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Projecting Consequences of Altered Atmospheric Chemistry for Carbon Sequestration by Wisconsin's Aspen Forests

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Executive Summary

Background

Wisconsin's forests harbor the potential to sequester considerable amounts of the carbon emitted (as carbon dioxide) through fossil fuel combustion, thereby helping to mitigate effects of anthropogenic emissions on atmospheric chemistry and global climate. In turn, Wisconsin's forests are sensitive to atmospheric levels of carbon dioxide (CO₂), ozone (O₃) and other trace gases, which have increased substantially in the past several decades. The majority of these increases are known to be anthropogenic in origin, and, based on plausible emission scenarios, these trends will likely continue into the foreseeable future. ***How will carbon sequestration in Wisconsin forests be affected by future changes in atmospheric chemistry?*** The answer to this key question is complicated by the fact that the various primary and secondary air pollutants have different effects on trees. In particular, elevated CO₂ generally stimulates tree growth, whereas elevated O₃ has the opposite effect.

Research Objective

The principal aim of this study was to predict relative impacts of present and anticipated future levels of tropospheric O₃ and CO₂ on potential rates of carbon sequestration by Wisconsin's trembling aspen forests. Trembling aspen was chosen as the target tree species because 1) it is, from economic and ecological standpoints, an important component of Wisconsin's forests, and 2) there is a sufficient body of information concerning its responses to changes in atmospheric chemistry. Currently, no other Wisconsin tree species meets these criteria. The tropospheric O₃ and CO₂ levels examined in this assessment were bracketed on the low end by ambient concentrations of both gases recorded during the past 5 years, and on the high end with levels that could be realized by the end of the 21st Century. These include a 30% increase in the growing-season average for tropospheric O₃ concentration, and nearly a doubling in CO₂ concentration.

Methods

We addressed our objective with a three-phase approach. The first involved calibration and validation of a canopy process model (BEWDY), which we then used to simulate aspen canopy photosynthesis under various scenarios of elevated CO₂ and/or O₃, at specific locations throughout Wisconsin. Simulation results were linked directly to C sequestration through the assumption that relative effects of atmospheric chemistry on C sequestration rate were proportional to corresponding effects on canopy photosynthesis. In the third phase, model output was used to determine spatial patterns of aspen response to altered atmospheric chemistry across the state. A brief description of each phase is provided below:

Model Calibration

- During the growing seasons of 1998, 2000 and 2002, we conducted an array of field measurements, at the Aspen FACE facility (near Rhinelander, WI), to assess the structural, biochemical and functional responses of aspen foliage to elevated concentrations of CO₂ and O₃.
- Using these data, we generated empirical Weibull functions characterizing the negative sigmoidal responses of leaf photosynthetic parameters to cumulative O₃ exposure.
- Using a canopy process model (BEWDY) that was calibrated with our empirical relationships, we estimated relative effects of elevated O₃ and CO₂, singly and in combination, on the amount of

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carbon sequestered by aspen canopies throughout a growing season at the Aspen Face site.

- We then assessed the accuracy and precision of BEWDY by evaluating the relation between observed and estimated treatment effects on carbon sequestration rates of experimental aspen stands at the Aspen Face site.

Estimating relative effects of altered atmospheric chemistry on aspen across Wisconsin

- Hourly average values for O₃ concentration and micrometeorological parameters, recorded at various locations in and around Wisconsin during each growing season from 2001 through 2005, were acquired from the EPA data repository for atmospheric chemistry (AQS) and the FAA/NWS weather data networks (AWOS/ASOS).
- Based on these data, we simulated canopy photosynthesis (using BEWDY) for each of the five growing seasons, at 27 locations, under recent micrometeorological conditions and several scenarios of altered atmospheric chemistry: recent O₃ levels, and 10-30% increases in O₃ concentration in combination with elevated CO₂ (3 levels: recent, 560 ppm and 700 ppm). Using recent conditions in the (hypothetical) absence of O₃ as a reference, we calculated relative impacts of altered atmospheric chemistry under each of the 12 scenarios, for each of the five growing seasons (2001-2005).

Determining spatial patterns of aspen response across Wisconsin

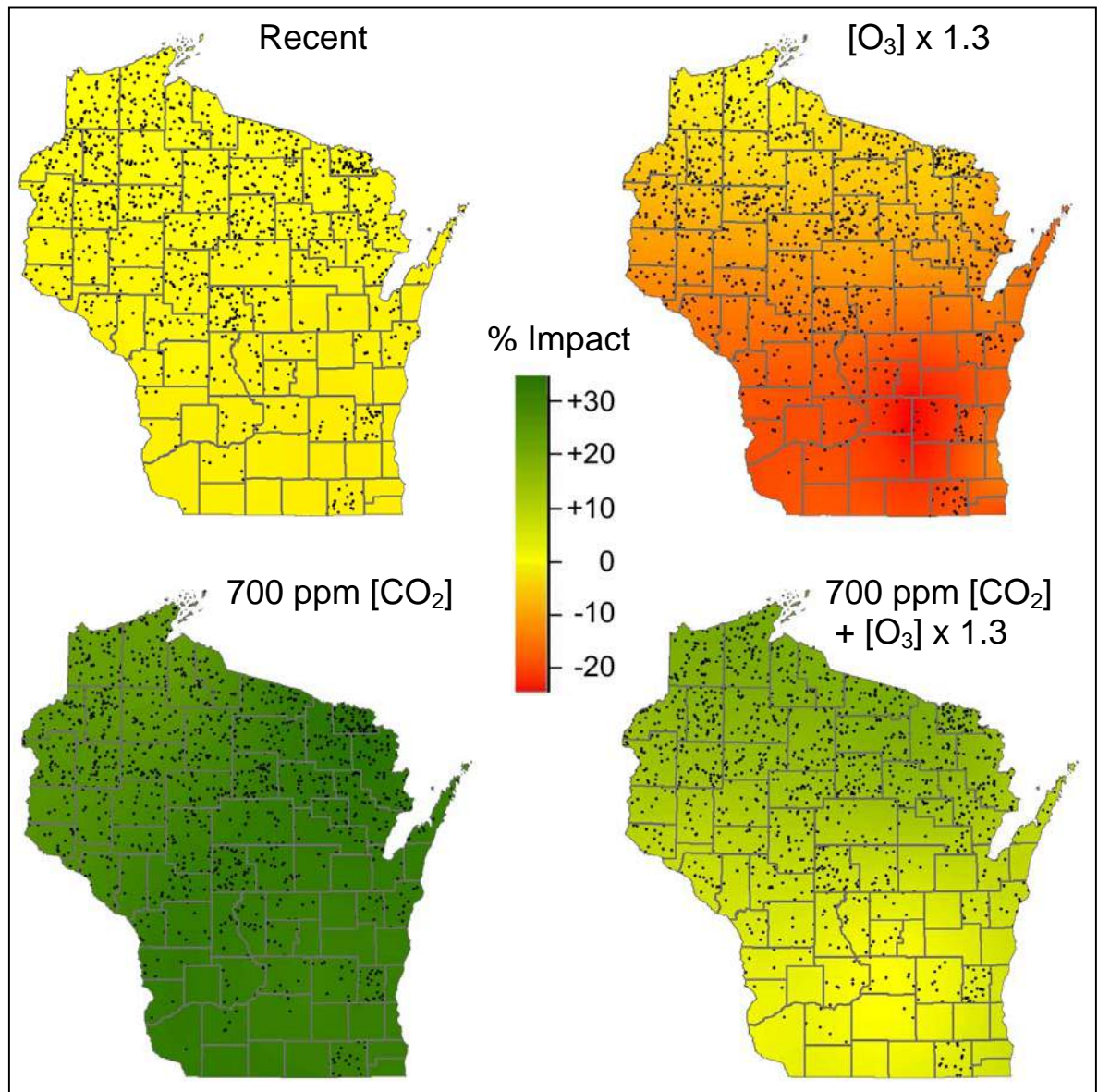
- Based on spatially explicit, 5-year averages for each scenario, we generated statewide maps of aspen canopy response to various combinations of atmospheric change using ordinary kriging techniques.
- The resulting spatially explicit data were used to create county-level predictions of average aspen response, which were then scaled to a state average based on the estimated acreage of each county currently occupied by aspen-dominated forest.

Results and Inferences

Given the spatially explicit nature of our findings, we have included in this summary maps showing relative impacts of various levels of tropospheric O₃ and CO₂ on aspen forests throughout the state (**page v**). Several inferences can be drawn from these maps:

- Across Wisconsin, the negative influence of O₃ on carbon sequestration by aspen has been modest in recent years. On average, sequestration rates appear to be roughly 2% less (range 1-3% across locations and years) than they would be in the absence of O₃.
- Plausible increases (e.g., 30%) in O₃ levels are predicted to cause substantial reductions in aspen carbon sequestration, especially in the southeastern quarter of Wisconsin, where decreases in certain years may approach or exceed 30%.
- If O₃ levels do not increase, the anticipated doubling of CO₂ concentration by 2100 will lead to an estimated 29% increase in the rate of aspen carbon sequestration. If, however, levels of O₃ increase by as little as 30%, the stimulus from elevated CO₂ will, statewide, be cut in half. In southeastern Wisconsin, the CO₂ stimulus would be completely offset by the damage caused from elevated O₃.
- Some of the geographic variation in impact is attributable to variation in growing season climate. This points to a key uncertainty regarding our predictions – potential influences of a changing climate on forest responses to altered atmospheric chemistry.

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Predicted relative responses of trembling aspen forests, in terms of carbon sequestration rate, to recent and anticipated future levels of tropospheric ozone (O₃) and carbon dioxide (CO₂) in Wisconsin. Reference sequestration rates (equivalent to response = 0) are those estimated at a recent ambient CO₂ concentration (photoperiod average ~360 ppm during the growing season) in the absence of O₃. Scenarios include an increase in the growing-season average for photoperiod CO₂ concentration to 700 ppm, a 30% increase in the growing-season average for O₃ concentration (O₃ x 1.3), or both combined. Spatially explicit extremes in forest response (based on a five-year average) include a 34% stimulation of sequestration rate in elevated CO₂ (at recent O₃ levels), and a 23% decrease in elevated O₃ (at the recent CO₂ level). Density of stippling represents proportional acreage of aspen-dominated forests in each county.

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Introduction

The anticipated doubling of atmospheric CO₂ concentration during the next 100 years will likely be accompanied by a sizable increase in the average concentration of tropospheric O₃ (Fishman 1991, Thompson 1992, Houghton *et al.* 2001), owing to the fact that fossil fuel combustion releases O₃ precursors (namely volatile organic compounds, VOCs, and oxides of nitrogen, NO_x) as well as CO₂. This expectation is supported by historical trends, as, in industrialized countries of the Northern Hemisphere, O₃ levels in the lower troposphere have risen by an average of 1-2% per year since the middle of the 20th Century (Figure 1). Forecasts of increased O₃ levels in the eastern U.S. vary according to assumptions about future emission and climate trends, but they tend to fall within the range of 20-30% by 2050, and 30-50% by 2100 (Thompson 1992, Fowler *et al.* 1999, Prather *et al.* 2001).

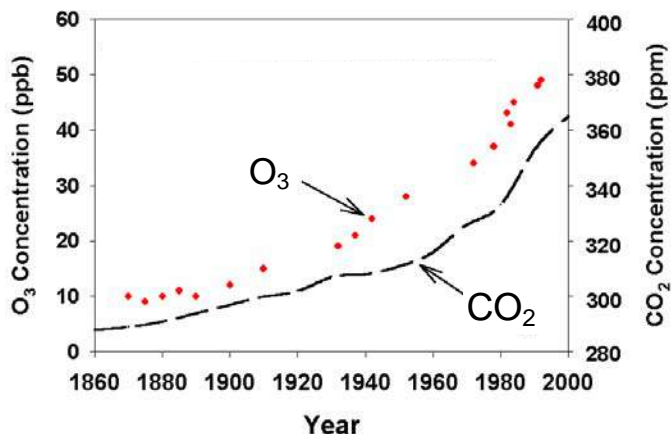


Figure 1. Similar historical trends in tropospheric concentrations of carbon dioxide (CO₂) and ozone (O₃) have been documented in the Northern Hemisphere. The O₃ trend was drawn using data from Marengo *et al.* (1994). More recent O₃ data of this sort are not currently available.

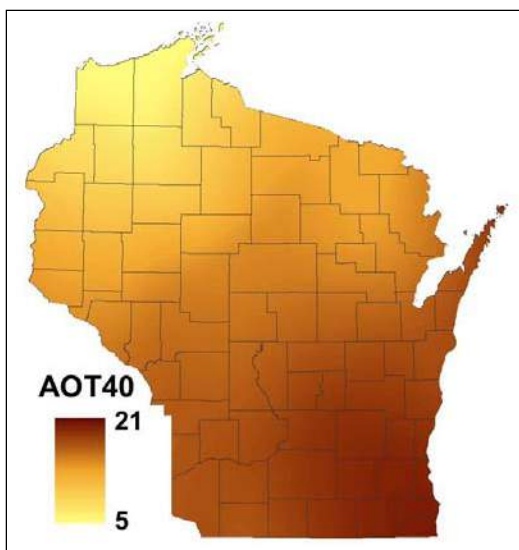


Figure 2. While tropospheric CO₂ concentration is relatively constant across Wisconsin, O₃ level varies a great deal, as is illustrated in the spatial distribution of cumulative O₃ exposure (AOT40, ppm·h), during the photoperiod, in the growing season (May-September) of 2005.

These changes in atmospheric chemistry will likely have pronounced impacts on the structure and function of forest ecosystems (Eamus and Jarvis 1989, Graham *et al.* 1990, Taylor *et al.* 1994, Percy *et al.* 2002). As CO₂ is a substrate for photosynthesis, increases in its concentration will generally lead to accelerated rates of photosynthesis, tree growth and, in many cases, carbon sequestration (Saxe *et al.* 1998). On the other hand, O₃ in the lower troposphere may have the greatest impact on vegetation of all regional atmospheric pollutants (Taylor *et al.* 1994, Felzer *et al.* 2004, Ollinger *et al.* 2002). Chronically elevated levels of this oxidant in industrialized regions likely reduce photosynthesis in many and probably most plant species (Reich 1987, Cooley and Manning 1988, Morgan *et al.* 2003). These deleterious effects can culminate in significant growth reductions for agricultural crops, trees and other vegetation (Heck 1989, Taylor *et al.* 1994, McLaughlin and Downing 1995). Notably, these consequences are distinct from, but must be

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considered along with, those relating to the influences of atmospheric change on global climate. Atmospheric chemistry is a critical issue for Wisconsin, as levels of O₃ exposure in the southeastern corner of the state (Figure 2) have in recent decades been among the highest in the nation (EPA 2007). Moreover, despite reluctance by the current U.S. administration to embrace the Kyoto Treaty, many policy and economic analysts contend that management of CO₂ and precursor emissions will soon be an important factor in our regional and national economies (e.g., Felzer *et al.* 2005).

While atmospheric change has important implications for forest structure and function, the reverse is also true. Terrestrial vegetation has been sequestering a significant fraction of the “extra” carbon (C) emitted through anthropogenic activities (EPA 2006), and the importance of this carbon “sink” may increase in the future (Dixon *et al.* 1994). Recognition of the critical role of North American forests in this context provided much of the motivation for substantial federal underwriting of larger-scale studies of forest responses to atmospheric change, including several free-air CO₂ enrichment (FACE) facilities such as the Aspen FACE site in northern Wisconsin (Figure 3).



Figure 3. Photograph in 2001 of Aspen FACE, a multi-institutional project examining the effects of elevated CO₂ and O₃ on the structure and function of model forest ecosystems through their life history. The site is located on a 32 ha USDA Forest Service experimental farm near Rhinelander, WI. There are twelve plots, each 30 m in diameter, comprising three replicate blocks of control, elevated CO₂ (target ~ 560 ppm) rings, elevated O₃ (target ~1.5 x ambient), and elevated CO₂ + O₃.

Correspondingly, an impressive amount of time and effort has been invested in generating the conceptual and empirical underpinnings of models that can accurately predict forest responses to elevated CO₂ (e.g., Saxe *et al.* 1998, McMurtrie and Dewar 1999, Constable and Friend 2000, Luo *et al.* 2001, Joos *et al.* 2002, Medlyn *et al.* 2003). However, these predictions, which could have significant economic, political and social ramifications, typically do not consider the full complexity of atmospheric change and its consequences. Namely, with some notable exceptions (e.g., Ollinger *et al.* 2002, Felzer *et al.* 2005, Karnosky *et al.* 2005), there have been few published attempts to model forest responses to the “cocktail” of changes (e.g., increases in both CO₂ and O₃) that are simultaneously occurring in the atmosphere, and even fewer attempts to also account for existing spatial variation in O₃ exposure across the landscape (Felzer *et al.* 2004). A quick glance at findings from Aspen FACE (Figure 4) reveals that this oversight could undermine the utility and

credibility of such efforts. For example, the potential acceleration of forest C gain in response to CO₂ enrichment could be completely negated by moderate increases in O₃ levels.

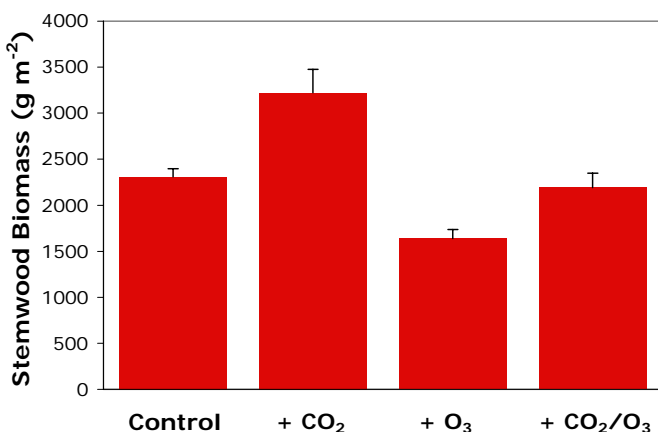


Figure 4. Effects of elevated CO₂ and/or O₃ concentrations on the cumulative stemwood production by 7-yr-old trembling aspen stands at the Aspen FACE facility near Rhinelander, WI. The target CO₂ enrichment level is 560 ppm, while the target O₃ concentration is roughly 50% higher than current ambient levels in northern WI, which are relatively low. Data are for 2003, and are taken from King et al. (2005). Notably, the stimulation of stemwood production in elevated CO₂ (+CO₂) is completely offset by dysfunction resulting from a concomitant increase in O₃ concentration (+CO₂/O₃).

indicator of pollution and other stresses (Mankovska *et al.* 2005), and 3) there is a sufficient body of information concerning its growth and physiological responses to changes in atmospheric chemistry. Currently, no other Wisconsin tree species meets all of these criteria. The tropospheric O₃ and CO₂ levels examined in this assessment were bracketed on the low end by ambient concentrations of both gases recorded during the past 5 years, and on the high end with levels that could be realized by the end of the 21st Century. These include a 30% increase in growing-season averages for tropospheric O₃ concentration, and nearly a doubling in CO₂ concentration.

Methods

We addressed our objective with a three-phase approach. The first involved calibration and validation of a canopy process model (BEWDY), which we then used to simulate aspen canopy photosynthesis (assumed in this project to be the primary determinant of variation in carbon sequestration rate) under various scenarios of elevated CO₂ and/or O₃, at specific locations throughout Wisconsin. In the third phase, this output was used to determine spatial patterns of aspen response to altered atmospheric chemistry across the state.

Phase I: During the growing seasons of 1998, 2000 and 2002, we conducted an array of field measurements at the Aspen FACE facility (near Rhinelander, WI), to assess the structural,

In light of these uncertainties, we aimed in this project to generate credible predictions of the extent to which anticipated changes in atmospheric CO₂ and O₃ during the next 50-100 years will directly alter the carbon sequestration rate of a major forest type in Wisconsin. Accurate estimates of carbon sequestration rate are essential to the planning and implementation of emission control and mitigation strategies (particularly those based in part on carbon sequestration by existing or newly planted forests), and they are also effective indicators of emission impacts on the health and integrity of forest ecosystems.

We chose trembling aspen (*Populus tremuloides*) as our target tree species because 1) it is, from economic and ecological standpoints, an important component of Wisconsin's forests, 2) it is widely recognized as a useful bio-

biochemical and functional responses of aspen foliage to elevated concentrations of CO₂ and O₃. Using these data, we generated a Weibull function characterizing the observed effects of O₃ exposure on a key leaf photosynthetic parameter, the maximum velocity of carboxylation (V_{Cmax}). Reduced V_{Cmax} is widely recognized as a primary lesion to the photosynthetic apparatus resulting from chronic exposure of foliage to O₃ (Dizengremel 2001). Details of our methodology and findings are provided in **Appendix A**.

Phase II: Using a canopy process model (BEWDY) calibrated with our empirical relationships from Phase I, we estimated relative effects of elevated O₃ and CO₂, singly and in combination, on the amount of carbon sequestered by aspen canopies throughout a growing season at the Aspen Face site. We then assessed the accuracy and precision of BEWDY by evaluating the relation between observed and estimated treatment effects on carbon sequestration rates of experimental aspen stands at the Aspen Face site. The relation between observed and predicted rates of stand carbon sequestration (woody biomass production), expressed as fractions of the rate observed in control stands, was reasonably close (slope ~ 1, intercept ~ 0, regression r² = 0.89, P < 0.001). Details of our methodology and findings from Phase II are provided in **Appendix B**.

Phase III: Hourly averages for O₃ concentration and relevant micrometeorological parameters, recorded at various locations in and around Wisconsin during each growing season from 2001 through 2005, were acquired from the EPA data repository for atmospheric chemistry (AQS) and the FAA/NWS weather data networks (AWOS/ASOS), respectively. Based on these data, we simulated canopy photosynthesis (using BEWDY) for each of the five growing seasons, at 27 locations, under recent meteorological conditions and several scenarios of altered atmospheric chemistry: recent O₃ levels, and 10-30% increases in ozone

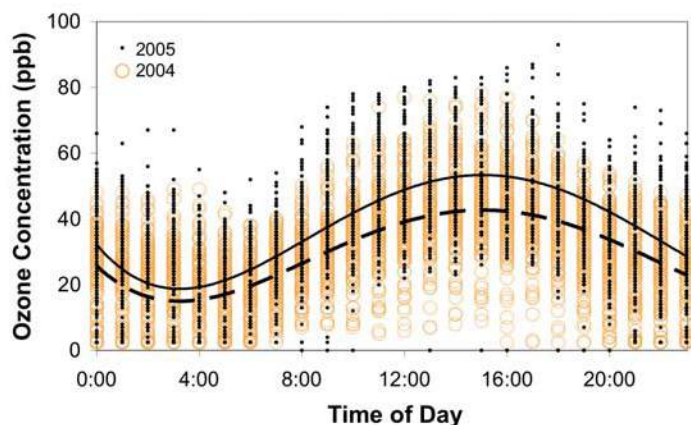


Figure 5. The temporal dynamics illustrated here provide a basis for our simulated future increases in surface O₃ concentration ([O₃]). Namely, a comparison of diel [O₃] trends between growing seasons possessing relatively low (2004) and high (2005) O₃ levels indicated that, throughout most of an average day, [O₃] in 2005 (solid line) was consistently about 25% higher than that in 2004 (dashed line). We mimicked this simple diel pattern in our future [O₃] scenarios. (Data were collected in Dane County from May 15 through September 15.)

concentration in combination with elevated CO₂ (three levels: recent ambient, 560 ppm and 700 ppm). The specific temporal pattern of relative differences between present and future O₃ levels mimicked recent patterns observed in south-central Wisconsin (Figure 5). Using recent ambient conditions in the absence of O₃ as a reference, we calculated the relative impacts of altered atmospheric chemistry under each of the 12 scenarios, for each of the five growing seasons (2001-2005). The details of our methodology and findings are provided in **Appendix C**.

Using spatially explicit, 5-year averages based on each of the 12 scenarios at all 27 locations, we generated maps of aspen canopy

responses to various combinations of atmospheric change across Wisconsin, using ordinary kriging techniques (in ArcMAP[®], ESRI Inc.). The resulting spatially explicit data were also used to create county-level predictions of average aspen response, which were then scaled to a state average based on the estimated acreage of each county currently occupied by aspen-dominated forest (WISCLAND 2007).

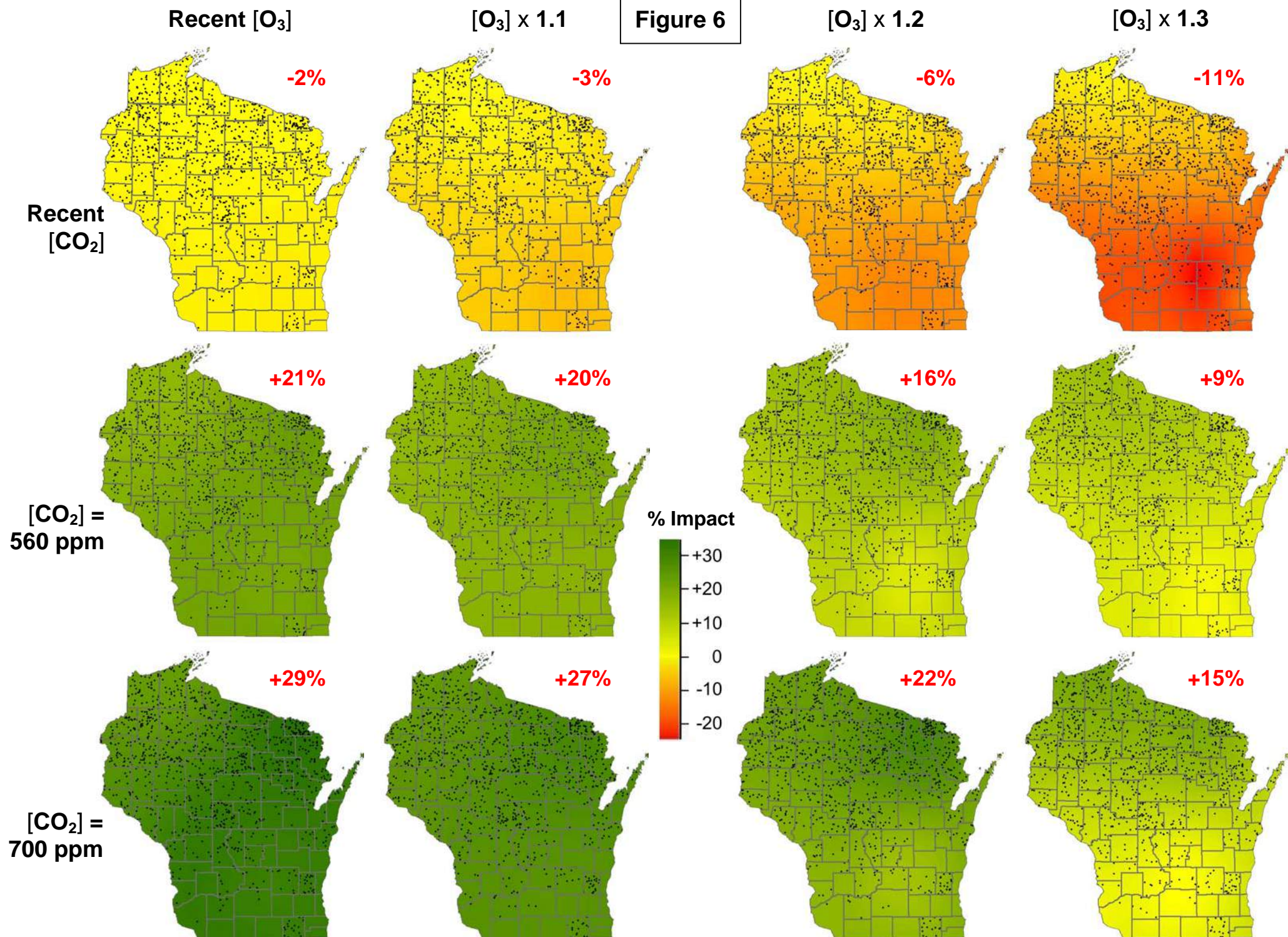
Results and Discussion

Our modeling output points to substantial and spatially variable consequences of anticipated changes in atmospheric chemistry for rates of carbon (C) sequestration by aspen-dominated forests in Wisconsin. The estimated relative impacts of recent and anticipated future levels of tropospheric O₃, in concert with present and expected future CO₂ levels, are portrayed in Figure 6 (next page). Across Wisconsin, the negative influence of O₃ on C sequestration by aspen has, according to our estimates, been modest in recent years. On average, sequestration rates appear to be roughly 2% less (range 1-3% across locations and years) than they would be in the absence of any tropospheric O₃. On the other hand, plausible increases in tropospheric O₃ concentration (e.g., 30%) are predicted to cause marked reductions in aspen C sequestration, especially in southeastern Wisconsin. While the statewide average reduction corresponding to a 30% increase in [O₃] is 11%, negative impacts range from 2-23% across locations. We note that in southeastern Wisconsin a 30% increase in [O₃] results in cumulative exposures resembling those in O₃-treated stands at Aspen FACE (e.g., growing season AOT40 ~ 45 ppm·h).

If O₃ exposures do not increase appreciably, the near doubling of CO₂ concentration ([CO₂]) during this century will lead to an estimated 29% increase in the rate of aspen C sequestration statewide. Moreover, under current meteorological conditions, much of the potential benefit of CO₂ enrichment for aspen C sequestration will be realized by the time [CO₂] reaches 560 ppm. If, however, levels of O₃ increase by as little as 30%, the stimulus from elevated CO₂ will, on average, be cut nearly in half. In certain areas of Wisconsin, the CO₂ stimulus would be completely offset by the damage caused from elevated O₃. At recent O₃ concentrations, the predicted CO₂-mediated enhancement of C sequestration varies by as much as 6% across the state owing primarily to spatial variation in climate. Cooler summers in northern Wisconsin, for example, result in lower stimulations of C gain.

Caption for Figure 6 (on following page). Simulated relative effects of recent and anticipated future levels of tropospheric ozone (O₃) and carbon dioxide (CO₂) on potential rates of carbon sequestration in aspen-dominated forests across Wisconsin. Reference sequestration rates (equivalent to impact = 0) are those estimated at the recent CO₂ concentration (photoperiod average ~360 ppm during the growing season) in the absence of O₃. Scenarios include an increase in CO₂ concentration to 560 or 700 ppm, 10-30% increases in the growing-season average for O₃ concentration (10% = O₃ x 1.1, 20% = O₃ x 1.2, and 30% = O₃ x 1.3), or combined increases in both gases (for a total of 12 scenarios). Spatially explicit extremes in forest response (based on a five-year average) include a 34% stimulation of sequestration rate in elevated CO₂ (at present O₃ levels), and a 23% decrease in elevated O₃ (at the present CO₂ level). Density of stippling represents proportional acreage of aspen-dominated forests in each county. Values in the upper right corner of each map are estimated average impacts of each scenario, on a statewide basis, weighted for the spatial distribution of aspen forest in the state.

Figure 6



The observed spatial and temporal variation in aspen response points to a key uncertainty regarding our predictions – potential influences of a changing climate on forest responses to altered atmospheric chemistry. The implications of a continuing warming trend and related climate variation are difficult to predict owing in large part to uncertainty regarding the specific nature of climate change. For example, growing seasons may become warmer (i.e., higher mean, maximum and/or minimum temperatures) and/or longer, or remain essentially unchanged (with warmer winters). And these trends may be accompanied by marked changes in the overall amount as well as temporal and spatial distribution of precipitation (Houghton *et al.* 2001). Each of the different scenarios could exert distinct influences on forest responses to altered atmospheric chemistry. To further complicate matters, we currently lack adequate information to forecast the manner in which forests will respond to altered climate alone.

Regarding forest response to CO₂ enrichment, our predictions align closely with the overall trend gleaned from the aggregate of forest FACE experiments (Norby *et al.* 2005). With respect to O₃ effects, our results are not directly comparable with those of similar assessments, as each study has adopted a different approach in simulating atmospheric change and its effects. Given this qualifier, we note that our estimate of the magnitude of

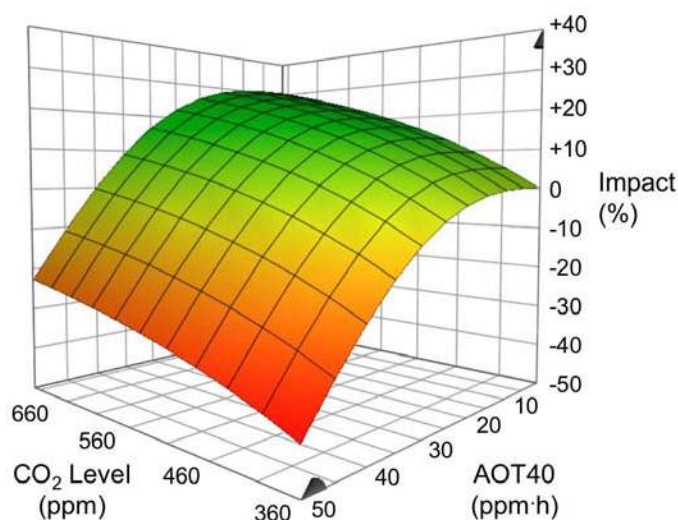


Figure 7. Predicted relative impacts of elevated CO₂ and cumulative O₃ exposure (AOT40) on rates of aspen canopy photosynthesis (and, by extension, C sequestration). The impact surface is based on estimated effects of altered atmospheric chemistry at 27 locations in and around Wisconsin during 2001-2005. The modeled impact surface combines a hyperbolic function of [CO₂] and a Weibull function of AOT40 ($r^2 = 0.95$, $P < 0.0001$). See footnote* for model structure.

the overall variation across sites, years and scenarios is explained by the product of two functions* – a hyperbolic response to [CO₂] and a sigmoidal Weibull response to AOT40 (Figure 7). The predicted impact surface reinforces our contention that aspen-dominated

O₃'s negative effect on C sequestration in recent years resembles the spatially explicit output, for forested areas of northern Wisconsin, reported by Felzer *et al.* (2004). On the other hand, our estimates are considerably lower than those of Felzer *et al.* (2004) for southern Wisconsin, and those by Ollinger *et al.* (1997, 2002) for forests of the northeastern U.S. exposed to similar O₃ dosages. The contrast stems largely from differences in the modeled impact of increasing O₃ exposure on canopy function – our response surface is non-linear (Figure 7), whereas that of Ollinger *et al.* (1997), which was also adopted by Felzer *et al.* (2004), is linear.

Although in our study the estimated impact on C sequestration from any particular combination of [CO₂] and O₃ exposure varies spatially, 95% of

* Impact (%) = $170 \cdot ([CO_2] - 93)/([CO_2] + 93) \cdot e^{-(A/62)^3} - 100$, where A = AOT40.

forests in certain parts of Wisconsin are poised at a precipice – in that increased O₃ exposure will likely cause a steep decline in forest C sequestration. The consequences of rising O₃ exposure illustrated by our impact surface reflect similar effects of the oxidant on a key enzyme (ribulose biphosphate carboxylase/oxygenase) governing photosynthesis at leaf and canopy levels (see Appendix A). In contrast, the hyperbolic response of stand carbon sequestration to increasing [CO₂] reflects in large part the saturation kinetics of the same enzyme at high substrate (CO₂) concentrations (Farquhar et al 1980).

As mentioned previously, our modeled impact surface masks spatial variation across Wisconsin as well as inter-annual variation across the five-year experimental interval. Most of this stems from climate dynamics, but the question remains as to how much variation may occur as a result of factors not considered in this modeling exercise. A litany of additional biotic as well as abiotic factors, such as variation in the genetic make-up of aspen populations, edaphic characteristics, insect and disease dynamics, severe physical disturbances (e.g., wind damage), and land-use practices, harbor the potential to temper forest response to atmospheric change (e.g., Ollinger *et al.* 2002, Felzer *et al.* 2005). We presently do not have access to adequate data regarding the variation, extent and frequency of these factors.

Nevertheless, we can explore the sensitivity of our impact estimates to variation in certain intrinsic factors, such as canopy structure and leaf biochemistry, as well as extrinsic factors, such as soil moisture content. These explorations are detailed in Appendix C, and thus will only be briefly highlighted here. In our sensitivity analyses, the predicted relative impact was influenced only slightly (<2%) by variation in canopy foliage density, known as leaf area index (LAI), which is a major determinant of canopy photosynthetic rate and, by extension, C sequestration rate. Conversely, we did find that estimated impact was sensitive to variation in another key determinant of canopy photosynthesis, the amount of nitrogen in the foliage. Namely, the stimulus resulting from CO₂ enrichment was enhanced, whereas the deleterious impact of elevated O₃ was reduced, at high leaf nitrogen contents. The magnitude of difference in estimated impacts was as much as 6% (at elevated CO₂) across a typical range in leaf nitrogen status. These influences of foliar nitrogen status on tree responses to altered atmospheric chemistry are consistent with results of several empirical and modeling studies (e.g., Commins and McMurtrie 1993, Paakkonen and Holopainen 1995), and inconsistent with others (e.g., Ollinger *et al.* 1997). The underlying causes of this sensitivity, which has implications for the potential roles of other forms of atmospheric pollution, such as nitric acid and ammonium deposition, are discussed in Appendix C.

Another noteworthy issue concerning our impact estimates is the relation between forest response and stand age. In our modeling we assume that all acreage is occupied by mature aspen stands that have reached canopy closure and, with respect to inter-annual variation, a relatively “stable” leaf area index (LAI). Young stands in particular will show more pronounced responses to altered atmospheric chemistry because of the compounding relation between growth rate, stand biomass, and a dynamic LAI. The importance of this consideration is clearly evident in the findings from Aspen FACE, where, for instance, accelerated growth in elevated CO₂ results in a higher LAI, which in turn further accelerates growth. Elevated O₃ has the opposite effect. Incorporating this consideration into a model, however, is difficult because the nature of this dynamic response is dependent on factors

such as climate and soil resource availability - as these constrain growth rate and thus the rate of increase in LAI through time (e.g., Ruark and Bockheim 1988). We currently lack sufficient information regarding variation in growth rate of young aspen stands across the range of edaphic and climatic conditions in Wisconsin. A simple simulation, however, indicates that the discrepancy in our estimates associated with exaggerated responses by young stands (e.g., < 10 years old) is on the order of 2% or less (data not shown).

A related possibility we have not formally entertained is that altered atmospheric chemistry might cause changes in the “stable” LAI of mature aspen stands mentioned above. At the Aspen FACE site, LAI in the elevated CO₂ treatment has consistently been higher (by more than 20% in some years) than that in the control (ambient) treatment (Karnosky *et al.* 2005). A persistent treatment effect on LAI of mature stands following canopy closure is not an outcome presently supported by evidence from other studies of hardwood species at forest FACE sites (Norby *et al.* 2005). Moreover, it is inconsistent with the observed similarity in patterns of biomass partitioning among treatments thus far at Aspen FACE (King *et al.* 2005). If, however, treatment LAI differences persist at Aspen FACE, our predictions will have to be adjusted accordingly.

We also acknowledge the somewhat tenuous nature of our assumption that variation in C sequestration rate is proportional to that in canopy photosynthesis. While a straightforward relation between tree biomass gain and photosynthesis has been affirmed (Kruger and Volin 2006), our approach ignores the potential direct and indirect effects of altered atmospheric chemistry on tree- and ecosystem-level processes “downstream” from canopy photosynthesis, such as changes in resource allocation patterns or heterotrophic respiration (e.g., Ollinger *et al.* 2002). We contend, however, that unequivocal and/or sufficiently comprehensive evidence of these perturbations is lacking. To date, for example, there have been few if any clear indications at the Aspen FACE site that these “downstream” processes have responded to treatments in a manner that does not scale with corresponding effects on canopy photosynthesis and stand biomass gain (Karnosky *et al.* 2003, Loya *et al.* 2003, Karnosky *et al.* 2005, King *et al.* 2005).

Finally, our predictions stem from observed effects of altered atmospheric chemistry on the growth and physiology of five aspen clones. These clones, collected from locations in the Upper Great Lakes region, were included in the Aspen FACE experiment because of their putative variation in sensitivity to CO₂ or O₃ enrichment (Dickson *et al.* 2000). A number of studies have indicated that, as a species, trembling aspen possesses considerable genetic amplitude with respect to O₃ sensitivity (e.g., Coleman *et al.* 1995, Yun and Laurence 1999). At this point we have no way of knowing the degree to which our experimental genotypes represent the spectrum of salient attributes inherent in Wisconsin's aspen population.

Our findings have important implications not only for the health of Wisconsin's forests but also for mitigation of the state's CO₂ emissions. Aspen-dominated forests currently occupy nearly 2.8 million acres in the state (WISCLAND 2007), and, based on published estimates, annual C sequestration (i.e., net C accrual in branch and bolewood, coarse roots, and soil organic matter) in closed-canopy aspen stands presently averages roughly 2 metric tons C per acre statewide (Crow 1978, Ruark and Bockheim 1988, Fassnacht and Gower 1997, Green *et al.* 2003, Loya *et al.* 2003). This equates with a net annual absorption of approximately 20

MT CO₂, which is similar to estimates of the state's combined CO₂ emissions from commercial and industrial sectors (World Resources Institute 2007).

As is emphasized by Felzer *et al.* (2005), O₃'s impairment of C sequestration by forests and other terrestrial vegetation will likely entail substantial increases in costs associated with stabilizing atmospheric [CO₂] through reductions and/or offsets of anthropogenic CO₂ emissions. Relying on the economic figures in Felzer *et al.* (2005), we estimate that the consequences of our worst-case projection, a 30% increase in [O₃], could result in marginal costs exceeding 50 million dollars (present value) per year in Wisconsin (assuming that [CO₂] is stabilized at ~ 560 ppm). We note that our worst case lies well within the range of possible future trajectories generated in recent analyses of emission-driven changes in atmospheric chemistry (e.g., Houghton *et al.* 2001, Felzer *et al.* 2005). For example, our 30% increase in [O₃] culminates in a growing season O₃ exposure (AOT40) similar to that in a plausible outcome (coined GSTAB, Felzer *et al.* 2005) involving substantial future reductions in CO₂ emissions – but no explicit cap on other gaseous pollutants – where AOT40 reaches ~10 ppm-h per month by 2100. Notably, both of these trajectories are much less extreme than that forecasted in the absence of any emission controls (Felzer *et al.* 2005). In light of these considerations, we as a society will clearly be remiss if we ignore the importance of tropospheric O₃ as an agent of global change.

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APPENDIX A. Estimating effects of cumulative O₃ exposure on the photosynthetic metabolism of aspen foliage

Context: Despite a wealth of studies on leaf photosynthetic responses to O₃ exposure (e.g., see reviews by Pye 1988, Chappelka and Samuelson 1998), the published literature does not contain adequate information (in the form of empirical data or predictive models) with which to construct a credible relation between key photosynthetic parameters and levels of O₃ exposure in trembling aspen. Specifically, insufficient information is available to quantify the influence of cumulative O₃ exposure on biochemical variables of a widely used model of photosynthesis and its response to environment (Farquhar *et al.* 1980). This model underpins our estimates of canopy photosynthesis and stand carbon sequestration.

Objective: Generate estimates of the direction and magnitude of change, resulting from varying cumulative exposures of the leaf mesophyll to O₃, in biochemical parameters underlying photosynthetic performance in aspen leaves.

Methods: Data on rates of leaf gas exchange were acquired from the Aspen FACE facility, near Rhinelander, WI, during the growing season in each of three years - 1998, 2000, and 2002. Responses of photosynthesis to a range of incident light intensities or cuvette CO₂ concentrations were assessed with a Li-Cor 6400 portable photosynthesis system (Li-Cor Biosciences, Lincoln NE). In the measurement cuvette, incident light intensity was controlled with a red-blue LED array and leaf temperature was maintained at 25 ± 0.6 °C. In 1998, we sampled fully expanded, recently mature foliage from the upper half of the tree crown. In 2000 and 2002, fully expanded, mature leaves were systematically sampled from different positions in the aspen canopy. Measurements were conducted on clear to partly cloudy days in July, August and early September.

Data on leaf gas exchange were used to estimate the relative effects of treatment on parameters characterizing photosynthetic performance, including stomatal conductance, the maximum velocity of carboxylation by the enzyme rubisco (V_{Cmax}), maximum rate of electron transport, dark respiration rate, and apparent quantum yield. Of these variables, only V_{Cmax} differed significantly between O₃ treatments. This result is consistent with a broadly supported inference that impairment of rubisco function is a primary lesion to the photosynthetic apparatus resulting from O₃ exposure (Dizengremel 2001).

Data for estimating the cumulative amount of O₃ to which aspen foliage was exposed at the Aspen FACE site were extracted from the Aspen FACE data archive (Brookhaven National Laboratory 2007). The data were hourly averages of O₃ concentration recorded with O₃ analyzers sampling air drawn from the center of fumigated and control rings. Cumulative O₃ exposure was quantified using a conventional index called AOT40. This index, arising from evidence that O₃ concentrations greater than 40 ppb cause damage to many plant species (Furher 2000), is the sum of all departures (during the photoperiod) between hourly average concentration and the 40 ppb threshold, when hourly concentration exceeds the threshold, where, across *i* hours and *j* days,

$$\text{AOT40 (ppm.h)} = \sum_{i=1}^{24} \sum_{j=1}^n [([O_3] - 40)/1000]_{ij}.$$

In general, the effect of O₃ on leaf photosynthesis is primarily a function of the degree to which leaf mesophyll (as opposed to leaf epidermis) is exposed to the oxidant (Samuelson and Kelly 1997, Fuhrer 2000). In light of this, we adopted a hybrid index of ozone exposure based on the premise that 1) exposure of the leaf mesophyll is a combined function of atmospheric [O₃] and leaf conductance to O₃, and 2) O₃ concentrations greater than 40 ppb tend to injure plants. Our hybrid index, UOT40, reflects the marginal amount of O₃ absorbed by the leaf when atmospheric [O₃] exceeds 40 ppb. The index requires calculation of leaf conductance (g_l), which is a function of stomatal and boundary layer conductances, and is adjusted for the relative diffusivity of ozone in a gaseous medium, which theoretically is 40% less than that for water vapor (Laisk *et al.* 1989).

We note that our approach differs somewhat from other conventions (e.g., Karlsson *et al.* 2004). Namely, we have not adopted a simple estimate of cumulative O₃ uptake or a similar calculation of cumulative uptake when uptake rates (as opposed to O₃ concentrations) exceed a certain threshold. We avoid these strategies because results from studies with aspen, its congeners and other species (e.g., Coleman *et al.* 1989, Yun and Laurence 1999, Bortier *et al.* 2000) indicate that relatively high uptake rates do not necessarily coincide with detectable visual or functional symptoms as long as the atmospheric concentration is modest (i.e., < 40 ppb), whereas damage can occur at comparatively low uptake rates when atmospheric [O₃] is high. Thus, reliance on uptake alone, even when qualified with a threshold uptake level, does not appear to be a sufficient approach. Our strategy resembles that employed by Ollinger *et al.* (1997), except that in our case the index (UOT40) is calculated using hourly, as opposed to cumulative, dosage estimates: where, across *i* hours in *j* days,

$$\text{UOT40 (mmol m}^{-2}\text{)} = \sum_{i=1}^{24} \sum_{j=1}^n [3.6g_l([\text{O}_3] - 40)]_{ij}.$$

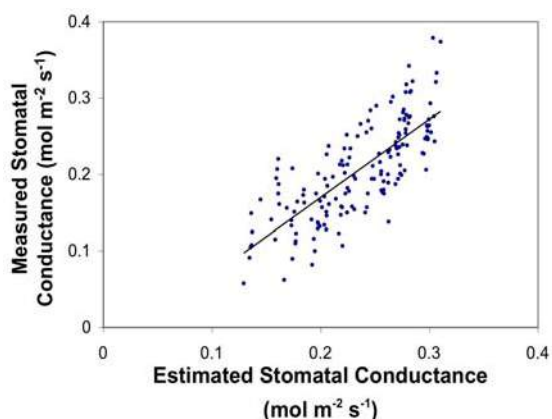
To estimate leaf conductance, we needed information on boundary layer conductance (g_{bl}). Lacking a feasible means of simulating canopy-level g_{bl}, we instead estimated g_{bl} for individual leaves, as a function of wind speed, using the equation provided in the footnote*. Estimates of leaf conductance also relied on predictions of stomatal behavior, which were generated using a semi-empirical Jarvis-type model (Jarvis 1976) involving several parameters known to influence stomatal opening, including incident light intensity, leaf temperature, vapor pressure gradient between leaf and air, and soil moisture content (Figure A1). The model was calibrated with data collected during the growing season of 2005 from the canopy of an aspen forest located in the Chequamegon National Forest southeast of Park Falls, WI (Loranty *et al.* 2007). This data set was employed because the data were collected using protocols specifically designed to effectively capture stomatal responses to light environment. Leaf gas exchange was measured *in situ* with a Li-Cor LI-6400 photosynthesis system. Model parameters included maximum stomatal conductance (G_{max}), which was calculated as a Weibull function of soil moisture deficit (Θ, cm), where G_{max} = 0.4·e^{(-3Θ/12)⁴}. The predicted sensitivity of G_{max} to Θ was based on observations of stomatal behavior in the previously mentioned aspen forest near Park Falls, WI. Observed values of stomatal

* g_{bl} = 1/[4(1/μ)^{0.5}/(2.42·10⁻⁵)(0.022642(T_l/273.16))]; l = average path length over the leaf (m), μ = wind speed (m s⁻¹), and T_l = leaf temperature (°K), which in our case was assumed to equal air temperature (Campbell and Norman 1997).

conductance for light-saturated foliage collected in 2000 and 2002 at the Aspen FACE site, which averaged $0.29 \text{ mol m}^{-2} \text{ s}^{-1}$ across treatments, did not differ significantly from values generated with our conductance model (data not shown).

Hourly estimates of average leaf conductance were generated using microenvironment data from the Aspen FACE site (FACE Data Management System 2007), except that soil moisture deficit was calculated daily based on precipitation data (ASOS 2007) and estimated evapotranspiration rates drawn from an empirical relationship between aspen canopy transpiration and the difference in vapor pressure between leaf and air in northern Wisconsin (Ewers *et al.* 2002). We used a soil moisture capacity of 16 cm (in the upper 1 m of the soil profile) in this calculation, based on soil data from the Aspen FACE site (Dickson *et al.* 2000). We assumed that 1) evapotranspiration from the soil surface and understory vegetation was negligible, 2) soil moisture content was at field capacity at the onset of each growing season, and 3) when soil was at field capacity, it did not retain excess precipitation.

Figure A1. Relation ($r^2 = 0.59$, $P < 0.001$) between measured and predicted values of stomatal conductance in the canopy of an aspen forest located near Park Falls, WI. Data were collected in June and July of 2005. The regression slope (1.02) does not differ significantly from unity ($P = 0.74$), and the intercept (-0.03) does not differ significantly from 0 ($P = 0.26$). See footnote * for predictive model.



Results

Maximum velocity of carboxylation ($V_{C_{max}}$) declined with increasing cumulative exposure of leaf mesophyll to O_3 (UOT40) (Figure A2). The relation between $V_{C_{max}}$ and UOT40 was

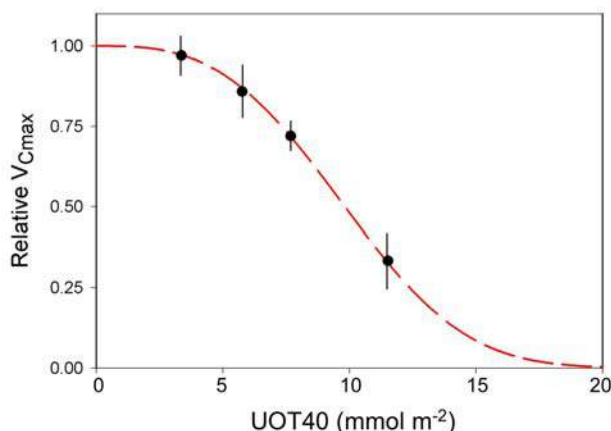


Figure A2. Relation between the maximum velocity of carboxylation ($V_{C_{max}}$), expressed as a fraction of the observed value in control (ambient) treatments early in each growing season (i.e., July - following minimal O_3 exposure), and UOT40, an index of cumulative exposure of leaf mesophyll to potentially damaging O_3 levels, in aspen foliage. The trend, fitted with a Weibull function ($\text{Relative } V_{C_{max}} = e^{(-U/11)^3}$, where $U = \text{UOT40}$) is based on data collected in 1998, 2000 and 2002 at the Aspen FACE facility.

* Predictive model: $g_s = G_{max} \ln Q [(4 \cdot 10^6 T_1^3 - 1.8 \cdot 10^3 T_1^2 + 0.914 T_1 - 0.131) / 7.6] / D^{0.3}$, where g_s = stomatal conductance ($\text{mol m}^{-2} \text{ s}^{-1}$), G_{max} = maximum stomatal conductance ($\text{mol m}^{-2} \text{ s}^{-1}$), Q = incident light intensity ($\mu\text{mol m}^{-2} \text{ s}^{-1}$), T_1 = leaf temperature ($^{\circ}\text{C}$), and D = vapor pressure difference between leaf and air (kPa). In this data set, G_{max} was estimated to be $0.4 \text{ mol m}^{-2} \text{ s}^{-1}$.

characterized by a Weibull function, where $V_{C_{max}}$ was expressed as a fraction of the observed value in control (ambient) treatments early in each growing season (i.e., July - following minimal O_3 exposure). The observed nonlinear consequence of cumulative O_3 exposure for $V_{C_{max}}$ was consistent with the results of several studies involving tree and crop species (Pell *et al.* 1992, Reid and Fiscus 1998, Grams *et al.* 1999). We did not observe a significant effect of O_3 treatment on several other parameters governing photosynthetic performance, including stomatal conductance, dark respiration, apparent quantum yield, and maximum rate of electron transport (J_{max}).

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APPENDIX B. Estimating relative effects of elevated atmospheric CO₂ and/or O₃ on aspen canopy photosynthesis and stand carbon sequestration at Aspen FACE

Context: Various modeling approaches have been used to predict the consequences of atmospheric and climatic change for forest productivity and C sequestration (e.g., Ollinger *et al.* 1997, Medlyn and Dewar 1996, Constable and Friend 2000, Laurence *et al.* 2001, Luo *et al.* 2001, Martin *et al.* 2001, Medlyn *et al.* 2003, Felzer *et al.* 2005). For the purpose at hand, we chose to use the canopy process model “BEWDY,” which has been employed in several assessments of forest response to global change (Medlyn and Dewar 1996, Medlyn *et al.* 2000, Halliday *et al.* 2003). BEWDY is analytically tractable, employs highly regarded and widely used photosynthetic submodels, and requires a modicum of input data relative to comparable strategies. The last point is important, as we have limited information on the physiological characteristics of aspen-dominated forests in Wisconsin.

In relying solely on a canopy process model, we are ignoring the potential direct and indirect effects of atmospheric change on processes “downstream” from canopy photosynthesis, such as changes in allocation patterns for carbon and nitrogen, and heterotrophic respiration (e.g., Ollinger *et al.* 2002). Our rationale for this omission is the absence of compelling and/or sufficiently comprehensive evidence to justify incorporation in our modeling effort. In other words, to date there are few if any indications at the Aspen FACE site that these “downstream” processes have responded in a manner that does not scale with treatment effects on canopy photosynthesis and stand biomass gain (Karnosky *et al.* 2003, Loya *et al.* 2003, Karnosky *et al.* 2005, King *et al.* 2005).

Objectives: 1) Using a canopy process model (BEWDY) calibrated with our empirical relationships (from Appendix A), estimate relative effects of elevated O₃ and CO₂, singly and in combination, on the amount of C sequestered by aspen canopies throughout a growing season at the Aspen FACE site. 2) Assess the accuracy and precision of BEWDY by evaluating the relation between observed and estimated treatment effects on C sequestration rates (i.e., annual stemwood and coarse root production) of experimental aspen stands at the Aspen FACE site.

Methods: BEWDY uses an analytical technique to calculate instantaneous rates of canopy-level photosynthesis ($\mu\text{mol CO}_2$ assimilated m^{-2} ground area s^{-1}), which can then be integrated to estimate net carbon acquisition by the canopy through any time period. The model, which distinguishes between sunlit and shaded portions of the canopy, requires several inputs, including canopy leaf area index (LAI), the extinction coefficient characterizing light penetration through the canopy, intensities of direct beam and diffuse radiation incident on the upper portion of the canopy, and leaf nitrogen (N) content at the top of the canopy.

Estimates of canopy LAI at the Aspen FACE site were generated using treatment-level data on foliage mass (King *et al.* 2005) for 1999-2003, and treatment-level data on leaf morphology (i.e., specific leaf area) and chemistry collected at the site throughout the growing season in 2000 (E.L. Kruger and E.P. McDonald, unpublished data). Simulated temporal trends in LAI throughout the growing season tracked those observed at the Aspen

FACE site in 2002 (Karnosky *et al.* 2005). The timing of canopy phenological events (i.e., leaf flush, canopy senescence) was estimated based on personal observations.

Photosynthetic rates were calculated as the minimum of two limiting processes, carboxylation of the five-carbon sugar ribulose biphosphate, and its subsequent regeneration in the Calvin-Benson cycle, each of which was estimated using an established biochemical model of photosynthesis (Farquhar *et al.* 1980). The model was rearranged so that atmospheric CO₂ partial pressure ($p\text{CO}_2$) and leaf conductance to CO₂ (rather than intercellular $p\text{CO}_2$) were key driving variables. This modification was necessary because we lacked sufficient data with which to adequately estimate intercellular $p\text{CO}_2$ dynamics. Leaf conductance was modeled according to the methods detailed in Appendix A. Other input variables included leaf nitrogen content (g N m⁻² leaf area), leaf temperature (assumed to equal air temperature), estimated leaf absorptance of incident light, quantum yield of electron transport, the relationship between V_{cmax} and J_{max} (as well as the sensitivity of each to leaf temperature), and light intensity incident on the upper portion of the tree canopy. Additionally, and importantly, V_{cmax} (at a given leaf N content) was modified as a function of cumulative exposure of leaf mesophyll to O₃ (based on UOT40), using the model presented in Appendix A.

Results & Discussion:

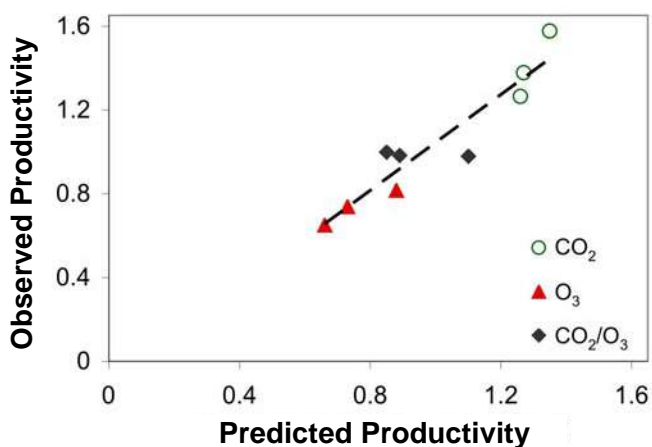


Figure B1. Relation ($r^2 = 0.89$, $P < 0.001$) between observed and predicted effects of atmospheric CO₂ and/or O₃ enrichment on wood production (stem plus coarse roots) in aspen stands at the Aspen FACE facility. Wood production is expressed as a fraction of that observed or predicted in control (ambient) stands, based on data (i.e., treatment means for 2000, 2002 and 2003) from King *et al.* (2005). The regression slope (1.14) does not differ significantly from unity ($P = 0.12$), and the intercept (-0.098) does not differ significantly from 0 ($P = 0.38$).

Using empirical relationships from Appendix A along with data on stand structure from the Aspen FACE site (King *et al.* 2005), we generated estimates of relative treatment effects on annual production of aboveground woody biomass plus coarse roots (a proxy for C sequestration) that were reasonably close to observed impacts (Figure B1). This outcome is encouraging, as predictions were generated in the absence of a complete multi-year data set on key foliar attributes such as leaf nitrogen content and specific leaf area, and without detailed information on soil moisture dynamics, etc. These constraints are similar to those we encounter when making predictions across Wisconsin (Appendix C).

In an effort to assess the consequences of certain assumptions (required in the absence of sufficient data) for our estimates of relative impacts, we explored the implications of variation in canopy traits that potentially exert a strong influence on output from the canopy

process model BEWDY. Somewhat surprisingly, we found that the relative impact of elevated CO₂ and/or O₃ at a given leaf area index (LAI) did not vary much (< 2%) across a wide range in LAI (i.e., 2-5 m² m⁻²). On the other hand, we did find that estimated relative impact was sensitive to variation in leaf N content. Namely, the stimulus resulting from CO₂ enrichment was enhanced, whereas the deleterious impact of elevated O₃ was reduced, at high leaf N contents. The magnitude of difference in impacts was as much as 6% (at elevated CO₂) when leaf N content was raised from 1.5 g m⁻² to 2.5 g m⁻². This is a typical range of values observed in the foliage of aspen canopies in Wisconsin (e.g., Donaldson *et al.* 2006).

Based on an analysis of model output, our rationale for the influence of leaf N on canopy photosynthetic responses to altered atmospheric chemistry revolves around the modeled (and well established) link between photosynthetic biochemistry and leaf N content (Appendix A). First, leaf and canopy photosynthetic response to CO₂ enrichment under high light is enhanced by N-mediated increases in electron transport capacity (J_{max}). Second, the relative inhibition of photosynthesis resulting from O₃-induced losses in V_{Cmax} declines with increasing leaf N content owing ultimately to the non-zero intercept in the relation between net photosynthesis and [CO₂] inside the leaf, the slope of which is governed by V_{Cmax}. In other words, because of the non-zero intercept, and especially at high light intensities and ambient [CO₂], a given relative decrease in V_{Cmax} leads to a proportionally greater decline in net photosynthesis when initial (undamaged) V_{Cmax} is low.

One qualifier regarding these findings is that our model contained no allowance for the potential relation between stomatal conductance and leaf N content (Schulze *et al.* 1994, Ollinger *et al.* 1997). Inclusion of this coupling would tend to offset the influence of leaf N content on canopy responses to both CO₂ and O₃. (Increased stomatal conductance associated with high leaf N content enhances photosynthesis to a greater extent at low atmospheric [CO₂], and decreased stomatal conductance associated with lower leaf N content decreases mesophyll exposure to O₃.) Our personal observations during recent field studies (e.g., Stevens *et al.* 2007, Loranty *et al.* 2007) have indicated, however, that stomatal conductance is not necessarily coupled with variation in leaf N content in aspen.

Finally, we expect that, all other factors aside, canopy photosynthetic responses to elevated [CO₂] and [O₃] would be enhanced and reduced, respectively, by moisture depletion in a given soil, owing to the positive relation between stomatal conductance and soil moisture availability. We speculate, however, that variation in soil moisture-holding capacity would not imply the same outcome owing to the fact that canopy structural attributes, namely leaf area index (LAI), tend to scale with moisture-holding capacity (e.g., Fassnacht and Gower 1997), and thus demand for moisture, in relation to its supply, may typically be relatively constant across broad edaphic gradients.

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APPENDIX C. Estimating relative effects of altered atmospheric chemistry on rates of carbon sequestration by aspen forests across Wisconsin

Objective: Based on the results of Appendices A and B, simulate canopy photosynthesis (and rate of C sequestration) for each of five growing seasons (2001-2005), at 27 locations in and around Wisconsin, under ambient micrometeorological conditions and several scenarios of altered atmospheric chemistry.

Methods: Hourly averages for O₃ concentration and meteorological parameters, recorded at various locations in and near Wisconsin during each growing season from 2001 through 2005, were acquired from the EPA data repository for atmospheric chemistry (AQS 2007), the FAA/NWS weather data networks (ASOS/AWOS), and the WI-MN Cooperative Extension Agricultural Weather Page (AWON 2007). Based on these data, we simulated canopy photosynthesis (using BEWDY) for each of the five growing seasons, at 27 locations, under recent meteorological conditions and several scenarios of altered atmospheric chemistry: recent O₃ levels, and 10-30% increases in ozone concentration in combination with different CO₂ concentrations (3 levels: recent, 560 ppm and 700 ppm). Using recent conditions and a hypothetical atmosphere lacking O₃ as a reference, we calculated relative impacts of altered atmospheric chemistry under each of the 12 scenarios, for each of the five growing seasons (2001-2005).

Stand canopy traits were held constant in all simulations: the seasonal peak for leaf area index (LAI) = 3, with a seasonal dynamic mimicking the pattern observed at Aspen FACE (Karnosky *et al.* 2005), canopy extinction coefficient = 0.55, leaf absorptance = 0.9, quantum yield of electron transport = 0.24, maximum leaf N content = 2 g m⁻², slope of relation between V_{Cmax} and leaf N content = 60 μmol [g N]⁻¹ s⁻¹ (at 25 °C); slope for J_{max} vs. leaf N content = 90 μmol [g N]⁻¹ s⁻¹ (at 25 °C). The latter two relationships were derived from gas exchange measures at Aspen FACE in 1998 (unpublished data, see Appendix A). Fraction of diffuse light = 0.1 unless under overcast conditions, where fraction = 1. Soil water balance was calculated daily using the approach outlined in Appendix A.

Spatial variation in aspen canopy phenology, namely budbreak and leaf senescence, was estimated in each year based on observations at the Aspen FACE site. Using the timing of events at Aspen FACE to calibrate our estimates, budbreak and canopy senescence were delayed and accelerated with increasing latitude by 3 days per degree (accounting for the typical delay near the Great Lakes). Hence, according to our simulations, buds typically broke nearly two weeks earlier in southern versus northern WI, and leaf senescence (defined by functional LAI = 0) was about two weeks earlier in northern versus southern WI. Both events were delayed by a week, in relation to inland locations at the same latitude, near the shores (i.e., within 10 km) of Lake Michigan and Lake Superior.

Ozone and meteorological data were missing for varying durations at most if not all locations through the 5-year period of interest (2001-2005). This situation necessitated the use of data gap-filling protocols. We adopted the following strategies for ensuring that our O₃ and meteorology data sets were as complete as possible:

- If gap duration was less than 4 h, we relied on interpolation. Preliminary tests indicated that this method led to predictions that matched actual values fairly well (based on assessments of goodness of fit for replacement following random data deletion), $r = 0.93$, $P < 0.001$, slope = 1.03, intercept = 0.01. Longer gap durations led to a rapid erosion of accuracy and precision using interpolation.
- If gap duration was greater than 4 h, we explored the feasibility of gap-filling with estimates based on data from a proximal monitor(s). This was allowed if data from the two monitors were closely correlated (i.e., $r > 0.8$, $P < 0.001$) during the time period surrounding the gap. The observed relationship was used, where $[O_3]_{\text{missing}} = a + b[O_3]_{\text{proximal}}$, with a and b representing the observed intercept and slope, respectively, of the relation between reported $[O_3]$ values from the target and proximal monitors during a 20-100 h period surrounding the data gap. (The amount of data used in modeling was adjusted to scale with the size of the gap.)
- If individual gaps > 72 hours constituted (cumulatively) more than 10% of all hourly data for a given season, or if satisfactory proxies could not be developed for larger gaps, that data set (for a given year and site) was not used in our analysis. That situation arose for counties and years indicated in Tables C1-C5. In the remaining cases, the largest individual gap was 116 hours (~3% of total for growing season).

Results: The spatially explicit modeling output presented in Tables C1-C5 (pages 27-31) was used to generate the kriged maps depicting spatial variation in responses of aspen-dominated forests to altered atmospheric chemistry (Figure 6), as well as the overall impact surface in Figure 7. Underlying that AOT40-based surface, however, was canopy photosynthetic response to the index of leaf mesophyll exposure to O_3 , UOT40 (see Appendix A). Across sites and years, variation in predicted impact was closely related to a model combining a hyperbolic CO_2 response and a Weibull function¹ of UOT40 (Figure C1).

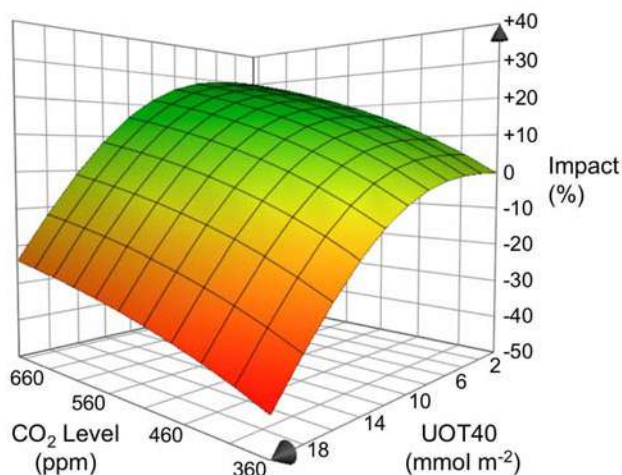


Figure C1. Predicted relative impacts of elevated CO_2 and cumulative exposure of leaf mesophyll to O_3 (UOT40) on rates of aspen canopy photosynthesis (and thus C sequestration). The impact surface is based on estimated effects of altered atmospheric chemistry at 27 locations in and around Wisconsin during 2001-2005. The modeled impact surface combines a hyperbolic function of $[CO_2]$ and a Weibull function of UOT40 ($r^2 = 0.96$, $P < 0.0001$). See footnote¹ for model structure and coefficients.

¹ Impact (%) = $170 \cdot ([CO_2] - 94.1)/([CO_2] + 94.1) \cdot e^{-(U/24.6)^3} - 100$, where $U = UOT40$ ($mmol\ m^{-2}$).

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Table C1. Averages and observed ranges (minima and maxima) for an index of cumulative O₃ exposure (AOT40) in each of the five growing seasons (May 1 – Sept. 30) during the period 2001 through 2005. Estimates are for 27 locations in which O₃ was monitored in WI, eastern MN and northern IL. Note that sufficient O₃ monitoring data were not available at some stations in certain years. Values of AOT40 are expressed in ppm-h. Increases in [O₃] are 10% ([O₃] × 1.1), 20% ([O₃] × 1.2), and 30% ([O₃] × 1.3).

Ozone Monitor Location			AOT40 2001-2005			AOT40 when [O ₃] × 1.1			AOT40 when [O ₃] × 1.2			AOT40 when [O ₃] × 1.3		
County	Lat	Long	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max
Ashland ¹	46.6	-90.7	5.6	–	–	9.0	–	–	13.1	–	–	17.8	–	–
Brown	44.5	-87.9	12.0	7.5	13.8	17.4	11.6	19.7	23.5	16.6	26.2	30.1	22.3	33.3
Carlton (MN) ³	46.7	-92.5	3.8	2.4	5.2	6.2	4.3	8.2	9.3	6.8	11.7	12.9	10.0	15.8
Columbia	43.3	-89.1	15.1	7.6	18.1	21.5	12.1	25.2	28.6	17.5	32.9	36.1	23.5	41.1
Dane	43.1	-89.4	14.5	7.2	16.8	20.5	11.3	23.5	27.2	16.2	30.8	34.3	21.7	38.6
Dodge	43.6	-89.0	16.0	8.4	20.0	22.8	13.2	27.6	30.2	18.8	35.7	38.2	25.0	44.3
Door	45.2	-87.0	14.4	9.9	17.7	20.4	14.5	24.3	27.2	20.0	31.6	34.5	26.2	39.4
Florence	45.8	-88.4	8.8	5.5	10.2	13.5	9.4	15.0	18.9	14.0	20.7	25.0	19.4	27.3
Fond du Lac	43.7	-88.4	14.9	7.9	18.4	21.2	12.4	25.5	28.2	17.7	33.3	35.8	23.7	41.6
Forest ²	45.6	-88.8	9.0	5.6	12.3	13.8	9.6	18.1	19.5	14.6	24.5	26.0	20.4	31.6
Goodhue (MN) ²	44.5	-93.0	10.7	7.0	14.4	16.0	11.4	20.7	22.0	16.5	27.6	28.6	22.2	34.9
Jefferson	43.0	-88.8	16.8	9.0	20.7	23.4	13.8	28.0	30.5	19.3	35.8	38.1	25.5	44.1
Kenosha	42.5	-87.8	18.9	10.9	22.8	25.5	15.9	29.8	32.8	21.6	37.7	40.6	27.9	46.1
Kewaunee	44.4	-87.5	13.8	8.3	15.9	19.6	12.5	21.9	26.0	17.5	29.1	33.1	23.2	36.7
Manitowoc	44.1	-87.6	13.7	8.6	15.8	19.3	12.7	21.6	25.6	17.6	28.0	32.4	23.3	35.2
Marathon	44.7	-89.8	11.6	7.7	13.5	17.3	12.3	19.6	23.5	17.6	26.6	30.4	23.8	34.1
Milwaukee	43.0	-87.9	11.5	5.5	15.7	16.2	8.7	21.4	21.6	12.6	27.6	27.6	17.1	34.4
Oneida ²	45.7	-89.6	9.2	7.0	12.4	14.2	11.3	18.1	19.9	16.6	24.5	26.2	22.7	31.4
Ozaukee	43.5	-87.8	15.6	8.3	19.9	21.4	12.3	26.8	28.0	17.1	34.4	35.1	22.5	42.6
Racine	42.7	-87.8	14.4	7.5	18.7	19.9	11.4	25.0	26.1	16.0	32.0	32.8	21.1	39.6
Rock	42.5	-89.1	16.4	8.5	20.4	22.7	13.0	27.6	29.6	18.2	35.3	36.9	23.9	43.3
Sauk	43.4	-89.7	13.6	7.9	15.9	19.9	12.8	22.7	27.0	18.5	30.2	34.5	24.8	38.2
St. Croix	45.1	-92.7	10.4	7.2	14.0	15.5	11.3	19.9	21.2	16.2	26.4	27.3	21.7	33.4
St. Louis (MN) ³	46.8	-92.1	5.6	3.9	9.9	9.1	6.8	15.1	13.4	10.0	21.1	18.3	13.7	27.7
Vernon	43.7	-90.6	12.8	6.5	17.1	18.9	10.6	24.3	25.8	15.6	32.2	33.2	21.3	40.5
Vilas	46.0	-89.7	9.4	6.3	13.7	14.5	10.4	19.9	20.4	15.7	26.9	26.9	21.9	34.4
Winnebago (IL)	42.3	-89.1	12.8	7.7	16.5	18.3	12.2	22.8	24.5	17.3	29.8	31.1	23.0	37.2

¹Data from 2005 only; ²Data from 2004 and 2005; ³Data from 2003, 2004 and 2005.

Table C2. Averages and observed ranges (maxima and minima) for an index of cumulative leaf O₃ uptake (UOT40) in each of five growing seasons during the period 2001 through 2005. Estimates are for aspen forests near 27 locations in which O₃ was monitored in WI, eastern MN and northern IL. Superscripts denote that sufficient O₃ data were absent at some monitoring stations in certain years. Values of UOT40 are in mmol O₃ m⁻² leaf area. Increases in [O₃] are 10% ([O₃] × 1.1), 20% ([O₃] × 1.2), and 30% ([O₃] × 1.3).

Ozone Monitor Location			UOT40 in 2001-2005			UOT40 when [O ₃] × 1.1			UOT40 when [O ₃] × 1.2			UOT40 when [O ₃] × 1.3		
County	Lat	Long	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max
Ashland ¹	46.6	-90.7	2.0	—	—	3.3	—	—	4.9	—	—	6.8	—	—
Brown	44.5	-87.9	4.9	2.8	5.7	6.9	4.3	7.9	9.2	6.0	10.3	11.7	8.0	13.0
Carlton (MN) ³	46.7	-92.5	1.8	0.9	2.6	2.8	1.6	4.0	4.2	2.4	5.8	5.7	3.6	7.7
Columbia	43.3	-89.1	6.2	2.6	7.2	8.7	4.2	9.9	11.5	6.0	12.9	14.4	8.2	16.0
Dane	43.1	-89.4	5.7	2.4	6.7	8.0	3.9	9.3	10.6	5.7	12.2	13.3	7.7	15.3
Dodge	43.6	-89.0	6.2	3.0	8.1	8.7	4.8	11.1	11.6	6.9	14.3	14.6	9.1	17.7
Door	45.2	-87.0	5.8	3.7	7.2	8.0	5.4	9.6	10.5	7.3	12.3	13.2	9.5	15.2
Florence	45.8	-88.4	3.2	1.8	3.7	4.9	3.1	5.5	6.9	4.6	7.5	9.1	6.5	9.7
Fond du Lac	43.7	-88.4	5.8	2.7	7.3	8.2	4.3	10.1	10.9	6.2	13.2	13.8	8.3	16.5
Forest ²	45.6	-88.8	3.2	1.7	4.7	4.9	3.0	6.9	6.9	4.6	9.3	9.2	6.5	11.9
Goodhue (MN) ²	44.5	-93.0	4.6	2.7	6.4	6.9	4.5	9.3	9.5	6.6	12.4	12.4	9.0	15.8
Jefferson	43.0	-88.8	6.7	3.1	8.5	9.3	4.8	11.5	12.0	6.7	14.6	15.0	8.9	18.0
Kenosha	42.5	-87.8	7.7	4.4	9.7	10.4	6.4	12.7	13.2	8.7	15.9	16.3	11.3	19.2
Kewaunee	44.4	-87.5	5.8	3.2	6.6	8.0	4.7	9.0	10.5	6.5	11.7	13.2	8.5	14.5
Manitowoc	44.1	-87.6	5.9	3.6	6.9	8.2	5.2	9.2	10.7	7.1	11.8	13.4	9.2	14.6
Marathon	44.7	-89.8	4.6	2.5	5.5	6.7	4.0	7.9	9.1	5.9	10.6	11.6	8.0	13.4
Milwaukee	43.0	-87.9	5.2	2.2	6.6	7.2	3.5	9.0	9.5	4.9	11.6	12.0	6.7	14.4
Oneida ²	45.7	-89.6	3.5	2.4	4.6	5.5	4.0	6.7	7.9	6.0	9.1	10.5	8.3	11.7
Ozaukee	43.5	-87.8	6.4	3.3	7.6	8.7	4.8	10.1	11.2	6.6	12.9	13.9	8.5	15.7
Racine	42.7	-87.8	5.8	2.9	8.1	8.0	4.4	10.6	10.4	6.0	13.4	13.0	8.0	16.4
Rock	42.5	-89.1	6.9	3.3	8.4	9.0	5.0	10.8	11.7	7.1	13.7	15.3	9.3	19.3
Sauk	43.4	-89.7	5.2	2.6	6.0	7.6	4.3	8.7	10.3	6.6	11.6	13.1	8.6	14.7
St. Croix	45.1	-92.7	4.9	3.1	6.9	7.2	4.8	9.7	9.7	6.9	12.8	12.5	9.3	16.1
St. Louis (MN) ³	46.8	-92.1	2.2	1.2	3.6	3.5	2.0	5.6	5.2	3.1	8.0	7.1	4.4	10.6
Vernon	43.7	-90.6	5.2	2.1	6.4	7.6	3.5	9.2	10.3	5.3	12.2	13.2	7.3	15.5
Vilas	46.0	-89.7	3.5	2.2	4.8	5.3	3.6	7.1	7.5	5.6	9.6	9.9	7.9	12.3
Winnebago (IL)	42.3	-89.1	5.0	2.5	6.2	7.1	4.0	8.5	9.4	5.8	11.0	11.9	7.7	13.7

¹Data from 2005 only; ²Data from 2004 and 2005; ³Data from 2003, 2004 and 2005.

Table C3. Averages and observed ranges (maxima and minima) for estimated relative (%) impacts of ambient and increased O₃ concentrations on rates of carbon sequestration, in each of the five growing seasons during the period 2001 through 2005. Estimates are for aspen forests near 27 locations in which O₃ was monitored in WI, eastern MN and northern IL. Superscripts denote that sufficient O₃ data were absent at some monitoring stations in certain years. Values are percent differences from C sequestration rates estimated in absence of O₃. Increases in [O₃] are 10% ([O₃] x 1.1), 20% ([O₃] x 1.2), and 30% ([O₃] x 1.3).

Ozone Monitor Location			Impact in 2001-2005			Impact if [O ₃] x 1.1			Impact if [O ₃] x 1.2			Impact if [O ₃] x 1.3		
County	Lat	Long	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max
Ashland ¹	46.6	-90.7	0	-	-	0	-	-	-1	-	-	-2	-	-
Brown	44.5	-87.9	-1	-1	0	-2	-2	0	-5	-6	-1	-10	-13	-2
Carlton (MN) ³	46.7	-92.5	0	0	0	0	0	0	-1	-1	0	-2	-3	0
Columbia	43.3	-89.1	-2	-2	0	-4	-5	0	-10	-14	-1	-21	-27	-4
Dane	43.1	-89.4	-1	-2	0	-3	-4	0	-8	-11	-1	-17	-23	-3
Dodge	43.6	-89.0	-1	-2	0	-4	-7	0	-11	-17	-2	-22	-30	-4
Door	45.2	-87.0	-1	-2	0	-3	-5	-1	-8	-12	-1	-16	-23	-4
Florence	45.8	-88.4	0	0	0	-1	-1	0	-2	-2	0	-5	-6	-1
Fond du Lac	43.7	-88.4	-1	-2	0	-4	-6	0	-9	-14	-1	-19	-28	-3
Forest ²	45.6	-88.8	0	-1	0	-1	-2	0	-2	-5	0	-7	-13	-1
Goodhue (MN) ²	44.5	-93.0	-1	-2	0	-2	-5	0	-6	-12	-1	-13	-24	-3
Jefferson	43.0	-88.8	-2	-2	0	-4	-6	-1	-11	-15	-2	-20	-27	-4
Kenosha	42.5	-87.8	-2	-5	0	-6	-12	-1	-13	-23	-3	-23	-36	-7
Kewaunee	44.4	-87.5	-1	-1	0	-3	-4	0	-7	-10	-1	-15	-20	-3
Manitowoc	44.1	-87.6	-1	-1	0	-3	-4	-1	-7	-9	-1	-15	-18	-4
Marathon	44.7	-89.8	-1	-1	0	-2	-2	0	-5	-6	-1	-10	-15	-2
Milwaukee	43.0	-87.9	-1	-1	0	-2	-3	0	-3	-6	0	-8	-13	-1
Oneida ²	45.7	-89.6	0	0	0	0	-1	0	-2	-4	-1	-6	-10	-3
Ozaukee	43.5	-87.8	-1	-2	0	-4	-5	0	-9	-12	-2	-16	-22	-2
Racine	42.7	-87.8	-1	-2	0	-2	-5	0	-5	-11	-1	-11	-20	-2
Rock	42.5	-89.1	-2	-3	0	-5	-7	-1	-10	-15	-2	-20	-28	-5
Sauk	43.4	-89.7	-1	-1	0	-3	-4	0	-8	-11	-1	-17	-22	-4
St. Croix	45.1	-92.7	-1	-1	0	-2	-3	0	-5	-8	-1	-10	-17	-3
St. Louis (MN) ³	46.8	-92.1	0	0	0	0	-1	0	-1	-3	0	-4	-9	-1
Vernon	43.7	-90.6	-1	-1	0	-3	-4	0	-8	-11	-1	-17	-23	-2
Vilas	46.0	-89.7	0	-1	0	-1	-2	0	-3	-6	-1	-6	-13	-3
Winnebago (IL)	42.3	-89.1	-1	-1	0	-2	-3	0	-5	-7	-1	-11	-15	-2

¹Data from 2005 only; ²Data from 2004 and 2005; ³Data from 2003, 2004 and 2005.

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Table C4. Averages and observed ranges (maxima and minima) for estimated relative (%) impacts of an **increase in atmospheric CO₂ concentration to 560 ppm**, at recent ambient and increased O₃ concentrations, on rates of carbon sequestration in each of the five growing seasons during the period 2001 through 2005. Estimates are for aspen forests near 27 locations in which O₃ was monitored in WI, eastern MN and northern IL. Superscripts denote that sufficient O₃ data were absent at some monitoring stations in certain years. Values are percent differences from C sequestration rates estimated at recent [CO₂] (~360 ppm during growing season) in the absence of O₃. Increases in [O₃] are 10% ([O₃] x 1.1), 20% ([O₃] x 1.2), and 30% ([O₃] x 1.3). ¹Data from 2005 only; ²Data from 2004 and 2005; ³Data from 2003, 2004 and 2005.

Ozone Monitor Location			Impact at recent [O ₃]			Impact if [O ₃] x 1.1			Impact if [O ₃] x 1.2			Impact if [O ₃] x 1.3		
County	Lat	Long	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max
Ashland ¹	46.6	-90.7	18	–	–	18	–	–	17	–	–	15	–	–
Brown	44.5	-87.9	24	23	24	22	21	24	18	16	23	10	7	21
Carlton (MN) ³	46.7	-92.5	19	18	19	18	18	19	18	17	19	16	14	19
Columbia	43.3	-89.1	22	20	23	18	17	20	9	5	18	-5	-11	15
Dane	43.1	-89.4	23	20	25	20	19	20	12	9	19	0	-6	16
Dodge	43.6	-89.0	23	21	24	18	15	21	8	1	19	-5	-16	19
Door	45.2	-87.0	23	21	25	20	16	23	13	7	22	3	-7	19
Florence	45.8	-88.4	25	24	25	24	23	24	22	21	24	18	16	22
Fond du Lac	43.7	-88.4	23	20	24	19	17	21	10	5	18	-2	-12	15
Forest ²	45.6	-88.8	25	25	25	24	23	25	21	17	24	15	6	23
Goodhue (MN) ²	44.5	-93.0	20	19	21	18	14	21	12	5	19	4	-9	17
Jefferson	43.0	-88.8	22	21	23	18	15	20	9	3	18	-4	-12	14
Kenosha	42.5	-87.8	21	18	24	16	8	23	7	-6	20	-6	-22	14
Kewaunee	44.4	-87.5	23	22	25	20	18	24	14	10	23	4	-3	21
Manitowoc	44.1	-87.6	23	22	24	20	18	24	14	11	22	4	0	19
Marathon	44.7	-89.8	24	23	24	22	20	24	18	14	24	9	3	20
Milwaukee	43.0	-87.9	24	22	25	22	19	25	19	14	24	13	5	23
Oneida ²	45.7	-89.6	22	19	24	21	19	22	18	17	18	12	10	14
Ozaukee	43.5	-87.8	23	21	25	19	17	24	12	7	23	2	-6	21
Racine	42.7	-87.8	24	22	25	22	18	25	17	9	24	10	-3	22
Rock	42.5	-89.1	22	20	24	18	15	20	9	3	17	-3	-12	13
Sauk	43.4	-89.7	23	20	24	20	17	21	12	8	18	0	-6	14
St. Croix	45.1	-92.7	21	20	21	19	17	21	15	10	19	8	-1	16
St. Louis (MN) ³	46.8	-92.1	18	18	19	18	17	19	17	14	18	13	7	17
Vernon	43.7	-90.6	24	21	25	18	10	21	15	9	20	0	-7	17
Vilas	46.0	-89.7	23	19	25	22	19	24	19	16	22	14	5	18
Winnebago (IL)	42.3	-89.1	25	24	26	23	21	26	18	15	25	10	4	24

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Table C5. Averages and observed ranges (maxima and minima) for estimated relative (%) impacts of an **increase in atmospheric CO₂ concentration to 700 ppm**, at recent ambient and increased O₃ concentrations, on rates of carbon sequestration in each of the five growing seasons during the period 2001 through 2005. Estimates are for aspen forests near 27 locations in which O₃ was monitored in WI, eastern MN and northern IL. Superscripts denote that sufficient O₃ data were absent at some monitoring stations in certain years. Values are percent differences from C sequestration rates estimated at recent [CO₂] (~360 ppm during growing season) in the absence of O₃. Increases in [O₃] are 10% ([O₃] x 1.1), 20% ([O₃] x 1.2), and 30% ([O₃] x 1.3). ¹Data from 2005 only; ²Data from 2004 and 2005; ³Data from 2003, 2004 and 2005.

Ozone Monitor Location			Impact at Recent [O ₃]			Impact if [O ₃] x 1.1			Impact if [O ₃] x 1.2			Impact if [O ₃] x 1.3		
County	Lat	Long	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max
Ashland ¹	46.6	-90.7	25	–	–	25	–	–	24	–	–	22	–	–
Brown	44.5	-87.9	32	32	34	30	29	33	25	23	32	17	14	30
Carlton (MN) ³	46.7	-92.5	25	25	25	25	24	25	24	23	25	22	20	25
Columbia	43.3	-89.1	31	27	33	26	25	27	15	12	25	1	-6	21
Dane	43.1	-89.4	32	27	34	27	26	28	19	15	25	6	0	23
Dodge	43.6	-89.0	32	30	35	25	22	28	14	7	26	-1	-11	21
Door	45.2	-87.0	31	30	33	28	24	34	21	14	31	9	-1	27
Florence	45.8	-88.4	33	33	34	32	32	34	30	29	33	25	23	31
Fond du Lac	43.7	-88.4	31	27	33	27	25	28	18	13	25	4	-5	22
Forest ²	45.6	-88.8	34	33	35	33	33	33	30	26	33	23	14	31
Goodhue (MN) ²	44.5	-93.0	29	27	30	26	22	29	20	12	28	11	-3	25
Jefferson	43.0	-88.8	30	27	32	25	23	26	15	10	24	2	-6	20
Kenosha	42.5	-87.8	30	26	33	24	15	30	13	-1	27	0	-17	20
Kewaunee	44.4	-87.5	31	31	33	28	26	33	21	17	32	11	4	29
Manitowoc	44.1	-87.6	32	31	33	28	26	33	21	18	31	11	6	27
Marathon	44.7	-89.8	32	32	34	30	29	33	25	22	32	17	10	29
Milwaukee	43.0	-87.9	33	31	35	32	28	35	28	22	34	24	18	33
Oneida ²	45.7	-89.6	29	25	33	28	25	31	25	23	26	19	17	20
Ozaukee	43.5	-87.8	31	29	33	27	24	33	19	14	32	8	0	29
Racine	42.7	-87.8	33	31	35	31	26	35	25	16	34	17	3	32
Rock	42.5	-89.1	31	27	35	25	22	30	16	9	24	3	-7	19
Sauk	43.4	-89.7	31	27	33	28	26	29	19	15	25	6	0	21
St. Croix	45.1	-92.7	29	28	30	27	25	29	22	17	28	14	5	24
St. Louis (MN) ³	46.8	-92.1	25	25	25	24	23	25	23	20	25	23	22	24
Vernon	43.7	-90.6	32	27	34	28	27	29	20	15	26	6	-2	23
Vilas	46.0	-89.7	31	25	33	30	25	32	27	23	30	21	12	25
Winnebago (IL)	42.3	-89.1	34	33	35	31	29	34	26	22	33	16	10	30