The Photosynthetic Potential of *Quercus rubra* L. as Estimated From Chlorophyll Fluorescence Along an Urban to Rural Transect

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Abstract:

Urbanization is increasing rapidly on a global scale, creating novel environments with which organisms must interact. The purpose of this study is to determine the effects of urbanization on the photosynthetic apparatus of *Quercus rubra*, a dominant tree species in the Northeastern United States. I measured photosynthetic differences in *Ouercus rubra* using chlorophyll fluorescence along an urban to rural transect during Autumn 2006. I measured fluorescence at four sites from New York, New York (the most urban) to the Ashokan Reservoir, New York (the most rural site). Although there was no significant differences in either total biomass or relative growth rates along the transect, there were differences in physiology and leaf chemistry. Our results showed that Fv/Fm (a measure of maximal photosynthetic efficiency) was significantly higher in urban as opposed to rural sites during 3 out of 4 sampling periods. Fv/Fm was negatively correlated with distance from the city in three of the four sampling periods. For 1 of 4 sampling periods, maximal electron transport rates in plant photochemistry (ETR max) were negatively correlated with distance from the city. It is hypothesized that diurnal temperature range differences, atmospheric nitrogen deposition, and ozone and carbon dioxide gradients are the main factors be responsible for site differences in Fv/Fm and ETR max.

Contents				
Introduction	4			
Thesis Statement				
Methods	8			
Preliminary Results	12			
Discussion	25			
Implications of research	29			
Acknowledgements	31			
References	31			
Supplementary material	36			
Figures and Tables				
Figure 1: Greater biomass of cottonwood found in New York City (Greg et al 2003)	5			
Figure 2: Graph explaining chlorophyll fluorescence	10			
Figure 3: Fv/Fm of four field sites	14			
Figure 4: Linear regression analyses of Fv/Fm				
Figure 5: ETR max of four field sites	17			
Figure 6: Linear regression analyses of ETR max				
Figure 7: Biomass of four sites	20			
Figure 8: Model for calculating relative growth rates	21			
Figure 9: Leaf Carbon and Nitrogen percentage and ratio	22			
Figure 10: Leaf δC^{13} and δN^{15}	23			
Figure 11: Diurnal Temperature Range (DTR) of four sites				
Table 1: DTR on days on which measurements were taken	25			

Introduction:

Urbanization drastically alters the environmental factors that influence the photosynthetic efficiency of plant life. Urban environments contain higher levels of CO₂, higher temperatures, greater amounts of pollutants, higher nitrogen deposition, and lower levels of tropospheric ozone (O_3) than surrounding rural areas (Gatz 1991; Nicholson et al 2000; Zhu 2003; Chen 2006). Some of these factors positively influence plant growth and photosynthesis, while others are harmful. Given the current climate change due to increasing levels of CO₂, it is essential to know how plant life, particularly trees which can function as major carbon sinks, will respond in urban environments, and the factors that influence their photosynthetic machinery. It is postulated that the biosphere is the "missing carbon sink" (i.e., the biosphere is fixing the anthropogenic emission of CO_2 that is unaccounted for) (Field 2001). Models can predict leaf-level response in C_3 plants to increased CO_2 levels, yet modeling CO_2 assimilation at the ecosystem level is difficult to determine precisely (Field 2001). In general, as greater CO₂ concentrations become available, plants respond by fixing more carbon. However, as plants become acclimated to higher CO₂ concentrations, they become less efficient at assimilating carbon (Delucia 1985, 1999; Chen 2005). An examination of the variables affecting photosynthesis in urban versus rural environments can provide better understanding of the mechanisms underlying a tree's ability to maximize photosynthesis and carbon fixation.

Gregg, Jones and Dawson (2003) found that the biomass of a cottonwood clone grown in New York City was double that of the same cottonwood clone grown in rural

areas (Figure 1).



Figure 1: Cottonwood growth in urban and rural sites. Final season shoot and root biomass (mean \pm s.e., potting soils) for cottonwoods grown in urban (filled, NY₁₋₄) and rural (open; HV₁, LI₁₋₂) sites in the vicinity of New York City for three consecutive growing seasons (a–c). Values that fall below the zero line are for belowground biomass. F and P statistics are for linear contrasts of analyses of variance comparing total biomass for urban versus rural sites. Independent comparisons for above- and belowground biomass gave the same result. Bars with different letters indicate values significantly different using the Tukey–Kramer HSD. Figure and caption from Gregg et al 2003.

Gregg et al. (2003) attributed the lower growth rates in rural and suburban areas to higher levels of tropospheric O₃. My study attempts to further the understanding of the effect of urban and rural landscapes on plant form and function. Because Gregg et al. (2003) did not use a native species and lacked mechanistic data, in this study I used the native red oak, *Quercus rubra* to examine not only differences in biomass along an urban to rural transect, but also the mechanistic aspects which underlie any differences between areas. My study focuses on the differences in photosynthetic function of red oak by measuring chlorophyll fluorescence across this transect. I hypothesize that the O₃ gradient is not the only factor strongly influencing differences between oaks from urban to rural areas; instead, diurnal temperature ranges (DTR), ambient CO₂ concentrations, nitrogen deposition, and other pollutants may also cause significant differences.

Numerous studies have found that pollutants such as nitrogen oxides are present at much higher rates in urban areas, and this trend tends to increase plant net primary production (Zhu 1999; Lovett 2000). Other studies found that pollutants such as CuSO₄ and SO₂ can have harmful effects on plant photosynthesis (Garty et al. 2005; Geiser & Neitlich 2006). The negative effects of O₃ on plant physiology can be a major factor in reduction of photosynthetic rates (Ranford & Reiling 2005); tropospheric ozone levels are lower in the city due to interaction with other pollutants such as NO_xs (Nicholson et al. 2000).

Increased temperatures can have either negative or positive effects on photosynthetic function. Fv/Fm is a measure of a plant's maximal ability to absorb electrons to drive its photochemical pathways in the light reactions of photosynthesis. A plant with a higher Fv/Fm is more efficient at utilizing all of the photons of light it receives than a plant with a lower Fv/Fm. A plant's Fv/Fm can be reduced when a plant undergoes heat stress as well as when a plant undergoes "chill stress" and freezing (Baker 2004). Cities are typically warmer than surrounding areas because of the greater presence of absorptive black top causing the urban heat island effect (Chen 2006). Increased city temperatures may counter chilling stress, but if too high, may incur heat stress. It is likely that increased temperatures in the city will be most prevalent at night, which will reduce the difference between daytime and nighttime temperatures (Diurnal Temperature Range also known as: DTR) in urban areas. To say a location has a lower DTR is to say that its temperature varies less than a location with a higher DTR. Reduced variation in

temperature may in turn lead to reduced temperature stress for plants. Thus, since urban areas have a significantly lower DTR than comparable rural areas, photosynthetic differences between sites may be due to differences in temperature stress.

Increases in atmospheric CO₂ are predicted to raise global temperatures, which could potentially cause a higher respiration to photosynthesis ratio (Turnbull et al. 2005). This change would reduce the biosphere's efficiency as a carbon sink. In addition, experiments on grassland species demonstrate that elevated temperatures could have either a negative or positive effect on plant photosynthesis depending on the species (Gielen et al. 2005). Some species will be able to prolong their growing season at higher temperatures, thereby fixing more carbon. Other species experience water stress from elevated temperatures, causing them to end their growing season early, thereby fixing less carbon than prior conditions (Gielen et al. 2005).

This study aims to clarify the interaction of a native plant species with its rapidly changing native environment. Red oak *(Quercus rubra)* was chosen because it represents a dominant native species of the northeastern United States and is also a significant carbon sink (Field 2001). The NYC urban environment should be representative of the effect of heavy anthropogenic activity on plant photosynthesis. As land use changes cause larger areas to become developed, it is important to know how the photosynthetic machinery of the plants will change as a result.

Thesis Statement:

It is postulated that due to diurnal temperature differences (Turnbull, Murthy & Griffin 2002), tropospheric O₃ gradients (Gregg et al 2003), and nitrogen deposition (Zhu 2003) there will be a higher maximum quantum efficiency and more efficient photosynthetic output for *Quercus rubra* at the urban site and lower rates progressing northward along an urban to rural transect.

Methods:

Sites: We chose four sites along an urban to rural transect, each of which contained 25-35 potted trees. The four sites were Central Park, New York, New York, the most urban of the sites; a suburban site, Lamont Doherty Earth Observatory in Palisades, New York (30 km from Central Park); a rural site, Black Rock Forest in Cornwall, New York (90 km from Central Park); and the Ashokan reservoir in Ashokan, New York (120 km north of Central Park). The Ashokan reservoir is located in New York's Catskill Mountains and is the most rural of the sites.

All the oaks originated as acorns from a single oak tree in Black Rock Forest. 300 red oak seedlings were grown in a root box in a common garden in Black Rock Forest from 2003-2005. In the winter of 2005, the oaks were transferred to the sites along the gradient. The urban plants over wintered in Swindler's cove in Manhattan, but were transferred to Central Park before the first leaves emerged. The trees spent all of the growing season of 2006 at the site where sampling occurred.

Experiment: On 21-23 September 2006, chlorophyll fluorescence of ten trees was measured at each site. These ten trees were then harvested and their leaves and roots were dried and measured to determine biomass. On 21-23 September 2006, other measurements such as CO₂ assimilation rates, leaf area, and stomatal density were also collected. From 29 September to 10 November, Central Park and Lamont were visited an additional seven times, and Black Rock Forest and Ashokan Reservoir were visited an additional three times (see supplementary material for exact dates). Chlorophyll fluorescence measurements were made on each of these site visits and leaf gas exchange measurements were taken on the weekend of 21 October. Of the twenty trees at each site, Chlorophyll fluorescence measurements were taken on ten trees at each site. The ten trees chosen were different for each sampling period. A specialized leaf clip was put on a single upper canopy leaf of each of the ten trees for a minimum of 20 minutes in order to dark-adapt a small section of the leaf. After the leaf was fully dark-adapted a Hansatech Fluorescence Monitoring System (FMS 2, Hansatech, UK) was used to measure chlorophyll fluorescence using a modulating beam from a light-emitting diode (LED).

<u>Chlorophyll Fluorescence</u>: Fluorometers measure the chlorophyll fluorescence of a leaf at various light levels. A fluorometer reports the photosynthetic efficiency of a leaf and its maximum potential of using a photon to perform photosynthesis (Maxwell and Johnson 2000). The fluorometer acquires a suite of variables in order to calculate the ratio of variable fluorescence to maximum fluorescence (Fv/Fm), the quantum yield of photosystem II photochemistry (ΦPSII), electron transport rates (ETR), and photochemical and non-photochemical quenching (White and Critchley 1998).

Fv/Fm is measured when the leaf is dark-adapted and all the photochemical centers are fully oxidized. It represents the highest possible maximal efficiency of absorbing electrons. Fv'/Fm' (other known as Φ PSII) is measured 9 times as the leaf becomes light adapted and represents the leaf's ability to use photons to drive photosynthesis as it becomes light adapted. Φ PSII is used to calculate electron transport rates (ETR) (Figure 2).



Figure 2: This graph shows the measurement of chlorophyll fluorescence of a leaf from fully dark-adapted (0 seconds) to fully light adapted (110 seconds). Numbers represent light in μ mol m²s⁻¹ modified from Epstein 2004.

Light is reorganized in three ways when interacting with a leaf: 1) photosynthesis, 2) dissipation as heat, or 3) re-emission as fluorescence. Measurements of fluorescence can be used to calculate the amount of energy in the other two processes, photosynthesis (qP) and heat dissipation (qNP) (Maxwell and Johnson 2000). PAR is the incident photosynthetically active radiation, which increases until saturation at approximately 1800 μ mol/m²s⁻¹. Electron transport rates (ETR) are calculated using PAR in the following equation:

ΦPSII *PAR*0.5*0.84 (Equation 1)

where 0.84 the standard incident quanta absorbed by the leaf (White and Critchley, 1998). ETR max is the maximum electron transport rate at light saturation.

We recorded Fv/Fm, ΦPSII, qP, and qNP for the plants at each site. The fluorescence origin (Fo) is the background fluorescence of the leaf when dark-adapted and before it receives a pulse of light (Figure 2). When the dark-adapted leaf is suddenly exposed to the first pulse of the light from the fluorometer all the photochemical reaction centers are completely saturated, causing excess light to be emitted back as fluorescence. The maximal amount of fluorescence emitted back is the fluorescence maximum (Fm) (Figure 2). Fv is the difference between Fm and Fo (Fm-Fo) (Figure 2). Fv/Fm determines maximum quantum efficiency of photosystem II photochemistry. ΦPSII is the quantum efficiency of photosystem II as the reaction centers transition from dark-adapted to a steady light adapted state. ΦPSII is measured as the corresponding Fv'/Fm', where Fm' is the maximal fluorescence at a particular light level, Fv' is the distance from Fm'

to Fs, and Fs is the steady state background fluorescence (Figure 2). The photochemical quenching co-efficient (qP) indicates the fraction of light that is used to saturate the reaction centers in photosystem II with electrons. qNP is the non-photochemical quenching co-efficient; this indicates the fraction of light that is wasted as dissipated heat.

Leaf Carbon and Nitrogen:

Leaves from trees harvested on 22-24 September were used to assess differences in leaf nitrogen and carbon across the transect. Five trees from each site were chosen and the leaves from each tree were ground into a fine powder. This powder was then packaged and shipped to Washington State University Stable Isotope Core Laboratory where a mass spectrometer and a C:N analyzer was used to assess leaf %C, %N, δC^{13} , and δN^{15} . When a plant is water stressed it closes its stomates to prevent further water loss; and when it closing its stomates, a plant in unable to obtain new CO₂ from the outside atmosphere. Plants must then use the C from the available CO₂ inside the leaf. Plants prefer C¹² and will use all the available C¹² atoms, but when C¹² atoms are all used up, a plant will use C¹³ atoms out of necessity. Thus, the δC^{13} measurements allow one to see if a plant was water stressed (West et al 2006).

Preliminary Results:

<u>Fv/Fm</u>

On 22 September Central Park had the highest mean Fv/Fm, followed by Black Rock Forest, Ashokan, and Lamont. Based on means alone, the expected trend (high values in the city and lower values progressing northward along the transect) was

followed with the exception of Lamont. However, a linear regression analysis indicated that the relationship between Fv/Fm and distance from New York City was not significant (p= 0.075) (Figure 4a). However, the sites were significantly different from each other (ANOVA; $F_{3,40}$ = 13.6, p <0.0001). Central Park was significantly higher than Lamont and Ashokan, and similar to Black Rock, as determined using the Tukey HSD post-hoc means comparison (Figure 3a).

During 2-7 October, the highest mean Fv/Fm was at Black Rock Forest followed by Central Park, Lamont, and Ashokan. Black Rock Forest was not significantly different from Central Park and Lamont was not significantly different from Ashokan (Tukey HSD, Figure 3b). However, trees in Black Rock and Central park had significantly higher Fv/Fm than trees at Lamont and Ashokan (Figure 3b). There was a significant negative relationship between Fv/Fm and distance from the city (95% CI on slope from regression analysis=-0.015, -0.003, p=0.006; Figure 4b).

On 13-14 October, the highest mean Fv/Fm was at Central Park, followed by Black Rock, Lamont, and Ashokan. Only Central park was significantly different from the other sites (ANOVA; $F_{3,36}$ = 6.00, p=0.002; Figure 3c). There was a negative relationship between Fv/Fm and distance from the city (95% CI= -0.017, -0.051, p=0.0003; Figure 4c).

On 21-22 October 2006, the highest mean Fv/Fm was found at Black Rock Forest followed by Central Park, Lamont and Ashokan. Ashokan was significantly lower than the other sites, and was the only site different from the other sites (ANOVA; $F_{3,36} = 5.9$, p = 0.0023; Figure 3d). There is a negative relationship between Fv/Fm and distance from the city (95% CI=-0.026, -0.001, p=0.034; Figure 4d).



Figure 3: Fv/Fm averages from chlorophyll fluorescence at Central Park (CP), Lamont-Doherty Earth Observatory (LDEO), Black Rock Forest (BRF), and Ashokan Reservoir (ASH). Graphs are of measurements taken on A) 22-24 Sept B) 2-7 Oct C) 13-14 Oct D) 21-22 Oct. Fv/Fm measures the maximal ability of Photosystem II to utilize an electron for photochemical pathways. In A) leaf senescence has not yet begun; in B), C) senescence has begun; in D) senescence has developed in most leaves. Because Fv/Fm is a ratio, it has no units. F ratios and P values are for linear contrasts of analysis of variance comparing Fv/Fm and different sites. Boxes with different letters indicate significantly different values using the Tukey-Kramer HSD.



Figure 4: Linear regressions of Fv/Fm at 1 (CP), 2 (LDEO), 3 (BRF), and 4 (ASH), on the following dates: a) 22-24 Sept b) 29 Sept- 4 Oct c) 13-14 Oct d) 21-22 Oct. On b), c) and d) there exists a negative relationship between Fv/Fm and distance from New York City within the 95% confidence interval (CI) (regression analysis). Conversely, on a), there is no significant relationship between distance from the city and Fv/Fm (regression analysis). p values and confidence intervals are derived from a regression analysis. p=NS indicates that the linear relationship between site and Fv/Fm is not significant.

Electron Transport Rate

The expected trend for maximum Electron Transport rates was: Central Park with

the highest rates followed by, Lamont, Black Rock Forest, and Ashokan Reservoir.

Lamont, Black Rock Forest, Lamont, and Lamont was the highest mean ETR max on the

following respective sampling periods: On 22-24 September, 2-7 October, 13-14 October, 21-22 October (Figure 5). The expected hypothesis for ETR max was rejected.

On 22-24 September Ashokan was the only significantly different site, with the lowest ETR max value (ANOVA $F_{3,40} = 18.9$, p <0.0001; Tukey HSD; Figure 5a). On 2-7 October Black Rock were significantly higher than the other sites (ANOVA $F_{3,36} = 15.9$, p <0.0001; Tukey HSD; Figure 5b). On 13-14 October Lamont was the only significantly different site; it possessed a significantly higher ETR max than the other sites (ANOVA $F_{3,37} = 9.1$, p <0.0001; Tukey HSD; Figure 5c). On 21-22 October Lamont was again the only significantly different site; it possessed a significantly different site; figure 5c). On 21-22 October Lamont was again the only significantly different site; it possessed a significantly higher ETR max than the other sites (ANOVA $F_{3,37} = 9.1$, p <0.0001; Tukey HSD; Figure 5c). On 21-22 October Lamont was again the only significantly different site; it possessed a significantly higher ETR max than the other sites (ANOVA $F_{3,36} = 13.7$, p <0.0001; Tukey HSD; Figure 5d).

On 21-22 September there was a significant negative linear relationship between maximum ETR (ETR max) and distance from the city (95% CI= -20.7,-9.11, p=0.006) (Figure 6a). There was not significant relationship between distance and ETR max for the final three sampling dates.



Figure 5: Maximum Electron Transport Rates (ETR max) at Central Park (CP), Lamont-Doherty Earth Observatory (LDEO), Black Rock Forest (BRF), and Ashokan Reservoir (ASH). Graphs are of measurements taken on A) 22-24 Sept B) 2-7 Oct C) 13-14 Oct D) 21-22 Oct. Maximum Electron transport rates determine the maximum rate of electron transport in photosystem II photochemistry. In A) leaf senescence has not yet begun; in B) and C) senescence had begun; in D) senescence had developed in most leaves. ETR has no units. F and P statistics are for linear contrasts of analysis of variance comparing ETR max and different sites. Boxes with different letters indicate values significantly different using the Tukey-Kramer HSD.

R²= 0.3894 p= <0.0001 Slope (95% CI)= -20.7, -9.11



Figure 6: Linear regressions of ETR max at 1 (CP), 2 (LDEO), 3 (BRF), and 4 (ASH), on the following dates: a) 22-24 Sept b) 29 Sept- 4 Oct c) 13-14 Oct d) 21-22 Oct. For a) there exists a negative relationship between ETR max and distance from New York City within the 95% confidence interval (regression analysis). Conversely, on b), d) and e), there exists no relationship between distance from the city and ETR max (regression analysis). p values and confidence intervals are derived from a regression analysis. p=NS means that according to a regression analysis, the linear relationship between site and ETR max is not significant.

Biomass:

The total biomass of the oak trees at the suburban site (Lamont) was much higher than expected (figure 7a). The mean biomass was the largest at LDEO (237 g, SE=34.20), second largest at Central Park (205 g, SE=18.01), third largest at Black Rock Forest (185 g, SE=24.02), and the smallest at Ashokan (157 g, SE= 31.29; figure 7a).

None of the sites, however, were significantly different (ANOVA $F_{3,37} = 1.36$, p= 0.27)(Figure 7a). In addition, within a 95% confidence interval there was no linear relationship between total biomass and distance from the city (p=0.128)(Figure 7c).

However, before the trees were taken to their respective sites, they spent three years growing in the same location in Black Rock Forest. By random chance some groups of trees were larger at the outset before being transported to their final site (e.g. Lamont plants began as the largest) in 2005. Because this is the case, the relative growth rate of each tree during the 2006 growing season was measured. In April 2005 the diameter of every oak sapling was recorded. 40 trees were then harvested to determine their biomass. The diameter of the trees was plotted against their biomass (Figure 8). It was found that there was a very strong relationship between diameter and total biomass (R^2 = 0.9413) (Figure 8). A trend line fitting the relationship between biomass and tree diameter was calculated to be:

$$Y = 0.018x^{3.4182}$$
 (Equation 2)

When 10 trees from each site were harvested on 21-23 September 2006, equation 2 was used to determine a projected change in biomass during the growing season for each tree, based on its diameter measurements taken before the trees were sent to their sites. Relative growth rates calculated as:

[(September 2006 biomass) – (Projected 2005 biomass)] / (Projected 2005 biomass) (Equation 3).

Relative growth rates represent the amount an individual tree has grown over a set period of time. Central Park had the highest mean relative growth rate (35 g g⁻¹), followed by Black Rock (28 g g⁻¹), LDEO (18 g g⁻¹), and Ashokan (15 g g⁻¹; figure 7b). However,

there was no significant difference between relative growth rate and distance from the city (ANOVA $F_{3,36}$ = 1.24, p= 0.31)(Figure 7b). In addition, within a 95% confidence interval there was no relationship between relative growth rate and distance from the city (p=0.187)(Figure 7d).



Figure 7: Graph of biomass information. a) is the total biomass averaged for ten trees at each site on 22-24 Sept. b) is the relative growth rate of trees from just before being transported to their respective sites versus after spending an entire growing season at a site. c) is the linear regression analysis of distance from the city (CP, LDEO, BRF, and ASH) versus total biomass (g). d) is the linear regression analysis of distance from the city CP (1), LDEO (2), BRF (3), and ASH (4)) versus relative growth rate (g g⁻¹). In both c) and d) there no relationship within the 95% confidence interval. For a) and b) since none of the sites are significantly different, letters are omitted.



Figure 8: a model for determining a hypothesize biomass based upon tree diameter. This was used to determine a projected value of biomass of the trees before they were transported to their sites, which in turn was used later to determine relative growth rates.

Leaf Carbon and Nitrogen:

The percentage of C in leaf tissues was significantly lower at Central Park, and was similar at the other three sites (Figure 9a; Single Factor ANOVA $F_{3,36} = 10.1$, P <0.0001; Tukey HSD). Nitrogen percentage was significantly higher at Central Park than the other sites, which were all similar to each other (Figure 9b; ANOVA $F_{3,36} = 11.8$, p <0.0001; Tukey HSD). Carbon percentage was divided by nitrogen percentage to yield a leaf C:N ratio. The C:N ratio was significantly lower at Central Park than the other three sites, which were all similar to each other (Figure 9c; ANOVA $F_{3,36} = 12.2$, p<0.0001; Tukey HSD). A lower C:N ratio indicates an abnormally high amount of nitrogen or an abnormally low amount of carbon. Thus the results show that Central Park has significantly higher levels of nitrogen, and lower levels of carbon than the other three sites. Central park is uniquely different, as the other three sites are all similar.

Leaf δC^{13} and δN^{15} show the different isotopic compositions between sites. For δC^{13} , Central Park and Black Rock are significantly lower than Ashokan, and Lamont is similar to all the sites (Figure 10a; ANOVA $F_{3,36} = 5$, p = 0.0054; Tukey HSD). For

 δN^{15} , Central Park is significantly lower than Black Rock, and Lamont and Ashokan are similar to all sites (Figure 10b; ANOVA F_{3,36}= 3.2, p= 0.033; Tukey HSD).



Figure 9: Oak tree leaf Carbon percentage (a), Nitrogen percentage (b), and Carbon to Nitrogen ratio (C). Measurements are for CP, LDEO, BRF, and ASH. F and P statistics are for linear contrasts of analysis of variance comparing sites to Carbon percentage (a), Nitrogen percentage (b), and Carbon to Nitrogen ratio (C). Boxes with different letters indicate values significantly different using the Tukey-Kramer HSD.



Figure 10: δC^{13} (a) and δN^{15} (b) for CP, LDEO, BRF, and ASH. F and P statistics are for linear contrasts of analysis of variance comparing sites to δC^{13} and δN^{15} . Boxes with different letters indicate values significantly different using the Tukey-Kramer HSD.

Diurnal Temperature Range:

DTR data for the 2006 growing season showed that the diurnal temperature range in Central Park was significantly lower than the diurnal temperature ranges of the other three sites, and the other three sites were not significantly different from each other (ANOVA $F_{3,924} = 59.77$, p <0.0001; Tukey HSD) (Figure 11a). For simplicity an ANOVA is used. Figure 11b shows the DTR of the four sites from March through November 2006.



Figure 11: The diurnal temperature range (DTR) (C^o) of the four sites (CP; LDEO; BRF; ASH) from 20 March 2006 to 10 November 2006. Only Central Park is significantly different. F and P statistics are for linear contrasts of analysis of variance comparing DTR and different sites. Boxes with different letters indicate values significantly different using the Tukey-Kramer HSD

Site Visits

			DTR				DTR	
Central Park	DTR CP	Lamont	LDEO	Black Rock	DTR BRF	Ashokan	ASH	
9/24/06	5.74	9/22/06	10.74	9/23/06	12.22	9/23/06	9.44	
9/29/06	5.56	9/29/06	11.11	10/4/06	8.15	10/2/06	8.89	
10/7/06	5.19	10/6/06	8.52					
10/13/06	5.37	10/13/06	6.85	10/14/06	11.30	10/14/06	11.11	
10/22/06	7.22	10/21/06	9.26	10/21/06	10.19	10/21/06	8.52	
Fable 1: Table of three-day average of Diurnal temperature range (DTR) during the testing day and 2 days								

before testing dates.

Discussion:

Because Fv/Fm has been reported to be sensitive to particular variables and insensitive to others, it useful to isolate the possible environmental effects influencing plant photosynthesis. A plant grown with limited resources is generally more efficient at utilizing all of its available resources; shaded leaves on a tree receive less sunlight and therefore are expected to be more efficient at utilizing what little light they receive (Marek 2001). Fv/Fm reflects this general axiom, as it has been found that Fv/Fm is higher for shaded leaves versus upper canopy leaves (Marek 2001). As a response to increased CO₂ plants will fix more carbon, but as CO₂ becomes less limiting, the plant will become less efficient at assimilating CO₂ per unit area. Thus, Fv/Fm values were found to decrease slightly due to long-term increases in ambient CO₂ (Marek 2001). However, since the results do not find that Fv/Fm is consistently significantly lower at the urban site (where the highest level of ambient CO₂ is) than the other sites, the effects of elevated ambient CO₂ must be secondary to other factors.

Baker (2004) found that when using chlorophyll fluorescence to predict and diagnose external factors influencing crop failure and reduction that Fv/Fm is sensitive to

temperature stresses. Extreme heat, chilling and freezing all cause reductions in Fv/Fm values (Baker 2004). Furthermore, it was found that Fv/Fm values were lowered by a severe deficits of nitrogen and other essential nutrients (Baker 2004). Samuelson and Edwards (1993) using *Quercus rubra* saplings, found that Fv/Fm values were relatively insensitive to different O₃ levels. Fv/Fm values were also found to be insensitive to drought stress (Baker 2004).

ΦPSII and ETR are sensitive to different environmental variables than Fv/Fm. Both ΦPSII and ETR are sensitive to the same variables because ETR is derived from ΦPSII (Equation 1). Baker (2004) found that ΦPSII is sensitive to drought stress. ΦPSII is also more sensitive to nutrient availability than Fv/Fm; ΦPSII can indicate, for example if there is a modest nitrogen deficit, whereas Fv/Fm is only lowered if nitrogen levels are dangerously low (Baker 2004). Huang (2004) found that ETR responds immediately to nitrogen deficiency, whereas Fv/Fm takes over two weeks to begin to be negatively affected by N deficiency. In the analysis of leaf nitrogen levels it was shown that only Central Park possessed a significantly higher percentage of leaf nitrogen. This is due, most likely, to a higher atmospheric deposition of N in urban areas (Zhu 2003). ETR max is more sensitive than Fv/Fm of lack of N. If the suburban and rural sites were N deficient, then their ETR should be substantially lower than the urban site. This relationship, however, is not supported by the results of this study.

The results indicate that the inter-site differences in Fv/Fm are most likely due to temperature stress. Smaller diurnal temperature ranges reflect less extreme differences in temperature, which in turn may result in less temperature stress for plants. Particularly during the onset of autumn in the Northeastern United States when nights can become

much colder than days, plants are prone to experience chilling and possibly freezing stress. Because Fv/Fm is affected by temperature stress, and Central Park possesses both significantly higher Fv/Fm values than the other sites and significantly lower DTR than the other sites, it is likely that DTR is the main factor causing differences in Fv/Fm along the urban to rural transect.

Maximum electron transport rates were on average lower than expected. The expected trend was for the highest ETR max to be at Central Park followed by Lamont, Black Rock Forest, and Ashokan Reservoir. However, Central Park was did not have the highest average maximum ETR on any of the four site visits. A proposed reason for this is water stress. However, the δC^{13} measurements indicate that the trees in Central Park were not water stressed. The results showed that δC^{13} measurements were actually lower for Central Park and Black Rock, suggesting that if there was any water stress, it occurred at Ashokan. This would make sense, since Ashokan consistently possesses a significantly lower ETR max than the other sites. Electrons from the H₂O molecule are used to drive photophosphorylation in Photosystem I and II. When a plant is water stressed it lacks the vital substrate to drive photosynthesis and therefore the rate at which electrons are transported may be lowered. Thus, water stress at Ashokan may explain its significantly lower ETR.

In addition, if O_3 levels positively affect urban plants as has been suggested (Gregg et al 2003), maximum ETR of our transect does not support this claim. Lower urban tropospheric ozone (O_3) has been proposed as a cause for the increased biomass of *Populus deltoides* in New York City (Gregg et al 2003). *Quercus rubra*, however, is less sensitive to O_3 (Farage 1996; Reich, Schoettle and Amundson 1986; Samuelson and

Edwards 1993). Farage (1996) found that Fv/Fm for *Quercus rubra* seedlings was not affected by increased O_3 levels, and Reich et al (1986) found that the biomass of *Quercus rubra* was not significantly affected by increased O_3 fumigation. Furthermore, Samuelson and Edwards (1993) found that mature *Quercus rubra* were more sensitive to O_3 than seedlings (seedling biomass was not significantly affected by O_3). Max ETR was never the highest in the city, indicating that lower tropospheric O_3 in the city is not the most influential factor in determining ETR max. However, The ETR at the Ashokan site is consistently lower than the other sites, and this may be due, along with possible water stress, to higher tropospheric O_3 levels.

Implications of Research:

A long-standing question in the midst of the climate change debate is whether the biosphere will act as a carbon sink with changing environmental conditions. The cause of observed difference along the urban to rural gradient is crucial. Fv/Fm was found to be significantly higher in the city in 3 out of 4 comparisons; and this could be due to a lower diurnal temperature range. Smaller DTR has been a prediction of global warming (Wolfe-Bellin et al 2006). If smaller DTR leads to increased biomass, this means that changes in DTR may be indirectly responsible for capturing more carbon. This could be a natural feedback cycle of the biosphere that regulates atmospheric CO₂ levels (increased CO_2 causes lower DTR which in turn causes more carbon capture by plants which ultimately reduces atmospheric CO₂). Gregg et al. (2003) found that urban plants have greater biomass, however, our study after doing a similar experiment with a native species, found that biomass was not significantly different along urban to rural gradients. This is crucial knowledge for countries that seek to lower CO_2 emissions. Species identify – and particularly the sensitivity of those species to environmental factors - is vitally important when determining the ability of plants to capture carbon.

Increased ambient temperatures can either retard the natural rate of senescence or expedite it. Warmer temperatures can result in a longer growing season, which in turn results in higher carbon assimilation (Marchand et al. 2004; Ho et al. 2006; Lu et al. 2006). Other studies, however, have shown that if elevated temperatures cause water stress, it could cause the plants to undergo senescence more quickly, and therefore capture less carbon (Gielen et al. 2005). From our study we found that Fv/Fm is higher in the city, due most likely to lower DTR. Also ETR max is lower at Ashokan, due

possibly to water stress. DTR can positively affect photosynthesis, however, if water is scarce, a plant will not be able to take full advantage of the milder climate. This suggests that water availability will become a critical component in determining the effects of climate change on plant life. According to the 2007 IPCC report to policy makers, global precipitation patterns are changing; mesic areas are receiving even more precipitation, and xeric climates are receiving even less precipitation. A scarcity of water could exacerbate the rising temperatures, whereas enough water may increase plant productivity.

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Supplementary material:

Site Visits			
Central Park	Lamont	Black Rock	Ashokan
9/24/06	9/22/06	9/23/06	9/23/06
9/29/06	9/29/06	10/4/06	10/2/06
10/7/06	10/6/06		
10/13/06	10/13/06	10/14/06	10/14/06
10/22/06	10/21/06	10/21/06	10/21/06
10/27/06	10/28/06		
11/4/06	11/3/06		
11/10/06	11/10/06		

Temporal analysis:



