



Forest understory clover populations in enriched CO₂ and O₃ atmospheres: Interspecific, intraspecific, and indirect effects

Caroline S. Awmack, Edward B. Mondor*, Richard L. Lindroth

Department of Entomology, 1630 Linden Drive, University of Wisconsin, Madison, WI 53706, United States

Received 1 July 2005; received in revised form 17 October 2005; accepted 20 April 2006

Abstract

The effects of CO₂ and tropospheric O₃ on forest trees are increasingly the subject of experimental evaluation. Little is known, however, about the effects of these gases on understory plant taxa. At the Aspen free-air CO₂ and O₃ enrichment (Aspen FACE) site we assessed colonization and establishment of two common forest understory species, red (*Trifolium pratense*) and white (*Trifolium repens*) clover. To better understand these natural patterns in red clover, the more responsive of the two clover species, we also assessed intraspecific variation in growth performance to altered atmospheric conditions. Natural red clover populations were larger in enriched CO₂ atmospheres, whereas white clover populations showed no response to CO₂. Neither species showed beneficial or detrimental responses to enriched O₃ atmospheres. Nine red clover genotypes exhibited similar, but counterintuitive, decreases in shoot and root biomass, and increases in foliar nitrogen concentrations and root nodule numbers, under elevated CO₂. We suggest that in enriched CO₂ habitats, increased shading from rapidly growing trees offsets the positive benefits of CO₂ for understory plant performance. Enriched CO₂ and O₃ atmospheres may have large direct and indirect effects on colonization, establishment, and performance of common understory plants. Such changes may in turn alter forest community and ecosystem dynamics.

© 2006 Elsevier B.V. All rights reserved.

Keywords: Carbon dioxide; Climate change; Genetic variation; Greenhouse gas; Indirect effect; Ozone

1. Introduction

Rising concentrations of CO₂ and tropospheric O₃, as a result of increasing industrialized activity (IPCC, 2001), alter plant performance in both natural and managed ecosystems. Enriched CO₂ and O₃ atmospheres typically have opposing effects on plant productivity, with CO₂ resulting in increased plant growth and O₃ causing decreased growth (Makino and Mae, 1999; Krupa et al., 2001; Karnosky et al., 2003). In combination, however, elevated CO₂ may partially ameliorate the negative effects of elevated O₃ on plants (Heagle et al., 1998; Dickson et al., 1998; Donnelly et al., 2000; Percy et al., 2002; Karnosky et al., 2003).

Predicting plant population- and resulting community-level responses to such global atmospheric changes is problematical (Poorter and Navas, 2003). First, there may be interspecific changes in community structure, as increasing levels of

CO₂ and/or O₃ may alter species growth patterns to different degrees, leading to decreased performance of certain taxa (Hättenschwiler and Körner, 2000; Belote et al., 2004; Karnosky et al., 2005). Second, intraspecific variation in response to elevated CO₂ and O₃ atmospheres is common in plants (Pell et al., 1992; Foy et al., 1995; Dickson et al., 1998; Reichenauer et al., 1998; Van der Kooij et al., 2000; Lindroth et al., 2001; Castells et al., 2002; Goverde et al., 2002). As it is the relative fitness of plant genotypes in enriched CO₂, O₃, and +CO₂ + O₃ atmospheres that determines the outcome of intraspecific competition (Curtis et al., 1994, 1996; Bazzaz et al., 1995; Davison and Reiling, 1995; Andalo et al., 2001; McDonald et al., 2002), population and community differences will reflect selection for genotypes that are able to adapt to those changes. Thus, consequent changes in competitive ability both among and within species can significantly alter community composition.

The majority of research on plant responses to enriched CO₂ and/or O₃ atmospheres has focused on dominant agricultural (Mauney et al., 1992; Kimball et al., 1999, 2002) and forest (DeLucia et al., 1999; Karnosky et al., 2003, 2005) species. In comparison, relatively little work has been conducted on understory plant populations. Understory plant colonization (the

* Corresponding author. Present address: Kaua'i Agricultural Research Center, University of Hawai'i at Mānoa, 7370 Kuamo'o Road, Kapa'a, HI 96746, United States. Tel.: +1 808 822 4984x229; fax: +1 808 822 2190.

E-mail address: mondor@hawaii.edu (E.B. Mondor).

initial occupation of soil by seedlings; Lincoln et al., 1998) and establishment (successful growth and reproduction; Lincoln et al., 1998) may have large impacts on community dynamics. For example, trophic interactions may be altered, as both detrimental and beneficial insects frequent forest understory plants for food and harborage (Hamilton et al., 2004). Understanding how changing atmospheric conditions alter forest understory plant populations, however, presents a unique challenge. As overstory taxa exhibit differential growth rates under enriched CO₂ (DeLucia et al., 1999) and/or O₃ environments (Karnosky et al., 2003, 2005), tree canopy development may alter light levels which, along with atmospheric conditions, may concomitantly influence understory plant growth.

Here, we describe two experiments from the Aspen free-air CO₂ and O₃ enrichment (Aspen FACE) site, in which we sought to better understand patterns of forest understory colonization and establishment. First, we conducted a multiple-year survey of the natural abundance of red (*Trifolium pratense*) and white (*Trifolium repens*) clover colonizing FACE rings, to determine whether two closely related understory species show similar population-level responses to enriched CO₂ and/or O₃ atmospheres. Second, as red clover was found to be more responsive than white clover to altered atmospheric conditions, we assessed intraspecific variation in performance of nine red clover cultivars to enriched CO₂ and/or O₃ atmospheres, to better understand natural patterns of colonization and establishment.

2. Materials and methods

2.1. The Aspen FACE site

The Aspen FACE site, located near Rhinelander, WI, USA (45.7°N, 89.7°W), consists of aggrading forest stands exposed to realistic future concentrations of CO₂ and/or O₃ (Dickson et al., 2000). Each FACE ring is divided into three sections: mixed trembling aspen (*Populus tremuloides*) genotypes, aspen and paper birch (*Betula papyrifera*), and aspen and sugar maple (*Acer saccharum*) (Dickson et al., 2000). Site preparation for each ring included disking of the soil in summer 1996. Seedling trees were planted in 1997 and fumigation commenced in 1998. Roundup® herbicide was applied to the soil surface twice per year in 1998 and 1999 to control emergent vegetation while trees became established. Beginning in 2000, a diverse ground flora, derived from the soil seed bank and from natural seed dispersion, developed in each ring.

The Aspen FACE site consists of 12, 30 m diameter rings arranged in a 2 × 2 factorial randomized block design (Dickson et al., 2000). Four treatments comprise each block: (1) control, (2) elevated CO₂ (+CO₂), (3) elevated O₃ (+O₃), and (4) elevated CO₂ and O₃ (+CO₂ + O₃). Elevated CO₂ levels represent concentrations predicted for the year 2060 (Dickson et al., 2000). O₃ levels are elevated in a diurnal profile ca. 1.5-fold that of background concentrations, replicating levels of a moderately polluted city in the Great Lakes region of North America (Dickson et al., 2000). For each ring, a computer-controlled trace gas monitoring system adjusts the concentrations of both CO₂ and O₃ (Dickson et al., 2000).

Trace gas levels for May–August 2000 and 2002 were: (1) control (350 and 360 μl l⁻¹ CO₂; 36 and 33 nl l⁻¹ O₃), (2) elevated CO₂ (545 and 542 μl l⁻¹ CO₂; 36 and 33 nl l⁻¹ O₃), (3) elevated O₃ (350 and 360 μl l⁻¹ CO₂; 49 and 49 nl l⁻¹ O₃), and (4) elevated CO₂ and O₃ (545 and 542 μl l⁻¹; 49 and 49 nl l⁻¹), respectively. Average temperature and relative humidity for the same time periods were: (1) control (23.5 and 24.6 °C; 84 and 85% rh), (2) elevated CO₂ (23.9 and 23.2 °C; 82 and 83% rh), (3) elevated O₃ (23.3 and 24.2 °C; 84 and 84% rh), and (4) elevated CO₂ and O₃ (23.2 and 24.0 °C; 84 and 84% rh). Average precipitation levels for May–August 2000 and 2002 were 124 and 98 mm month⁻¹, respectively.

Due to the differential growth responses of overstory tree species to the trace gasses, light levels reaching the forest understory differed in response to gas treatments. Average maximum photosynthetic active radiation (PAR) levels, measured 2 m from the forest floor, were for 2000 and 2002: (1) control (1.97 and 1.83), (2) elevated CO₂ (1.42 and 1.04), (3) elevated O₃ (1.83 and 1.78), and (4) elevated CO₂ and O₃ (2.12 and 1.84), in mmol m⁻² s⁻¹.

2.2. Effects of elevated CO₂ and/or O₃ on natural clover colonization and establishment

To determine whether atmospheric composition alters natural colonization and establishment patterns of forest understory plants, numbers of red and white clover plants were surveyed in the aspen–maple section of each FACE ring in 2000 and 2002. Red and white clovers are appropriate representative species, as they are some of the most abundant dicotyledonous plants in the Aspen FACE understory (C.S. Awmack and R.L. Lindroth, unpublished data). In 2000, we recorded the number of red and white clover plants growing in each of four randomly placed 1 m × 1 m quadrats in the aspen–maple quadrant of each ring. In 2002, clover and other understory plant densities were much higher (C.S. Awmack, unpublished data) and we used only three randomly placed quadrats per ring.

2.3. Effects of elevated CO₂ and/or O₃ on red clover intraspecific performance

To better understand the natural colonization and establishment patterns of red clover in the FACE rings, in 2002 we investigated the performance of nine red clover cultivars commonly grown in the northern plains of the United States (Marathon, Arlington, Juliet, BY 222, HC 82, C 328, Reddy, Cinnamon, and Red Star) to enriched CO₂ and/or O₃ atmospheres. Red clover plants were initially grown from seed in standard potting medium (Scotts Metromix) in a greenhouse at ambient CO₂ and O₃ with daily watering. After 23 days, seedlings were individually transplanted into 1 l pots containing local topsoil (Mussons Brothers, Rhinelander, WI, USA). Plants were maintained in the greenhouse for an additional 20 days, until they were ca. 10 cm tall, whereupon they were distributed to the aspen–maple section of each FACE ring. Upon placement in the FACE rings, plants were only exposed to natural precipitation. Four plants of each cultivar were randomly allocated to each ring (*n* = 36 total

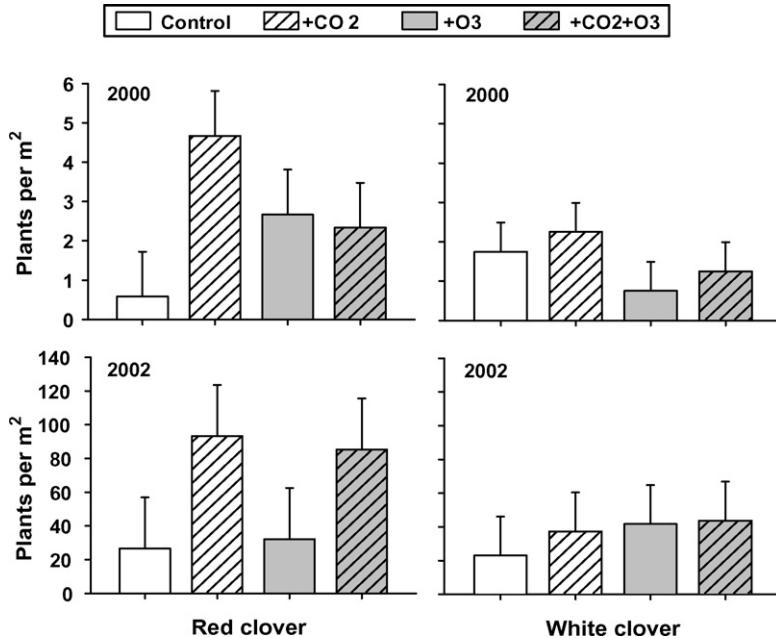


Fig. 1. Effects of CO₂ and/or O₃ on naturally occurring red and white clover plant populations, in the aspen–maple section of FACE rings. Data are means (+1S.E.) of three replicate FACE rings (year 2000, four samples per plot; year 2002, three samples per plot; $n = 12$ and 9, respectively). Note the difference in the scale of the y-axis between 2000 and 2002.

plants per ring). Plants were individually covered with a fine mesh sleeve, to prevent insect colonization. Three weeks later, after plants had grown substantially since initial out-planting, above- and below-ground plant biomass was harvested, root tissues were washed, and all plant material was freeze-dried. Shoot and root dry weights were assessed, the numbers of *Rhizobium* spp. containing root nodules on each plant were counted, and nitrogen concentrations of above-ground plant tissues were measured using a LECO FP528 nitrogen analyzer.

2.4. Statistical analyses

To determine whether atmospheric composition influenced the natural patterns of red and white clover colonization and establishment, data were analyzed using randomized block, two-way ANOVAs. As the number of quadrats differed between years, a separate analysis was conducted for each clover species in each year (SAS; Littell et al., 1996). As the Aspen FACE experiment is set up as a 2×2 factorial, main effects were: CO₂ (ambient versus elevated) and O₃ (ambient versus elevated). FACE ring block (1–3) was incorporated into the analysis as a random effect. The dependent variable, number of clover plants m⁻², was transformed ($x' = \log_{10}[x]$) to normalize the variance prior to analysis (Zar, 1984).

Intraspecific differences in red clover performance were evaluated with split-plot ANOVAs, using Proc Mixed (SAS; Littell et al., 1996). Whole-plot fixed effects were CO₂ (ambient versus elevated) and O₃ (ambient versus elevated), while ring block (1–3) was incorporated as a random effect. Sub-plot effects consisted of clover cultivar (1–9) and all second and third order interactions between CO₂, O₃, and clover cultivar. Dependent variables were shoot and root dry weights, numbers of root nod-

ules, and shoot nitrogen concentrations. Nitrogen concentrations were transformed ($x' = \arcsine \sqrt{x}$) to achieve normality prior to analysis (Zar, 1984).

3. Results

3.1. Effects of elevated CO₂ and/or O₃ on natural clover colonization and establishment

Red and white clover populations exhibited differential responses to elevated CO₂ (Fig. 1 and Table 1). In 2000, red clover populations were larger in enriched CO₂ atmospheres, whereas white clover populations showed no response. By 2002, the abundance of red and white clover plants in all the treatments had substantially increased, as had the magnitude of the positive

Table 1
Analyses of variance showing the effects of CO₂ and/or O₃ on the natural abundance of red and white clover in FACE rings

	Red clover		White clover	
	F _{1, 6} *	P	F _{1, 6}	P
Year 2000				
CO ₂	6.63	0.05	0.37	0.57
O ₃	0.37	0.57	0.30	0.56
CO ₂ × O ₃	2.39	0.18	0.48	0.52
Year 2002				
CO ₂	8.37	0.03	1.21	0.31
O ₃	0.21	0.66	0.04	0.86
CO ₂ × O ₃	2.12	0.20	0.21	0.67

* Subscripts indicate degrees of freedom for each analysis.

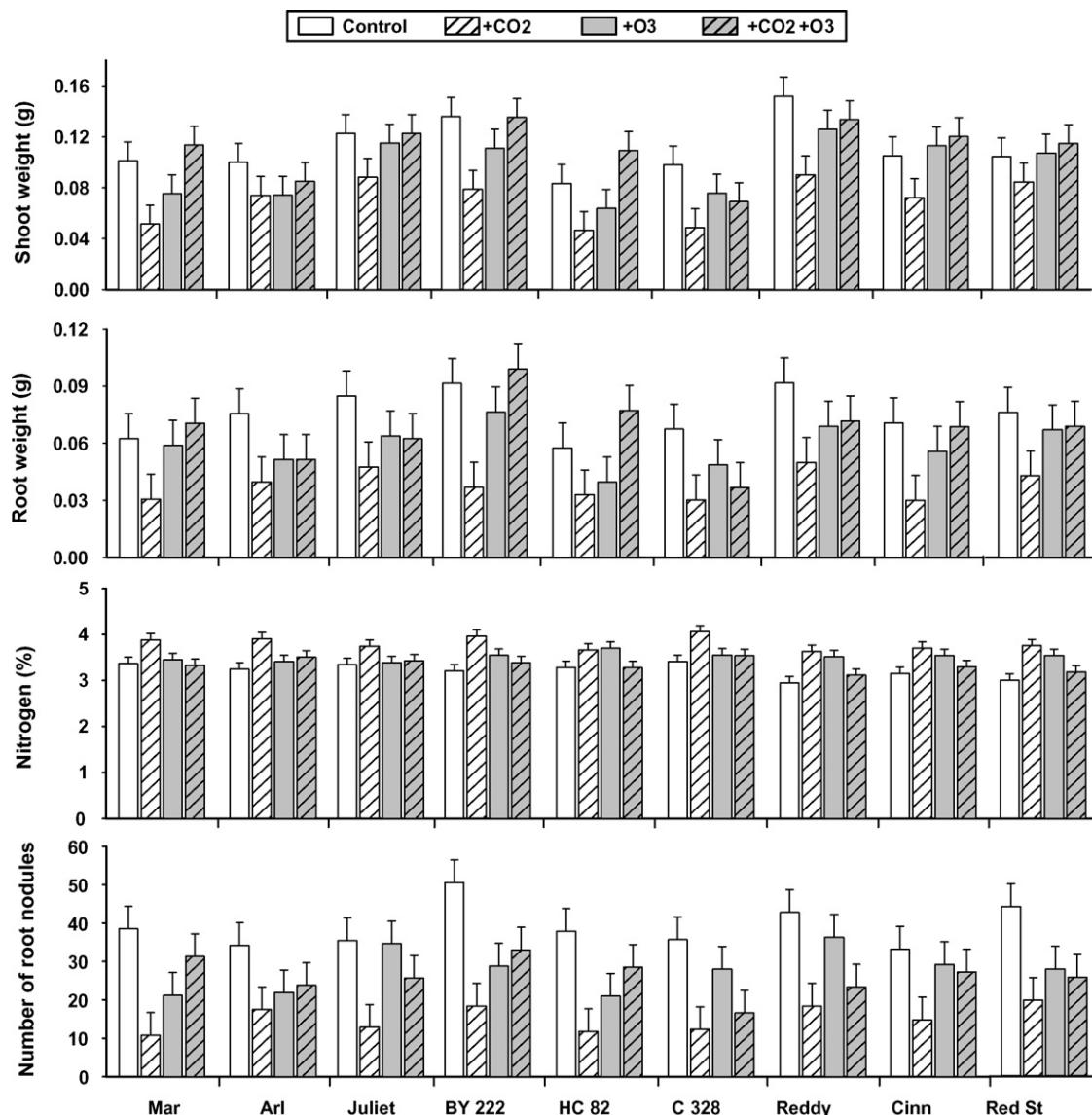


Fig. 2. Effects of CO₂ and/or O₃ on shoot biomass (dry weight), root biomass (dry weight), nitrogen (percent dry weight), and number of root nodules of nine red clover cultivars grown in the aspen–maple section of FACE rings. Data are means (+1S.E.) of three replicate FACE rings (four plants of each of nine cultivars per ring; $n=432$ total). For clover varieties: Mar, Marathon; Arl, Arlington; Cinn, Cinnamon; Red St, Red Star.

effects of elevated CO₂ on red clover abundance. Enriched O₃ atmospheres had no effect on red or white clover abundance in either year, and the lack of any significant interaction between CO₂ and O₃ suggests that elevated CO₂ did not modify plant

responses to elevated O₃. These results demonstrate that changing atmospheric conditions have the potential to alter natural colonization and establishment patterns of common understory plant populations.

Table 2

Analyses of variance showing the effects of CO₂, O₃, and/or plant cultivar on red clover plant performance in FACE rings

Treatment	Shoot dry weight		Root dry weight		Shoot nitrogen		Root nodules	
	F	P	F	P	F	P	F	P
CO ₂ (1, 6)*	2.62	0.16	2.51	0.16	5.76	0.05	14.43	< 0.01
O ₃ (1, 6)	2.61	0.16	0.52	0.50	0.99	0.36	0.01	0.94
CO ₂ × O ₃ (1, 6)	13.24	0.01	6.28	0.05	19.70	< 0.01	11.19	0.02
Cultivar(8, 376)	8.60	< 0.001	4.40	< 0.001	3.08	< 0.01	1.81	0.07
CO ₂ × cultivar(8, 376)	0.66	0.75	0.94	0.48	1.09	0.37	0.75	0.65
O ₃ × cultivar(8, 376)	0.74	0.65	1.44	0.18	0.71	0.68	0.61	0.77
CO ₂ × O ₃ × cultivar(8, 376)	0.83	0.57	0.78	0.62	1.18	0.31	1.32	0.23

* Subscripts indicate degrees of freedom for each analysis.

3.2. Effects of elevated CO₂ and/or O₃ on red clover intraspecific performance

Potted red clover plants grew ca. three-fold while in the FACE rings, sufficient to detect any but the most subtle effects of CO₂ or O₃ on plant performance. Red clover cultivars exhibited few significant responses to the main effects of CO₂ and O₃, but responded strongly to the interaction of the two fumigation treatments (Fig. 2 and Table 2). Elevated CO₂ atmospheres markedly reduced both shoot and root weights under ambient O₃, but increased weights when O₃ was also elevated (Fig. 2). Cultivars exhibited similar responses to CO₂ and O₃ in terms of plant quality (shoot nitrogen content) and root nodule formation. Enriched CO₂ atmospheres increased nitrogen concentrations and reduced root nodulation under ambient O₃, but had opposite or no effects under +CO₂ + O₃. While the nine cultivars exhibited a large degree of intraspecific variation in the magnitude of shoot growth responses, root growth responses, and nitrogen concentrations, they all responded similarly to altered atmospheric conditions (i.e., no significant CO₂ × cultivar, O₃ × cultivar, or CO₂ × O₃ × cultivar interactions). Thus, enriched CO₂ and O₃ atmospheres had modest to large effects on red clover growth patterns and plant quality, although little intraspecific variation was observed.

4. Discussion

Altered atmospheric conditions can influence community composition, such as the relative abundances of invasive C₃ and C₄ understory plants (Belote et al., 2004). Here, we have shown that atmospheric conditions can differentially influence the colonization and establishment of even closely related, naturalized understory plant taxa. In our assessment of red and white clover populations at Aspen FACE, interspecific variation in response to atmospheric composition was readily apparent. Natural populations of red clover were much more abundant in enriched CO₂ atmospheres and became even more plentiful over time. A sympatric species, white clover, however, did not exhibit changes in colonization and establishment in response to altered atmospheric conditions. Thus, elevated CO₂ atmospheres have the potential to alter the composition of forest understory plant communities.

Colonization and establishment patterns of red and white clover likely express differences in competitive ability between the two species. Greater red clover population sizes in +CO₂ rings at Aspen FACE may reflect changes in vegetative (clonal) growth patterns or increased survivorship. As red clover flower production generally decreases in elevated CO₂ atmospheres (Rusterholz and Erhardt, 1998), the increased abundance in enriched CO₂ conditions is likely not due to increased seed production. White clover, on the other hand, may not exhibit population increases in response to elevated CO₂ atmospheres because of nutrient constraints (Kemp and Blair, 1991; Niklaus et al., 1998). Nutrient limitation may render white clover unable to assimilate increased levels of CO₂ for increased vegetative growth. White clover seed production and tiller number are also

generally unaffected by elevated CO₂ (Clark et al., 1997; Wagner et al., 2001), correlating well with our results.

Augmented levels of tropospheric O₃ did not affect the abundance of naturally colonizing red or white clover plants. This result is surprising, as both species may be adversely affected by elevated O₃ (Leuthy-Krause et al., 1989; Heagle et al., 1991). Heagle et al. (1991) showed that exposure of natural clover populations to elevated O₃ atmospheres resulted in a rapid (within 2 years) increase in the proportion of O₃-tolerant genotypes. Thus, elevated O₃ atmospheres at the Aspen FACE site may have already eliminated O₃-sensitive genotypes by the time this study was conducted. Analogous changes in the relative fitness of O₃-sensitive and O₃-tolerant aspen genotypes were observed within the first several years at Aspen FACE (McDonald et al., 2002).

With respect to intraspecific variation, red clover cultivars expressed similar, but counterintuitive, growth responses to CO₂ and O₃. Red clover, like other plants, generally increases in biomass under elevated CO₂ conditions (Heagle et al., 1993; Saebo and Mortensen, 1995) although not invariably so (Leadley et al., 1999). Surprisingly, red clover grown at Aspen FACE in the +CO₂ treatment had lower root and shoot biomasses than plants grown under ambient conditions. This is not a unique response, however, as other plants growing in the understory of Aspen FACE show similar reductions in biomass under elevated CO₂ (E.B. Mondor, unpublished data). Elevated CO₂ atmospheres, at ambient ozone, were also associated with an increase in tissue nitrogen concentrations and a decrease in root nodule numbers. The tissue nitrogen response was also contrary to expectation, as enriched CO₂ atmospheres reduce shoot nitrogen concentrations in most plant species (Curtis, 1996; Bezemer and Jones, 1998). Plant growth trajectories under enriched O₃ atmospheres were similarly enigmatic. In general, increased O₃ levels adversely affect red clover performance (Leuthy-Krause et al., 1989; Mortensen, 1992). Conversely, we found little direct effect of O₃ on red clover growth.

Why, then, did our experimental red clover populations exhibit decreased shoot and root biomasses, increased nitrogen concentrations, and decreased *Rhizobium* root nodules in response to enriched CO₂ atmospheres? As even small reductions in light can substantially reduce, or even reverse, the benefits of increased CO₂ obtained by some understory tree seedlings (Hättenschwiler and Körner, 2000), we suggest that the atypical growth responses of our experimental clover populations also resulted from altered light levels. Maple, and especially aspen, trees at Aspen FACE have exhibited remarkable growth increases since project initiation in 1998 (Isebrands et al., 2001; Percy et al., 2002; Karnosky et al., 2003). These growth responses have been substantially influenced by atmospheric composition, as trees in the +CO₂ treatments are taller, have a larger volume index (D^2H), and leaf area index (LAI) relative to both ambient, and +O₃ conditions (Isebrands et al., 2001; Percy et al., 2002; Karnosky et al., 2003, 2005). As a result of increased LAI under +CO₂ conditions, levels of photosynthetic active radiation reaching the understory are much less than those of the control, +O₃, or +CO₂ + O₃ treatments.

Thus, rapid growth of overstory tree species has created different selective pressures on understory plant populations, over time. For instance, natural clover populations were first assessed in 2000 when aspen and maple tree canopies were more open, allowing higher light levels to reach the forest understory. Two years later, during the second census and also when our experimental (potted) clover was grown, trees were much larger and canopies were more fully developed. Consequently, natural red clover populations may not have been adversely affected by the decreasing light levels in +CO₂ conditions, as the plants had already colonized the area and become well-established. Furthermore, as marked changes in light availability occurred over several years, selection for red clover genotypes that exhibit optimal growth responses under these conditions may have occurred (e.g., Heagle et al., 1991). Performance of our experimental populations, however, was assessed when light levels were already greatly reduced. With only nine genotypes and no time for selection to occur, these red clover plants may have been more strongly influenced by the reduced light levels than by the growth-enhancing effects of CO₂. The indirect effect of CO₂, mediated through forest overstory growth, is the most parsimonious explanation as to why plants under +CO₂ atmospheres were smaller than, while plants growing under +O₃ atmospheres were in many instances as large as, those growing under ambient conditions. Decreased light levels would also explain why clover plants in +CO₂ environments, compared to ambient conditions, had higher foliar nitrogen concentrations, i.e., a typical shade response (McDonald et al., 1999). This does not preclude, however, the likely possibility of complex interactions between gas treatments and light levels.

In conclusion, this research demonstrates that forest understory communities are likely to change in response to both direct and indirect effects of atmospheric composition. Such changes in community composition may modify a wide range of ecological processes (e.g., trophic interactions and litter decomposition), in turn altering forest ecosystem dynamics.

Acknowledgements

Aspen FACE is principally supported by the Office of Science (BER), U.S. Department of Energy, grant no. DE-FG02-95ER62125 to Michigan Technological University, and contract no. DE-AC02-98CH10886 to Brookhaven National Laboratory, the U.S. Forest Service Northern Global Change Program and North Central Research Station, Michigan Technological University, and Natural Resources Canada—Canadian Forest Service. We thank A. Weldon and H. Barnhill for field assistance, L. Riel for laboratory assistance, M. Krakau for computer assistance, and J. Sober for FACE site maintenance. D Undersander and K.G. Silveira in the UW Department of Agronomy supplied the clover seed. Valuable statistical advice was provided by R. Nordheim and P. Crump. This work was funded by the U.S. National Science Foundation (grants DEB-9707263 and DEB-0129123), U.S. Department of Energy (grant DE-FG02-98ER62680), and University of Wisconsin (McIntire-Stennis grant).

References

- Andalo, C., Goldringer, I., Godelle, B., 2001. Inter- and intragenotypic competition under elevated carbon dioxide in *Arabidopsis thaliana*. *Ecology* 82, 157–164.
- Bazzaz, F.A., Jasinski, M., Thomas, S.C., Wayne, P., 1995. Microevolutionary responses in experimental populations of plants to CO₂-enriched environments: parallel results from two model systems. *Proc. Natl. Acad. Sci. U.S.A.* 92, 8161–8165.
- Belote, R.T., Weltzin, J.F., Norby, R.J., 2004. Response of an understory plant community to elevated [CO₂] depends on differential responses of dominant invasive species and is mediated by soil water availability. *New Phytol.* 161, 827–835.
- Bezemer, T.M., Jones, T.H., 1998. Plant–insect herbivore interactions in elevated atmospheric CO₂: quantitative analyses and guild effects. *Oikos* 82, 212–222.
- Castells, E., Roumet, C., Penuelas, J., Roy, J., 2002. Intraspecific variability of phenolic concentrations and their responses to elevated CO₂ in two Mediterranean perennial grasses. *Environ. Exp. Bot.* 47, 205–216.
- Clark, H., Newton, P.C.D., Bell, C.C., Glasgow, E.M., 1997. Dry matter yield, leaf growth and population dynamics in *Lolium perenne*/*Trifolium repens*-dominated pasture turfs exposed to two levels of elevated CO₂. *J. Appl. Ecol.* 34, 304–316.
- Curtis, P.S., 1996. A meta-analysis of leaf gas exchange and nitrogen in trees grown under elevated carbon dioxide. *Plant Cell Environ.* 19, 127–137.
- Curtis, P.S., Snow, A.A., Miller, A.S., 1994. Genotype-specific effects of elevated CO₂ on fecundity in wild radish (*Raphanus raphanistrum*). *Oecologia* 97, 100–105.
- Curtis, P.S., Klus, D.J., Kalisz, S., Tonsor, S.J., 1996. Intraspecific variation in CO₂ responses in *Raphanus raphanistrum* and *Plantago lanceolata*: assessing the potential for evolutionary change with rising atmospheric CO₂. In: Körner, C., Bazzaz, F.A. (Eds.), Carbon dioxide, Populations, and Communities. Academic Press, San Diego, pp. 13–22.
- Davison, A.W., Reiling, K., 1995. A rapid change in ozone resistance of *Plantago major* after summers with high ozone concentrations. *New Phytol.* 131, 337–344.
- DeLucia, E.H., Hamilton, J.G., Naidu, S.L., Thomas, R.B., Andrews, J.A., Finzi, A., Lavine, M., Matamala, R., Mohan, J.E., Hendrey, G.R., Schlesinger, W.H., 1999. Net primary production of a forest ecosystem with experimental CO₂ enrichment. *Science* 284, 1177–1179.
- Dickson, R.E., Coleman, M.D., Riemschneider, D.E., Isebrands, J.G., Hogan, G.D., Karnosky, D.F., 1998. Growth of five hybrid poplar genotypes exposed to interacting elevated CO₂ and O₃. *Can. J. Forest Res.* 28, 1706–1716.
- Dickson, R.E., Lewin, K.F., Isebrands, J.G., Coleman, M.D., Heilman, W.E., Riemschneider, D.E., Sober, J., Host, G.E., Zak, D.R., Hendrey, G.R., Pregitzer, K.S., Karnosky, D.F., 2000. Forest atmosphere carbon transfer storage-II (FACTS II)—the aspen free-air CO₂ and O₃ enrichment (FACE) project: an overview. USDA Forest Service North Central Research Station General Tech. Rep. NC-214.
- Donnelly, A., Jones, M.B., Burke, J.I., Schnieders, B., 2000. Elevated CO₂ provides protection from O₃ induced photosynthetic damage and chlorophyll loss in flag leaves of spring wheat (*Triticum aestivum* L., cv. ‘Minaret’). *Agric. Ecosyst. Environ.* 80, 159–168.
- Foy, C.D., Lee, E.H., Rowland, R.A., Devine, T.E., 1995. Ozone tolerance of soybean cultivars and near-isogenic lines in a fumigation chamber. *J. Plant Nutr.* 18, 649–667.
- Goverde, M., Arnone, J.A., Erhardt, A., 2002. Species-specific reactions to elevated CO₂ and nutrient availability in four grass species. *Basic Appl. Ecol.* 3, 221–227.
- Hamilton, J.G., Zangerl, A.R., Berenbaum, M.R., Pippen, J., Aldea, M., DeLucia, E.H., 2004. Insect herbivory in an intact forest understory under experimental CO₂ enrichment. *Oecologia* 138, 566–573.
- Hättenschwiler, S., Körner, C., 2000. Tree seedling responses to in situ CO₂-enrichment differ among species and depend on understory light availability. *Global Change Biol.* 6, 213–226.

- Heagle, A.S., McLaughlin, M.R., Miller, J.E., Joyner, R.L., Spruill, S.E., 1991. Adaptation of a white clover population to ozone stress. *New Phytol.* 119, 61–68.
- Heagle, A.S., Miller, J.E., Sherrill, D.E., Rawlings, J.O., 1993. Effects of ozone and carbon dioxide mixtures on two clones of white clover. *New Phytol.* 123, 751–762.
- Heagle, A.S., Miller, J.E., Pursley, W.A., 1998. Influence of ozone stress on soybean response to carbon dioxide enrichment: III. Yield and seed quality. *Crop Sci.* 38, 128–134.
- IPCC, 2001. Climate Change 2001: The Scientific Basis. Report of working group I of the intergovernmental panel on climate change. IPCC Secretariat, Geneva.
- Isebrands, J.G., McDonald, E.P., Kruger, E., Hendrey, G., Pregitzer, K., Percy, K., Sober, J., Karnosky, D.F., 2001. Growth responses of *Populus tremuloides* clones to interacting elevated carbon dioxide and tropospheric ozone. *Environ. Pollut.* 115, 359–371.
- Karnosky, D.F., Zak, D.R., Pretziger, K.S., Awmack, C.S., Bockheim, J.G., Dickson, R.E., Hendrey, G.R., Host, G.E., King, J.S., Kopper, B.J., Kruger, E.L., Kubiske, M.E., Lindroth, R.L., Mattson, W.J., McDonald, E.P., Noormets, A., Oksanen, E., Parsons, W.F.J., Percy, K.E., Podila, G.K., Riemschneider, D.E., Sharma, P., Thakur, R., Sober, A., Sober, J., Jones, W.S., Anttonen, S., Vapaavuori, E., Mankovska, B., Heilman, W., Isebrands, J.G., 2003. Tropospheric O₃ moderates responses of temperate hardwood forests to elevated CO₂: a synthesis of molecular to ecosystem results from the Aspen FACE project. *Funct. Ecol.* 17, 289–304.
- Karnosky, D.F., Pregitzer, K.S., Zak, D.R., Kubiske, M.E., Hendrey, G.R., Weinstein, D., Nosal, M., Percy, K.E., 2005. Scaling ozone responses of forest trees to the ecosystem level in a changing climate. *Plant Cell Environ.* 28, 965–981.
- Kemp, P.D., Blair, G.J., 1991. Phosphorus efficiency in pasture species. VI. A comparison of Italian ryegrass, phalaris, red clover and white clover over time. *Aust. J. Agric. Res.* 42, 541–558.
- Kimball, B.A., LaMorte, R.L., Pinter Jr., P.J., Wall, G.W., Hunsaker, D.J., Adamsen, F.J., Leavitt, S.W., Thompson, T.L., Matthias, A.D., Brooks, T.J., 1999. Free-air CO₂ enrichment and soil nitrogen effects on energy balance and evapotranspiration of wheat. *Water Resour. Res.* 35, 1179–1190.
- Kimball, B.A., Kobayashi, K., Bindl, M., 2002. Responses of agricultural crops to free-air CO₂ enrichment. *Adv. Agron.* 77, 293–368.
- Krupa, S., McGrath, M.T., Andersen, C.P., Booker, F.L., Burkey, K.O., Chappelka, A.H., Chevone, B.I., Pell, E.J., Zilinskas, B.A., 2001. Ambient ozone and plant health. *Plant Dis.* 85, 4–12.
- Leadley, P.W., Niklaus, P.A., Stocker, R., Körner, C., 1999. A field study of the effects of elevated CO₂ on plant biomass and community structure in a calcareous grassland. *Oecologia* 118, 39–49.
- Leuthy-Krause, B., Bleuler, P., Landolt, W., 1989. Black poplar and red clover as bioindicators for ozone at a forest site. *Angew. Bot.* 63, 111–118.
- Lincoln, R., Boxshall, G., Clark, P., 1998. A Dictionary of Ecology, Evolution and Systematics, second ed. Cambridge University Press, Cambridge.
- Lindroth, R.L., Roth, S., Nordheim, E.V., 2001. Genotypic variation in response of quaking aspen (*Populus tremuloides*) to atmospheric CO₂ enrichment. *Oecologia* 126, 371–379.
- Littell, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D., 1996. SAS System for Mixed Models. SAS Institute, Cary, NC.
- Makino, A., Mae, T., 1999. Photosynthesis and plant growth at elevated levels of CO₂. *Plant Cell Physiol.* 40, 999–1006.
- Mauney, J.R., Lewin, K.F., Hendrey, G.R., Kimball, B.A., 1992. Growth and yield of cotton exposed to free-air CO₂ enrichment (FACE). *Crit. Rev. Plant Sci.* 11, 213–222.
- McDonald, E.P., Agrell, J., Lindroth, R.L., 1999. CO₂ and light effects on deciduous trees: growth, foliar chemistry, and insect performance. *Oecologia* 119, 389–399.
- McDonald, E.P., Kruger, E.L., Riemenschneider, D.E., Isebrands, J.G., 2002. Competitive status influences tree-growth responses to elevated CO₂ and O₃ in aggrading aspen stands. *Funct. Ecol.* 16, 792–801.
- Mortensen, L.M., 1992. Effects of ozone on growth of seven grass and one clover species. *Acta Agric. Scand. B—Soil Plant Sci.* 42, 235–239.
- Niklaus, P.A., Leadley, P.W., Stocklin, J., Körner, C., 1998. Nutrient relations in calcareous grassland under elevated CO₂. *Oecologia* 116, 67–75.
- Pell, E.J., Sinn, J.P., Eckardt, N., Vinten-Johansen, C., Winner, W.E., Mooney, H.A., 1992. Response of radish to multiple stresses: II. Influence of season and genotype on plant response to ozone and soil moisture deficit. *New Phytol.* 123, 153–163.
- Percy, K.E., Awmack, C.S., Lindroth, R.L., Kubiske, M.E., Kopper, B.J., Isebrands, J.G., Pregitzer, K.S., Hendrey, G.R., Dickson, R.E., Zak, D.R., Oksanen, E., Sober, J., Harrington, R., Karnosky, D.F., 2002. Altered performance of forest pests under atmospheres enriched by CO₂ and O₃. *Nature* 420, 403–407.
- Poorter, H., Navas, M.-L., 2003. Plant growth and competition at elevated CO₂: on winners, losers, and functional groups. *New Phytol.* 157, 175–198.
- Reichenauer, T.G., Goodman, B.A., Kostecki, P., Soja, G., 1998. Ozone sensitivity in *Triticum durum* and *T. aestivum* with respect to leaf injury, photosynthetic activity and free radical content. *Physiol. Plantarum* 104, 681–686.
- Rusterholz, H.P., Erhardt, A., 1998. Effects of elevated CO₂ on flowering phenology and nectar production of nectar plants important for butterflies of calcareous grasslands. *Oecologia* 113, 341–349.
- Saebo, A., Mortensen, L.M., 1995. Growth and regrowth of *Phleum pratense*, *Lolium perenne*, *Trifolium repens* and *Trifolium pratense* at normal and elevated CO₂ concentration. *Agric. Ecosyst. Environ.* 55, 29–35.
- Van der Kooij, T.A.W., De Kok, L.J., Stulen, I., 2000. Intraspecific variation in the response of *Arabidopsis thaliana* lines to elevated atmospheric CO₂. *Phyton* 40, 125–132.
- Wagner, J., Luscher, A., Hillebrand, C., Kobald, B., Spitaler, N., Larcher, W., 2001. Sexual reproduction of *Lolium perenne* L. and *Trifolium repens* L. under free air CO₂ enrichment (FACE) at two levels of nitrogen application. *Plant Cell Environ.* 24, 957–965.
- Zar, J.H., 1984. Biostatistical Analysis, second ed. Prentice-Hall, Englewood Cliffs, NJ.