14), T05wm, p0(1), p0(2), 0, ' ', ');  
[A06wm, T006wm] = fitFlux(wet_marg06(:,14), T06wm, p0(1), p0(2), 0, ' ', ');  

[A03ms, T003ms] = fitFlux(mid_slope03(:,14), T03ms, p0(1), p0(2), 0, ' ', ');  
[A04ms, T004ms] = fitFlux(mid_slope04(:,14), T04ms, p0(1), p0(2), 0, ' ', ');  
[A05ms, T005ms] = fitFlux(mid_slope05(:,14), T05ms, p0(1), p0(2), 0, ' ', ');  
[A06ms, T006ms] = fitFlux(mid_slope06(:,14), T06ms, p0(1), p0(2), 0, ' ', ');  

[bet90_03chl, ypred90_03chl, resid90_03chl] = quantileFlux(T03chl, HF03chl(:,14), p0);  
[bet90_03ch2, ypred90_03ch2, resid90_03ch2] = quantileFlux(T03ch2, HF03ch2(:,14), p0);  
[bet90_03ch3, ypred90_03ch3, resid90_03ch3] = quantileFlux(T03ch3, HF03ch3(:,14), p0);  
[bet90_03ch4, ypred90_03ch4, resid90_03ch4] = quantileFlux(T03ch4, HF03ch4(:,14), p0);  
[bet90_03ch5, ypred90_03ch5, resid90_03ch5] = quantileFlux(T03ch5, HF03ch5(:,14), p0);  
[bet90_03ch6, ypred90_03ch6, resid90_03ch6] = quantileFlux(T03ch6, HF03ch6(:,14), p0);  
[bet90_03ch7, ypred90_03ch7, resid90_03ch7] = quantileFlux(T03ch7, HF03ch7(:,14), p0);  
[bet90_03ch8, ypred90_03ch8, resid90_03ch8] = quantileFlux(T03ch8, HF03ch8(:,14), p0);  
[bet90_03wm, ypred90_03wm, resid90_03wm] = quantileFlux(T03wm, wet_marg03(:,14), p0);  
[bet90_03ms, ypred90_03ms, resid90_03ms] = quantileFlux(T03ms, mid_slope03(:,14), p0);  
[bet90_03up, ypred90_03up, resid90_03up] = quantileFlux(T03up, upland03(:,14), p0);  

[bet90_04chl, ypred90_04chl, resid90_04chl] = quantileFlux(T04chl, HF04chl(:,14), p0);  

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\[ \\begin{align*}
[\beta_{90_{04ch2}}, \ ypred_{90_{04ch2}}, \\
resid_{90_{04ch2}}] &= \text{quantileFlux}(T04ch2, HF04ch2(:,14), p0); \\
[\beta_{90_{04ch3}}, \ ypred_{90_{04ch3}}, \\
resid_{90_{04ch3}}] &= \text{quantileFlux}(T04ch3, HF04ch3(:,14), p0); \\
[\beta_{90_{04ch4}}, \ ypred_{90_{04ch4}}, \\
resid_{90_{04ch4}}] &= \text{quantileFlux}(T04ch4, HF04ch4(:,14), p0); \\
[\beta_{90_{04ch5}}, \ ypred_{90_{04ch5}}, \\
resid_{90_{04ch5}}] &= \text{quantileFlux}(T04ch5, HF04ch5(:,14), p0); \\
[\beta_{90_{04ch6}}, \ ypred_{90_{04ch6}}, \\
resid_{90_{04ch6}}] &= \text{quantileFlux}(T04ch6, HF04ch6(:,14), p0); \\
[\beta_{90_{04ch7}}, \ ypred_{90_{04ch7}}, \\
resid_{90_{04ch7}}] &= \text{quantileFlux}(T04ch7, HF04ch7(:,14), p0); \\
[\beta_{90_{04ch8}}, \ ypred_{90_{04ch8}}, \\
resid_{90_{04ch8}}] &= \text{quantileFlux}(T04ch8, HF04ch8(:,14), p0); \\
[\beta_{90_{04wm}}, \ ypred_{90_{04wm}}, \\
resid_{90_{04wm}}] &= \text{quantileFlux}(T04wm, wet_marg04(:,14), p0); \\
[\beta_{90_{04ms}}, \ ypred_{90_{04ms}}, \\
resid_{90_{04ms}}] &= \text{quantileFlux}(T04ms, mid_slope04(:,14), p0); \\
[\beta_{90_{04up}}, \ ypred_{90_{04up}}, \\
resid_{90_{04up}}] &= \text{quantileFlux}(T04up, upland04(:,14), p0); \\
[\beta_{90_{05chl}}, \ ypred_{90_{05chl}}, \\
resid_{90_{05chl}}] &= \text{quantileFlux}(T05chl, HF05chl(:,14), p0); \\
[\beta_{90_{05ch2}}, \ ypred_{90_{05ch2}}, \\
resid_{90_{05ch2}}] &= \text{quantileFlux}(T05ch2, HF05ch2(:,14), p0); \\
[\beta_{90_{05ch3}}, \ ypred_{90_{05ch3}}, \\
resid_{90_{05ch3}}] &= \text{quantileFlux}(T05ch3, HF05ch3(:,14), p0); \\
[\beta_{90_{05ch4}}, \ ypred_{90_{05ch4}}, \\
resid_{90_{05ch4}}] &= \text{quantileFlux}(T05ch4, HF05ch4(:,14), p0); \\
[\beta_{90_{05ch5}}, \ ypred_{90_{05ch5}}, \\
resid_{90_{05ch5}}] &= \text{quantileFlux}(T05ch5, HF05ch5(:,14), p0); \\
[\beta_{90_{05ch6}}, \ ypred_{90_{05ch6}}, \\
resid_{90_{05ch6}}] &= \text{quantileFlux}(T05ch6, HF05ch6(:,14), p0); \\
[\beta_{90_{05ch7}}, \ ypred_{90_{05ch7}}, \\
resid_{90_{05ch7}}] &= \text{quantileFlux}(T05ch7, HF05ch7(:,14), p0); \\
[\beta_{90_{05ch8}}, \ ypred_{90_{05ch8}}, \\
resid_{90_{05ch8}}] &= \text{quantileFlux}(T05ch8, HF05ch8(:,14), p0); \\
[\beta_{90_{05wm}}, \ ypred_{90_{05wm}}, \\
resid_{90_{05wm}}] &= \text{quantileFlux}(T05wm, wet_marg05(:,14), p0); \\
[\beta_{90_{05ms}}, \ ypred_{90_{05ms}}, \\
resid_{90_{05ms}}] &= \text{quantileFlux}(T05ms, mid_slope05(:,14), p0); \\
[\beta_{90_{05up}}, \ ypred_{90_{05up}}, \\
resid_{90_{05up}}] &= \text{quantileFlux}(T05up, upland05(:,14), p0); \\
[\beta_{90_{06chl}}, \ ypred_{90_{06chl}}, \\
resid_{90_{06chl}}] &= \text{quantileFlux}(T06chl, HF06chl(:,14), p0); \\
[\beta_{90_{06ch2}}, \ ypred_{90_{06ch2}}, \\
resid_{90_{06ch2}}] &= \text{quantileFlux}(T06ch2, HF06ch2(:,14), p0); \\
[\beta_{90_{06ch3}}, \ ypred_{90_{06ch3}}, \\
resid_{90_{06ch3}}] &= \text{quantileFlux}(T06ch3, HF06ch3(:,14), p0); \\
[\beta_{90_{06ch4}}, \ ypred_{90_{06ch4}}, \\
resid_{90_{06ch4}}] &= \text{quantileFlux}(T06ch4, HF06ch4(:,14), p0); \\
[\beta_{90_{06ch5}}, \ ypred_{90_{06ch5}}, \\
resid_{90_{06ch5}}] &= \text{quantileFlux}(T06ch5, HF06ch5(:,14), p0); \\
[\beta_{90_{06ch6}}, \ ypred_{90_{06ch6}}, \\
resid_{90_{06ch6}}] &= \text{quantileFlux}(T06ch6, HF06ch6(:,14), p0); \\
[\beta_{90_{06ch7}}, \ ypred_{90_{06ch7}}, \\
resid_{90_{06ch7}}] &= \text{quantileFlux}(T06ch7, HF06ch7(:,14), p0); \\
[\beta_{90_{06ch8}}, \ ypred_{90_{06ch8}}, \\
resid_{90_{06ch8}}] &= \text{quantileFlux}(T06ch8, HF06ch8(:,14), p0); \\
[\beta_{90_{06wm}}, \ ypred_{90_{06wm}}, \\
resid_{90_{06wm}}] &= \text{quantileFlux}(T06wm, wet_marg06(:,14), p0); \\
[\beta_{90_{06ms}}, \ ypred_{90_{06ms}}, \\
resid_{90_{06ms}}] &= \text{quantileFlux}(T06ms, mid_slope06(:,14), p0); \\
[\beta_{90_{06up}}, \ ypred_{90_{06up}}, \\
resid_{90_{06up}}] &= \text{quantileFlux}(T06up, upland06(:,14), p0); \\
\end{align*}\]
[beta 90_06ch7, ypred90_06ch7, resid90_06ch7] = quantileFlux(T06ch7, H F 0 6 ch 7 (:,14), pO);
[beta 90_06ch8, ypred90_06ch8, resid90_06ch8] = quantileFlux(T06ch8, H F 0 6 ch 8 (:,14), pO);
[beta 90_06wm, ypred90_06wm, resid90_06wm] = quantileFlux(T06wm, wet_marg06(:,14), pO);
[beta 90_06ms, ypred90_06ms, resid90_06ms] = quantileFlux(T06ms, mid_slope06(:,14), pO);
[beta 90_06up, ypred90_06up, resid90_06up] = quantileFlux(T06up, upland06(:,14), pO);

soilNew04wm = getClosestSoil(wet_marg04, sm04);
soilNew05wm = getClosestSoil(wet_marg05, sm05);
soilNew06wm = getClosestSoil(wet_marg06, sm06);

soilNew04ms = getClosestSoil(mid_slope04, sm04);
soilNew05ms = getClosestSoil(mid_slope05, sm05);
soilNew06ms = getClosestSoil(mid_slope06, sm06);

soilNew04up = getClosestSoil(upland04, sm04);
soilNew05up = getClosestSoil(upland05, sm05);
soilNew06up = getClosestSoil(upland06, sm06);

dryTime03wm = processTimeSincePrecip(wet_marg03, met03);
dryTime03ms = processTimeSincePrecip(mid_slope03, met03);
dryTime03up = processTimeSincePrecip(upland03, met03);

dryTime04wm = processTimeSincePrecip(wet_marg04, met04);
dryTime04ms = processTimeSincePrecip(mid_slope04, met04);
dryTime04up = processTimeSincePrecip(upland04, met04);

dryTime05wm = processTimeSincePrecip(wet_marg05, met05);
dryTime05ms = processTimeSincePrecip(mid_slope05, met05);
dryTime05up = processTimeSincePrecip(upland05, met05);

dryTime06wm = processTimeSincePrecip(wet_marg06, met06);
dryTime06ms = processTimeSincePrecip(mid_slope06, met06);
dryTime06up = processTimeSincePrecip(upland06, met06);

function [new percRemoved] = filterZeroFlux(old)
% Removes flux values below detection limits

% Set counter to zero
for i = 1:length(old)
    if old(i,14) > 0.0024
        c = c + 1;  % Increment counter
        new(c,:) = old(i,:);  % Save information if flux > than 0.0024
    end
end
percRemoved = 100 - ((length(new)/length(old))*100);  % Calculate % removed

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function newT=closestMetT(chamber, met)
    length(chamber)
    for i=1:length(chamber)
        if mod(i,50)==0
            disp((i/length(chamber))*100)
        end
        idx=getClosest(chamber(i,1),met);
        if abs(chamber(i,1)-met(idx,1))<0.08333
            newT(i)=met(idx,16);
        else
            newT(i)=NaN;
        end
    end
    
function index=getClosest(value,array)

    % Searches an array for the closest value to a given value
    % and returns the index location of the nearest value
    % also returns stating value

    len=length(array);
    
    for i=1:len
        % Difference of value being tested and each value in array
        dff(i,1)=abs(value-array(i,1));
        % Index created to be used for value returned stored in same
        % array
        dff(i,2) = i;
    end
    
    % Sorts the differences from least to greatest
    [temp,idx]=sort(dff(:,1));
    dff2=dff(idx,:);
    % Returns the original index value corresponding to the
    % closest value
    index=dff2(1,2);
function [A To]=fitFlux(flux,soilT,A_p,To_p,show,name,year)
% Non-linear regression using Lloyd and Taylor equations
% accepts flux and temperature vectors (must be same length and on same
% sampling interval)
% Must include user-defined functions LloydTaylor.m and
% LloydTaylor2.m in same folder
%
% [A To]=fitFlux(flux,soilT,A_p,To_p,show)
%
% User inputs:
% flux = CO2 efflux data
% T = soil temperature data
% A_p = best-guess of "A" - scaling factor in L % T equation
% To_p = best-guess of "To" reference temperature
% show = binary flag to show graphical output (1 show, 0 do not show)
% default is show
% Function output:
% A(1) = best-fit estimate of scaling factor
% A(2) = 95% confidence interval (lower bound)
% A(3) = 95% confidence interval (upper bound)
% To(1) = best-fit estimate of reference temperature value
% To(2) = 95% confidence interval (lower bound)
% To(3) = 95% confidence interval (upper bound)

flux=makenans(flux);
soilT=makenans(soilT);

if (nargin<5 | isnan(show)==1)
    show=1; % Default turn plot on if no input
end

if (length(flux)~=length(soilT))
    error('Flux and soil temp. data must be of same length');
end

% Best guess based on user input
p0=[A_p To_p];

% Nonlinear regression: phat has fitted values
[phat resid jac]=nlinfit(soilT,flux,@LT2,p0);
fluxhat=LT2(phat,soilT);
rsquared=rSquared(resid,flux);
[fluxhatS idx]=sort(fluxhat);

if (show==1)
    figure(1)
    plot(soilT,flux,'k.',soilT(idx),fluxhat(idx),'r-');
    axis([min(soilT) max(soilT) min(flux) max(flux)]);%legend('Flux','Best Fit','Location','SouthEast');
    xlabel('Soil Temperature (°C)');
    ylabel('Soil Efflux \mumol CO_2/m^2/s');
end

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title([name ' during ' year])

disp('Best fit parameters')

disp('----------------------------------
A=phat(1)
To=phat(2)
disp('----------------------------------

disp('Begin Monte Carlo simulation...
end

% Calculate 95% confidence intervals using Monte Carlo
% (bootstrapping) simulations
[pl CIlow CIup]=monte_carlo(@LT2,soilT,flux,phat,resid,1000,show);

if (show==1)
    % Set measurement intervals for bins
    edges1=min(pl(:,1)):max(pl(:,1))-min(pl(:,1))/100:max(pl(:,1));
    edges2=min(pl(:,2)):max(pl(:,2))-min(pl(:,2))/100:max(pl(:,2));

    % Plot frequency distribution with best fit and CI values
    figure(2);
    subplot(2,1,1);
    nl=histc(pl(:,1),edges1);
    plot(edges1,n1,'k o :',phat(1),0:max(n1),'r .-',CIup(1),0:max(n1),'b .-'
      ,CIlow(1),0:max(n1),'b .-')
    title('Frequency distribution of simulated parameters (100 equal
    bins)');
    xlabel('A');
    ylabel('Frequency');
    axis([min(edges1) max(edges1) min(n1) max(n1)]);
    subplot(2,1,2);
    n2=histc(pl(:,2),edges2);
    plot(edges2,n2,'k o :',phat(2),0:max(n2),'r .-',CIup(2),0:max(n2),'b .-'
      ,CIlow(2),0:max(n2),'b .-')
    xlabel('To');
    ylabel('Frequency');

end

A(1)=phat(1);
A(2)=(abs(phat(1)-CIup(1))+abs(phat(1)-CIlow(1)))/2;
To(1)=phat(2);
To(2)=(abs(phat(2)-CIup(2))+abs(phat(2)-CIlow(2)))/2;

if(show==1)
    disp('----------------------
    disp(' Best fit +/- 95% Confidence Interval')
    disp('----------------------
    disp(sprintf('A: num2str(A(1)) ' num2str(A(2))));
    disp('')

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disp(['To:  '  num2str(To(1)) '  '  num2str(To(2))]);
disp('----------------------------------------')
disp(['R^2  '  num2str(r_squared)]);
disp('----------------------------------------')
end

function resp=LT(data,param)
A=param(1);
Eo=308;
To=param(2);
T=data+273.15;
len=length(data);
for i=1:len
    resp(i)=A*exp((-Eo/(T(i)-To)));
end
resp=resp';

function resp=LT2(param,data)
A=param(1);
Eo=308;
To=param(2);
T=data+273.15;
len=length(data);
for i=1:len
    resp(i)=A*exp((-Eo/(T(i)-To)));
end
resp=resp';

function [phat_boot CIlow
CIup]=monte_carlo(model,x,y,phat,resid,n_iter,show)
x=makenans(x);
y=makenans(y);

% Fit curve to data
%[phat, resid, jac]=nlfit(x,y,model,p0);
% Calculate best fit line
yhat=model(phat,x);
% Calculate root mean square error
RMS=std(noNaN(resid));

for i=1:n_iter
    % Show progress every 10 iterations
    if (mod(i,10)==0 & show==1)
        disp(['Iteration: ' num2str(i) ' of ' num2str(n_iter)]);
    end
    % Simulate synthetic data with random scatter based on original fit
    sim_data=yhat+RMS.*(randn(length(x),1));

    % Fit parameters to fake data
    phat_boot(i,:)=nlinfit(x,sim_data,model,[200 225]);
end

% Sort simulation results from smallest to greatest
for j=1:length(phat)
    [ps(:,j) idx(:,j)]=sort(phat_boot(:,j));
end

% Sets 95% confidence intervals
idxCIup=floor(0.95*n_iter);
didxCIlow=floor(0.05*n_iter);

for i=1:length(phat)
    CIup(i)=ps(idxCIup,i);
    CIlow(i)=ps(idxCIlow,i);
end

% Set percentiles for confidence interval 90%, 95%, 97.5%, 99%, 99.7%
perc = [10 90; 5 95; 2.5 97.5; 1 99; 0.3 99.7];
perc = perc./100;

% Calculate confidence intervals
for i=1:length(perc)
    idxCI(i,1)=floor(perc(i,1)*length(ps));
    idxCI(i,2)=floor(perc(i,2)*length(ps));
    for j=1:length(p0)
        CIlow(i,j)=ps(idxCI(i,1),j);
        CIup(i,j)=ps(idxCI(i,2),j);
    end
end

function r2=rSquared(yhat,yi)
% Accepts predicted y values of fit (yhat) and actual y values (yi)
% and calculates $r^2$
% Lengths of yi and yhat must match (1-D vectors)
if length(yi)~=length(yhat)
    length(yi)
    disp('does not equal')
    length(yhat)
    error('Dimensions of predicted and observed data do not match')
end

yi=noNaN(yi);
yhat=noNaN(yhat);

yi=noNaN(yi);
yi=yi';

% Mean of Y
ymean=mean(yi);

% Calculate R-squared
SST=0;
SSR=0;

%size(yhat)
%size(yi)
for i=1:length(yhat-1)
    SSR=SSR+(yhat(i)-0)^2;  % Sum of squares
    SST=SST+(yi(i)-ymean)^2;  % Sum of squares for treatments
end
r2=1-(SSR/SST);

function removed=noNaN(array)
% Removes values of NaN from a 1-D vector
% Output is shorter array with gaps removed

count=0;  % Set count to 0
for i=1:length(array)
    if isnan(array(i))==0  % If value is a real number not a NaN
        count=count+1;  % Increment count
        removed(count)=array(i);  % Add to new vector if a real value
    end
end
function \([t,s]=\text{noNaNseries}(x,y)\)

% Takes time series of values \(y\) occurring at times \(x\)
% and removes instances when there is a gap in \(y\) (\(y=\text{NaN}\)).
% Creates a time series with time \(t\) and variable \(y\)

\(\text{count}=0;\) \quad % Set count to 0
\(y';\)

for \(i=1:\text{length}(y)\)
    \(\text{if isnan}(y(i))==0\) \quad % If \(y\) is an actual value, not a NaN
        \(\text{count}=\text{count}+1;\) \quad % Increment count
        \(t(\text{count})=x(i);\) \quad % \(t = x\)
        \(s(\text{count})=y(i);\) \quad % \(s = y\)
    end
\(t=t';\)
\(s=s';\)

function array=makenans(array)

% Replaces all -9999, blanks, and negative values with NaN for any 2-D array

array(find(array==-9999))=NaN;
array(find(array==-9999))=NaN;
%array(find(array<-999))=NaN;
%array(find(array==0))=NaN;

function \(ci=\text{confidence\_interval}(sd,n)\)

% Tables for t-distribution for C.I. calculations
% alpha = 0.05
degreesOfFreedom=[10 20 30 40 50 60 70 80 90 100 110 120 130];
tPercentiles=[1.812 1.725 1.697 1.684 1.676 1.671 1.667 1.664 1.662 1.660 1.659 1.658 1.645];

dfIndex=getClosest(n-1,degreesOfFreedom'); \quad % degrees of freedom
t=tPercentiles(dfIndex); \quad % t-value for C.I.

% +/- this value for confidence intervals
\(ci=t*(sd/sqrt(n));\)

function \([\beta90 \; \text{ypred90} \; \text{resid90}]=\text{quantileFlux}(X,Y,pO)\)

[\beta90 \; \text{ypred90}]=\text{quantileRegression}(X,Y,0.9,pO);
\beta90

[y90s \; \text{idx90}]=\text{sort}(\text{ypred90});
for i = 1:length(Y)
    resid90(i)=Y(i)-ypred90(i);
end

% figure (1)
% plot(X,Y,'k.',X(idx90),ypred90(idx90),'r--','LineWidth',1.5)
% legend('Flux data','90th','Location','NorthWest')
% ylabel('C0_2 efflux (\mumol/m^2/ sec)');
% xlabel('10 cm Soil Temperature (\circC)');
% title(['90th Regression Quantile: ' name ' during ' year])

% figure (2)
% plot(X,resid,'k.' )
% ylabel('C0_2 efflux residuals (\mumol/m^2/sec)');
% xlabel('10 cm Soil Temperature (\circC)');
% title(['Residuals of the 90th Regression Quantile: ' name ' during ' year])

function [final, ypred]=quantileRegression2(X,Y,q,p0)

if (length(X)~=length(Y))
    error('X and Y must be of same length');
end

len=length(X);

[beta0, resid0, J0]=nlinfit(X',Y,@LT2,p0);

beta0;
ypredi=LT(X,beta0);

if q<.50
    inc(1)=beta0(1)/100;
    inc(2)=beta0(2)/14000;
    inc=-inc;
else
    inc(1)=beta0(1)/100;
    inc(2)=beta0(2)/10400;
end

c=0;
if q>=0.5
    q_temp=0;
    idx=1;
    while q_temp<q
        posC=0;
        negC=0;
        c=c+inc;
        ypred=LT(X,beta0+c);
        % code to update q_temp
    end

end

function ypred=LT(X,beta0)

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for j=1:len
    if (ypred(j)-Y(j))>0
        posC=posC+1;
        posResid(posC)=(ypred(j)-Y(j));
    end
    if (ypred(j)-Y(j))<=0
        negC=negC+1;
        negResid(negC)=(ypred(j)-Y(j));
    end
end
idx=idx+1;

q_temp(idx)=abs(sum(posResid))/ (abs(sum(posResid))+abs(sum(negResid)));
showq=q_temp;
if q_temp(idx)<q_temp(idx-1)
    break
end
end

if q<0.5
    pause
    q_temp=1;
    while q_temp>q
        posResid=0;
        negResid=0;
        posC=0;
        negC=0;
        c=c+inc;
        % Predicted y-values based on increment
        ypred=LT(X,beta0+c);
        for j=1:len
            % If a positive residual, store residual value
            if (ypred(j)-Y(j))>0
                posC=posC+1;
                posResid(posC)=(ypred(j)-Y(j));
            end
            % If a negative residual, store residual value
            if (ypred(j)-Y(j))<=0
                negC=negC+1;
                negResid(negC)=(ypred(j)-Y(j));
            end
        end
        % Calculates the quantile of residuals based on absolute residuals
        q_temp=abs(sum(posResid))/ (abs(sum(posResid))+abs(sum(negResid)));
        if q==0.95
            q_temp
        end
    end
end

% Final fit parameters
final=beta0+c;
function soilNew=getClosestSoil(flux,soil)
% Finds the closest (temporally) soil pit measurement for a given
% flux measurement

length(flux)
for i=1:length(flux)
    if mod(i,50)==0
        disp(floor((i/length(flux))*100))
    end
    c=0;
    for j =1:length(soil)
        % Make subset of measurements with the same day
        if floor(soil(j,6))==floor(flux(i,1))
            c=c+1;
            idxSoil(c)=j;
            subset(c,:)=soil(j,:);
        end
    end
    if c>0;
        idx_c=getClosest(flux(i,1),subset(:,6));
        idx=idxSoil(idx_c);
        if abs(flux(i,1)-soil(idx,6))<0.8333
            for x =1:42
                soilNew(i,x)=soil(idx,x);
            end
        else
            soilNew(i,:)=NaN;
        end
    else
        soilNew(i,:)=NaN;
    end
end

function time = processTimeSincePrecip(flux,met)
for i = 1:length(flux)
    if mod(i,50)==0
        disp(floor(i/length(flux)*100))
    end
    time(i)=timeSincePrecip(flux(i,1),met);
end

function time=timeSincePrecip(flux, met)
% Finds time in days since last precip
% Takes one flux time value
% Takes all met station data (2 D array)
% Returns time since last precip

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idx=getClosest(flux,met(:,1));
count=idx;

while met(count,6)==0
    count=count-1;
end

time = flux - met(count,1);

% automateGapFill

HF03ch1fill=masterGapFill(HF03chl,met03,'Chamber 1' ,'2003')
HF03ch2fill=masterGapFill(HF03ch2,met03,'Chamber 2' ,'2003')
HF03ch3fill=masterGapFill(HF03ch3,met03,'Chamber 3' ,'2003')
HF03ch4fill=masterGapFill(HF03ch4,met03,'Chamber 4' ,'2003')
HF03ch5fill=masterGapFill(HF03ch5,met03,'Chamber 5' ,'2003')
HF03ch6fill=masterGapFill(HF03ch6,met03,'Chamber 6' ,'2003')
HF03ch7fill=masterGapFill(HF03ch7,met03,'Chamber 7' ,'2003')
HF03ch8fill=masterGapFill(HF03chl,met03,'Chamber 8' ,'2003')

HF04ch1fill=masterGapFill(HF04chl,met04,'Chamber 1' ,'2004')
HF04ch2fill=masterGapFill(HF04ch2,met04,'Chamber 2' ,'2004')
HF04ch3fill=masterGapFill(HF04ch3,met04,'Chamber 3' ,'2004')
HF04ch4fill=masterGapFill(HF04ch4,met04,'Chamber 4' ,'2004')
HF04ch5fill=masterGapFill(HF04ch5,met04,'Chamber 5' ,'2004')
HF04ch6fill=masterGapFill(HF04ch6,met04,'Chamber 6' ,'2004')
HF04ch7fill=masterGapFill(HF04ch7,met04,'Chamber 7' ,'2004')
HF04ch8fill=masterGapFill(HF04chl,met04,'Chamber 8' ,'2004')

HF05ch1fill=masterGapFill(HF05chl,met05,'Chamber 1' ,'2005')
HF05ch2fill=masterGapFill(HF05ch2,met05,'Chamber 2' ,'2005')
HF05ch3fill=masterGapFill(HF05ch3,met05,'Chamber 3' ,'2005')
HF05ch4fill=masterGapFill(HF05ch4,met05,'Chamber 4' ,'2005')
HF05ch5fill=masterGapFill(HF05ch5,met05,'Chamber 5' ,'2005')
HF05ch6fill=masterGapFill(HF05ch6,met05,'Chamber 6' ,'2005')
HF05ch7fill=masterGapFill(HF05ch7,met05,'Chamber 7' ,'2005')
HF05ch8fill=masterGapFill(HF05chl,met05,'Chamber 8' ,'2005')

HF06ch1fill=masterGapFill(HF06chl,met06,'Chamber 1' ,'2006')
HF06ch2fill=masterGapFill(HF06ch2,met06,'Chamber 2' ,'2006')
HF06ch3fill=masterGapFill(HF06ch3,met06,'Chamber 3' ,'2006')
HF06ch4fill=masterGapFill(HF06ch4,met06,'Chamber 4' ,'2006')
HF06ch5fill=masterGapFill(HF06ch5,met06,'Chamber 5' ,'2006')
HF06ch6fill=masterGapFill(HF06ch6,met06,'Chamber 6' ,'2006')
HF06ch7fill=masterGapFill(HF06ch7,met06,'Chamber 7' ,'2006')
HF06ch8fill=masterGapFill(HF06chl,met06,'Chamber 8' ,'2006')
function filled=masterGapFill(chamber,met,name,year)

filledT=gapfillT(chamber,met);

[nxp dxp nypint dypint]= fit(chamber,[400 227],name,year);

filled=gapfillCO2(filledT,nxp,dxp,nypint,dypint,0,name,year)

function gaps=gapfinder(series)

% Expected sampling interval
int=.1667;

% Loops through all values to quantify gaps
for i = 1:length(series)-1
    % Time difference between values
    t_diff(i)=series(i+1,1)-series(i,1);
end

t_diff(i+1)=NaN; % Makes arrays same length for plotting

gap_idx=0; % Gap index

% Loops through all time differences to count gaps and lengths
for i = 1:length(t_diff)
    if t_diff(i)>int+.01
        gap_idx=gap_idx+1;
        gaps(gap_idx,1)=t_diff(i); % Gap length (in days)
        gaps(gap_idx,2)=series(i); % Gap start (frac. DOY)
        gaps(gap_idx,3)=series(i+1); % Gap end (frac. DOY)
    end
end

plot(series(:,1),t_diff,'k:');
axis([0 365 0 max(gaps(:,1))])
xlabel('Day of Year');
ylabel('Gap length (days)')
disp('----------------------------------------------------------')
disp('Gap length     Start       End')
disp(gaps)
disp('# of gaps:')
disp(length(gaps(:,1)))
disp('Largest gap (days):')
disp(max(gaps(:,1)))
disp('Smallest gap (days):')
disp(min(gaps(:,1)))
disp('Average gap duration (days):')
disp(mean(gaps(:,1)))
disp('Fraction of gaps in measurement period (%):')
measure_len=series(length(series),1)-series(1,1);
gap_sum=sum(gaps(:,1));
disp(gap_sum/measure_len*100)
disp('-----------------------------------')
gap_idx
sum(gaps(:,1))

function d=gapfillT(chamber,metT)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% function gapfillT
% Gapfills autochamber air temperature data based on a more
% temporally complete hourly temperature data (metT)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Returns length of chamber measurements
lenCh = length(chamber);
% Returns dimensions of met station measurements
lenMet = length(metT);
% Sets year length at 365 or 366 days
yearLen=365;

% Makes integer of day column in chamber measurements
day=chamber(:,1)-chamber(:,2);

% Counts # of measurements per day
for i=1:yearLen
    count=0;
    for j=1:lenCh
        if chamber(j,1) >= i & chamber(j,1)< i+1
            count=count+1;
        end
    end
    perDay(i,1)=count;
end

% Bar chart of measurements per day
figure(1);
bar(perDay);
ylabel('Number of measurements per day');
xlabel('Day of year');

% Creates 3-D array with gaps from 2-D chamber data
for i=1:yearLen
    count=0;
    for j=1:lenCh
        % Finds and copies chamber data
        while chamber(j,1) > i & chamber(j,1)< i+1
            count=count+1;
            compare(i,count,1) = i;  % Day
            compare(i,count,2) = chamber(j,2);  % Time
            compare(i,count,3) = chamber(j,12);  % Air temp
            compare(i,count,4) = chamber(j,14);  % CO2 flux
        end
    end
end

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break;
end
end

% If no chamber data, inserts NaN for gaps to keep continuity
perDay(i,2)=count;
for k=perDay(i,2)+1:6
    compare(i,k,1) = i; % Day
    compare(i,k,2) = NaN; % Time
    compare(i,k,3) = NaN; % Air temp
    compare(i,k,4) = NaN; % CO2 flux
end
end

% Plots T over year

count=0;
for i=1:yearLen
    for j = 1:perDay(i)
        count=count+1;
        day(count)=compare(i,j,1)+compare(i,j,2);
        temp(count)=compare(i,j,3);
    end
end

% figure(2);
% plot(day,temp,'bx');

% Creates blank 3-D array for final filled data
count=0;
for i=1:yearLen
    count=count+1;
    for j=1:6
        complete(i,j,1)=NaN;
        complete(i,j,2)=NaN;
        complete(i,j,3)=NaN;
        complete(i,j,4)=NaN;
        d(count,1)=NaN;
        d(count,2)=NaN;
        d(count,3)=NaN;
        d(count,4)=NaN;
    end
end

% Fills NaNs with the temperature value from the closest time from
% meteorological data set
count=0;
for i=1:yearLen
    for j=1:6
        count=count+1;
        % All parameter present
        if isnan(compare(i,j,2))==0 & isnan(compare(i,j,3))==0 &
            isnan(compare(i,j,4))==0
            complete(i,j,1)=i;
            complete(i,j,2)=compare(i,j,2);
        end
end
complete(i,j,3)=compare(i,j,3);  
close(i,j,4)=compare(i,j,4);  
filled=0;  
end

% No data at day/time  
if isnan(compare(i,j,2))==1  
  % Arbitrarily sets day and time  
  complete(i,j,1)=i;  
  complete(i,j,2)=(j*4)/24;  
  t=complete(i,j,1)+complete(i,j,2);  
  
  % Uses closest temperature value from the  
  % met data  
  x=getClosest(t,metT);  
  metT(x,2);  
  if isnan(metT(x,16))==0  
    complete(i,j,3)=metT(x,16);  
  else  
    complete(i,j,3)=metT(x,3);  
  end

  filled=1; 
end

% Data for day/time but no temp  
if compare(i,j,2)~=NaN & compare(i,j,3)==NaN  
  % Uses closest temperature value from the  
  % met data  
  x=getClosest(compare(i,j,1),metT);  
  complete(i,j,3)=metT(x,2);  
  filled=1;  
end

  d(count,1)=i+complete(i,j,2);  
  d(count,2)=complete(i, j, 3) ;  
  d(count,3)=complete(i, j, 4);  
  d(count,4)=filled;
end

% Plots T over year %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% figure(3);  
% plot(d(:,1),d(:,2),'bx');

% Counts # of measurements per day in gapfilled data %**********
for i=1:yearLen  
  count=0;  
  for j=1:length(d)  
    if d(j,1) >= i & d(j,1)< i+1  
      count=count+1;  
    end
  end
end
    perDayG(i,1)=count;
end

% Bar chart of measurements per day
% figure(4);
% bar(perDayG);
% ylabel('Number of measurements per day');
% xlabel('Day of year');

function [nxp dxp nypint dypint]=fit(chamber,pred,name,year)

% Soil temp and resp. values
x=chamber(:,13);
y=chamber(:,14);

% Remove data pairs with NaNs
C=0;
for i = 1 :length(x)
    if isnan(x(i))==0 & isnan(y(i))==0
        C=C+1;
        x2(C)=x(i);
        y2(C)=y(i);
    end
end

% Split into day and night values
day=floor(chamber(:,1));
time=chamber(:,1)-day;
nc=0;
dc=0;
for i = 1 :length(x2)
    if getDayNight(day(i),time(i))==0
        nc=nc+1;
        nx(nc)=x2(i);
        ny(nc)=y2(i);
    else
        dc=dc+1;
        dx(dc)=x2(i);
        dy(dc)=y2(i);
    end
end

% Evenly spaced grid of x and y values for testing
nxp=linspace(min(nx),max(nx),150)';
nyp=LloydTaylor(nx,pred);
dxp=linspace(min(dx),max(dx),150)';
dyp=LloydTaylor(dx,pred);
nx=nx';
ny=ny';
dx=dx';
dy=dy';

nypint=bootstrap(@LloydTaylor,nx,ny,pred, nxp);
dypint=bootstrap(@LloydTaylor,dx,dy,pred, dxp);
dypint=nypint;
% subplot(2,1,1);
% plot(nx,ny,'k .',nxp,nypint(:,1),'r-',
nxp,nypint(:,1)+nypint(:,2),'b:',nxp,nypint(:,1)-
nypint(:,2),'b:',nxp,nypint(:,3),'g--',nxp,nypint(:,5),'g--'
)% subplot(2,1,2);
% plot(dx,dy,'k .',dxp,dypint(:,1),'r-',
xp,dypint(:,1)+dypint(:,2),'b:',xp,dypint(:,1)-
dypint(:,2),'b:',xp,dypint(:,3),'g--',xp,dypint(:,5),'g--'

function chamber=gapfillCO2(chamber,nxp,dxp,nypint,dy,day, Tdev,name,year)

% Finds "measurements" of gapfilled T and uses
% best fit regression to fill CO2 flux and find uncertainty
% chamber: chamber measurements
% xp: x for testing
% nypint,dy: bootstrap output
% Tdev: standard deviation of temperature difference

day=floor(chamber(:,1));
time=chamber(:,1)-day;

for i=1:length(chamber)
    if isnan(chamber(i,1))==0

if getDayNight(day(i),time(i))==0
  % Use night fit
  ypint=nypint;
  xp=nxp;
else
  % Use day fit
  ypint=dypint;
  xp=dxp;
end

% Checks if actual value or filled from met. station
if isnan(chamber(i,3))==1 & isnan(chamber(i,2))==0
  % Gets index of closest T value in testing variable
  idx=getClosest(chamber(i,2),xp);

  % Sets new flux vlaue based on predicted for the closest T
  chamber(i,3)=ypint(idx,1);

  % Finds uncertainty using +-standard dev. including T
  up=chamber(i,2)+Tdev';
  low=chamber(i,2)-Tdev';
  idx=getClosest(up,xp);
  chamber(i,5)=chamber(i,3)+ypint(idx,2);
  idx=getClosest(low,xp);
  chamber(i,6)=chamber(i,3)-ypint(idx,2);
end
end
end

filledX=chamber((find(chamber(:,4)==1)),1);
filledY=chamber((find(chamber(:,4)==1)),3);
actualX=chamber((find(chamber(:,4)==0)),1);
actualY=chamber((find(chamber(:,4)==0)),3);

% size(actualX)
% size(actualY)
%
% plot(actualX,actualY,'k.',filledX,filledY,'r--');
% ylabel('CO_2 flux \text{\textmu mol/m}\text{^2/sec}','FontSize',14);
% xlabel(['Day of year ' year],'FontSize',14);
% legend('Actual','Filled')
% name
% year
% title([name ' during ' year],'FontSize',14)
% axis([0 365 0 10]);
%%% CALCULATE DAILY AVERAGES
[t_x, t_y] = meanDaily(FMET03(:,1),FMET03(:,2));
[wmx, wmy] = meanDaily(wet_marg03(:,1),wet_marg03(:,14));
[mx, my] = meanDaily(mid_slope03(:,1),mid_slope03(:,14));
[ux, uy] = meanDaily(upland03(:,1),upland03(:,14));
%%% ROBUST SPLINE SMOOTH DAILY AVERAGES
% t_y = rbsp(t_x, t_y, 0.2);
% wmys = rbsp(wmx, wmy, 0.2);
% msys = rbsp(msx, msy, 0.2);
% uys = rbsp(ux, uy, 0.2);

%%% FILLED %%%%

%%% CALCULATE DAILY AVERAGES
[t_xl, t_yl] = meanDaily(FMET04(:,1),FMET04(:,2));
[wmxl, wmyl] = meanDaily(wet_marg04(:,1),wet_marg04(:,14));
[mxsl, msyl] = meanDaily(mid_slope04(:,1),mid_slope04(:,14));
[uxl, uyl] = meanDaily(upland04(:,1),upland04(:,14));
%%% ROBUST SPLINE SMOOTH DAILY AVERAGES
% tyl = rbsp(txl, tyl, 0.2);
% wmysl = rbsp(wmlx, wmyl, 0.2);
% msy = rbsp(msxl, msyl, 0.2);
% uysl = rbsp(uxl, uyl, 0.2);

%%% CALCULATE DAILY AVERAGES
[t_x2, t_y2] = meanDaily(FMET05(:,1),FMET05(:,2));
[wmx2, wmy2] = meanDaily(wet_marg05(:,1),wet_marg05(:,14));
[mx2, my2] = meanDaily(mid_slope05(:,1),mid_slope05(:,14));
[ux2, uy2] = meanDaily(upland05(:,1),upland05(:,14));
%%% ROBUST SPLINE SMOOTH DAILY AVERAGES
% t_y2 = rbsp(tx2, ty2, 0.2);
% wmys2 = rbsp(wmx2, wmy2, 0.2);
% msys2 = rbsp(msx2, msy2, 0.2);
% uys2 = rbsp(ux2, uy2, 0.2);

%%% FILLED %%%%

%%% CALCULATE DAILY AVERAGES
[wmx3, wmy3] = meanDaily(wet_marg06(:,1),wet_marg06(:,14));
[mx3, my3] = meanDaily(mid_slope06(:,1),mid_slope06(:,14));
[ux3, uy3] = meanDaily(upland06(:,1),upland06(:,14));
%%% ROBUST SPLINE SMOOTH DAILY AVERAGES
% wmys3 = rbsp(wmx3, wmy3, 0.2);
% msys3 = rbsp(msx3, msy3, 0.2);
% uys3 = rbsp(ux3, uy3, 0.2);

% *** FILLED ****
% *** CALCULATE DAILY AVERAGES
% [fwmx, fmy] = meanDaily(wet_marg03fill(:,1),wet_marg03fill(:,3));
% [fmsx, fmsy] = meanDaily(mid_slope03fill(:,1),mid_slope03fill(:,3));

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% [fux, fuy]=meanDaily(upland03fill(:,1),upland03fill(:,3));
% %%% ROBUST SPLINE SMOOTH DAILY AVERAGES
% fwmys=rbsp(fwmx,fwmy,0.2);
% fmsys=rbsp(fmox,fmsy,0.2);
% fuys=rbsp(fux,fuy,0.2);
%
% %%%%%%%%%%%%%%%%%%% 2004 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %%%%% CALCULATE DAILY AVERAGES
% [fwmxl, fwmyl]=meanDaily(wet_marg04fill(:,1),wet_marg04fill(:,3));
% [fmsxl, fmsyl]=meanDaily(mid_slope04fill(:,1),mid_slope04fill(:,3));
% [fuxl, fuyl]=meanDaily(upland04fill(:,1),upland04fill(:,3));
% %%% ROBUST SPLINE SMOOTH DAILY AVERAGES
% fwmysl=rbsp(fwmxl,fwmyl,0.2);
% fmsysl=rbsp(fmsxl,fmsyl,0.2);
% fuysl=rbsp(fuxl,fuyl,0.2);
%
% %%%%%%%%%%%%%%%%%%%%% 2005 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %%%% CALCULATE DAILY AVERAGES
% [fwx2, fwmy2]=meanDaily(wet_marg05fill(:,1),wet_marg05fill(:,3));
% [fmsx2, fmsy2]=meanDaily(mid_slope05fill(:,1),mid_slope05fill(:,3));
% [fux2, fuy2]=meanDaily(upland05fill(:,1),upland05fill(:,3));
% %%% ROBUST SPLINE SMOOTH DAILY AVERAGES
% fwmys2=rbsp(fwmx2,fwmy2,0.2);
% fmsys2=rbsp(fmsx2,fmsy2,0.2);
% fuys2=rbsp(fux2,fuy2,0.2);
%
% %%%%%%%%%%%%%%%%%%%%% 2006 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %%%% CALCULATE DAILY AVERAGES
% [fwx3, fwy3]=meanDaily(wet_marg06fill(:,1),wet_marg06fill(:,3));
% [fmsx3, fmsy3]=meanDaily(mid_slope06fill(:,1),mid_slope06fill(:,3));
% [fux3, fuy3]=meanDaily(upland06fill(:,1),upland06fill(:,3));
% %%% ROBUST SPLINE SMOOTH DAILY AVERAGES
% fwmys3=rbsp(fwmx3,fwmy3,0.2);
% fmsys3=rbsp(fmsx3,fmsy3,0.2);
% fuys3=rbsp(fux3,fuy3,0.2);
%

% PLOT
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1)
subplot(4,1,1)
plot(wmx,wmys,'r. ',msx,msys,'b. ',ux,uys,'g. ')
axis([90 365 0 8])
xlabel('Day of Year 2003','FontSize',14)
legend('Wetland margin','Mid-slope','Upland')
title('Smoothed soil flux','FontSize',16)

subplot(4,1,2)
plot(wmxl,wmysl,'r. ',msxl,msyl,'b. ',uxl,uyl,'g. ')
axis([90 365 0 8])
xlabel('Day of Year 2004','FontSize',14)
ylabel('Soil Flux (\text{\textmu mol CO}_2 m^{-2} s^{-1})','FontSize',14)

subplot(4,1,3)
plot(wxm2,wmys2,'r-',msx2,msys2,'b-',ux2,uyys2,'g-')
axis([90 365 0 8])

subplot(4,1,4)
plot(wxm3,wmys3,'r .',msx3,msys3,'b .',ux3,uyys3,'g-')
axis([90 365 0 8])
xlabel('Day of Year', 'FontSize',14)

function [x avg2]=meanDaily(t,s)
days=1:365;
count=zeros(365,1);
sum=zeros(365,1);
for i=1:365
    for j=1:length(t)
        if floor(t(j))==i & isnan(s(j))==0
            count(i)=count(i)+1;
            sum(i)=sum(i)+s(j);
        end
    end
    if count(i)>3
        avg(i)=sum(i)/count(i);
    else
        avg(i)=NaN;
    end
end
[x avg2]=noNaNseries(days,avg);

%hysteresis.m

% 2003 averages
mo_avg03T = moAvg(met03(:,1), met03(:,16), 0);
mo_avg03wm = moAvg(wet_marg03(:,1), wet_marg03(:,14), 0);
mo_avg03ms = moAvg(mid_slope03(:,1), mid_slope03(:,14), 0);
mo_avg03up = moAvg(upland03(:,1), upland03(:,14), 0);
mo_avg03tow = moAvg(tower03(:,7), tower03(:,14), 0);

% 2004 averages
mo_avg04T = moAvg(met04(:,1), met04(:,16), 1);
mo_avg04wm = moAvg(wet_marg04(:,1), wet_marg04(:,14), 1);
mo_avg04ms = moAvg(mid_slope04(:,1), mid_slope04(:,14), 1);
mo_avg04up = moAvg(upland04(:,1), upland04(:,14), 1);
mo_avg04tow = moAvg(tower04(:,7), tower04(:,14), 0);
% 2005 averages
mo_avg05T = moAvg(met05(:,1), met05(:,16), 0);
mo_avg05wm = moAvg(wet_marg05(:,1), wet_marg05(:,14), 0);
mo_avg05ms = moAvg(mid_slope05(:,1), mid_slope05(:,14), 0);
mo_avg05up = moAvg(upland05(:,1), upland05(:,14), 0);

% 2006 averages
mo_avg06T = moAvg(met06(:,1), met06(:,16), 0);
mo_avg06wm = moAvg(wet_marg06(:,1), wet_marg06(:,14), 0);
mo_avg06ms = moAvg(mid_slope06(:,1), mid_slope06(:,14), 0);
mo_avg06up = moAvg(upland06(:,1), upland06(:,14), 0);

figure(1)
subplot(2,2,1)
plot(mo_avg03T,mo_avg03wm,'ro--',mo_avg03T,mo_avg03ms,'bd-
',mo_avg03T,mo_avg03up,'gA:','LineWidth',5.5)
axis([0 250 8])
subplot(2,2,2)
plot(mo_avg04T,mo_avg04wm,'ro--',mo_avg04T,mo_avg04ms,'bd-
',mo_avg04T,mo_avg04up,'gA:','LineWidth',5.5)
axis([0 250 8])
subplot(2,2,3)
plot(mo_avg05T,mo_avg05wm,'ro--',mo_avg05T,mo_avg05ms,'bd-
',mo_avg05T,mo_avg05up,'gA:','LineWidth',5.5)
axis([0 250 8])
ylabel('Monthly average CO_2 efflux (\umol/m^2/sec)')
subplot(2,2,4)
plot(mo_avg06T,mo_avg06wm,'ro--',mo_avg06T,mo_avg06ms,'bd-
',mo_avg06T,mo_avg06up,'gA:','LineWidth',5.5)
axis([0 250 8])
xlabel('Monthly average 10 cm Soil Temperature (\circC)')

figure(2)
subplot(1,2,1)
plot(mo_avg03T(4:11),mo_avg03tow(4:11),'ko:','LineWidth',5.5)
axis([0 250 8])
ylabel('Monthly average ecosystem respiration (\umol m^-2 sec^-1)')
subplot(1,2,2)
plot(mo_avg04T(4:12),mo_avg04tow(4:12),'ko:','LineWidth',5.5)
axis([0 250 8])
xlabel('Monthly average 10 cm Soil Temperature (\circC)')

mo_avg03tow
mo_avg04tow

function mo_avg = moAvg(time, data, leap)
% Takes two corresponding time and data vectors and creates monthly
% averages - time in fractional day of year, any data
% Leap year is a 1, non-leap is zero or empty

% Make sure vectors are same length
if (size(time) == size(data))
disp('Lengths must equal!');
error;
end

% Annual average
count = 0;
sum = 0;
for i = 1:length(time)
    if (isnan(time(i))==0 & isnan(data(i))==0)
        count = count + 1;
        sum = sum + data(i);
    end
end

sum
yr_avg = sum ./ count;

% Determines leap or non-leap and sets month boundaries
leap
if (nargin < 3 | isempty(leap))
    leap = 0;
end
if (leap == 0)
    moLim = [0 31 59 90 120 151 181 212 243 273 304 334 365];
else
    moLim = [0 31 60 91 121 152 182 213 244 274 305 335 366];
end

% Set month counter and sums to zero
mo_count = zeros(12,1);
mo_sum = zeros(12,1);
for i = 1:length(time)
    for j = 2:13
        if (time(i) <= moLim(j) & time(i) > moLim(j-1) &
            isnan(time(i))==0 & isnan(data(i))==0)
            mo_count(j-1) = mo_count(j-1) + 1;
            mo_sum(j-1) = mo_sum(j-1) + data(i);
        end
    end
for i = 1:12
    if mo_count(i)>1
        mo_avg(i) = mo_sum(i) / mo_count(i);
    else
        mo_avg(i) = NaN;
    end
end
function mo=getMonth(fracDOY)

if fracDOY <= 31
    mo=1;
end

if fracDOY <= 59 & fracDOY > 31
    mo=2;
end

if fracDOY <= 90 & fracDOY > 59
    mo=3;
end

if fracDOY <= 120 & fracDOY > 90
    mo=4;
end

if fracDOY <= 151 & fracDOY > 120
    mo=5;
end

if fracDOY <= 181 & fracDOY > 151
    mo=6;
end

if fracDOY <= 212 & fracDOY > 181
    mo=7;
end

if fracDOY <= 243 & fracDOY > 212
    mo=8;
end

if fracDOY <= 273 & fracDOY > 243
    mo=9;
end

if fracDOY <= 304 & fracDOY > 273
    mo=10;
end

if fracDOY <= 334 & fracDOY > 304
    mo=11;
end

if fracDOY > 334
    mo=12;
end