Burning coal seams in southern Utah: a natural system for studies of plant responses to elevated CO_2

J. R. EHLERINGER, D. R. SANDQUIST AND S. L. PHILIPS

*Stable Isotope Ratio Facility for Environmental Research,
Department of Biology, University of Utah, Salt Lake City, Utah 84112,
USA.*

SUMMARY

In the Burning Hills and Smoky Mountains of southern Utah (USA), coal deposits exposed to the surface have been ignited by lightning and have been burning for periods of years to over a century. We examined one of these sites, where the below-ground combustion of this low-sulfur coal releases gases to the atmosphere from vents above the burning seam. The surrounding vegetation is cold-desert shrub, typical of the region and consisted of both C_3 and C_4 perennial species.

Additionally, at least one weedy C_4 species had invaded disturbed locations immediately adjacent to the active vent area. Atmospheric CO_2 concentrations in the vicinity of the vents fluctuated significantly, however, CO_2 concentrations measured approximately 500 m from the most active vents were 7 ppm elevated above ambient concentrations measured at a control site 10 km from the burning vents. CO_2 concentrations at sites nearer the vents, but still with natural, undisturbed vegetation, were elevated 65 ppm above ambient background values. At vegetated sites nearest the vents, CO_2 concentrations were elevated by an average of 542 ppm above ambient values.

The continuous distribution of C_4 vegetation along the CO_2 concentration gradient provides a means of estimating the long-term integrated CO_2 concentrations at each location. Using the carbon isotope ratio of the C_4 vegetation (*Atriplex confertifolia* and *Salsola iberica*) to estimate the atmospheric CO_2 concentration, we observed that the ratio of intercellular to atmospheric CO_2 concentrations of C_3 vegetation decreased in response to elevated CO_2 concentrations. This decreased ratio for *Gutierrezia sarothrae* (C_3) was sufficient to result in a predicted doubling of water-use efficiency.

INTRODUCTION

Doelling & Graham (1972) described extensive coal deposits in southern Utah, which underlie existing sandstone but which frequently outcrop at the surface. Occasionally the coal deposits at the surface are ignited by lightning, resulting in underground fires. In the Burning Hills and Smoky Mountains of southern Utah, a number of these fires have been burning for many years, releasing CO_2 and other gases into the atmosphere. The plant communities surrounding these coal vents are cold-desert vegetation, consisting of both C_3 and C_4 shrub and perennial herb species (Caldwell, 1985; West, 1988; Comstock & Ehleringer, 1992). Gleason & Kyser (1984) reported that the carbon isotope ratio ($\delta^{13}C$) of CO_2 released from one of the burning coal sites was -32.5 ‰, which is significantly more negative than atmospheric values which tend to be near -8 ‰. For the vent system they investigated, the CO_2 released from this combustion had the potential for impacting the $\delta^{13}C$ values of vegetation at distances of up to 700-800 m from the vents. Our objective was to quantify the CO_2 concentrations and evaluate through stable isotope analyses the potential of these vent sites as natural field experiments for studying the influence of elevated atmospheric CO_2 conditions on growth of desert vegetation.

Carbon isotope ratios in C_3 plants are influenced by the isotope ratio of the source air, fractionation steps between the bulk atmosphere CO_2 and the initial photosynthetic reaction by RuBP carboxylase (Rubisco), and by the drop in CO_2 concentration between the air and the intercellular spaces within the leaf. The factors influencing C_3 leaf carbon isotope ratios can be described as

$$\delta^{13}C_{plant} = \delta^{13}C_{air} - a - (b_3 - a)c_i/c_a, \qquad [1]$$

where $\delta^{13}C_{plant}$ is the carbon isotope ratio (‰ relative to the PDB standard) of the plant sample, $\delta^{13}C_{air}$ is the carbon isotope ratio of CO_2 in the atmosphere (typically -8 ‰ in a non-enriched atmosphere), a is the fractionation associated with the slower diffusion of $^{13}CO_2$ air (4.4 ‰), and b_3 is the net fractionation associated with Rubisco (27 ‰), and c_a and c_i are the atmospheric and intercellular CO_2 concentrations, respectively

(Farquhar, O'Leary & Berry, 1982). Together the terms $(-a - (b_3 - a)c_i/c_a)$ are the discrimination (Δ) against ^{13}C by the leaf and represent the change in ^{13}C content between the atmosphere and fixed carbon in the leaf.

In C_4 plants, the initial carboxylation is by PEP carboxylase (PEPC), which discriminates much less than RuBP carboxylase (Rubisco), and the c_i/c_a ratio remains nearly constant because of high PEPC activity. Farquhar (1983) modeled the carbon isotope ratio of C_4 plants as

$$\delta^{13}C_{plant} = \delta^{13}C_{air} - a - (b_4 - b_3 f - a) \, c_i/c_a \qquad [2]$$

where b_4 is the net fractionation associated with PEP carboxylation (-5.7 ‰) and f is the bundle sheath leakiness, or the proportion of carbon fixed by PEPC that subsequently leaks out of the bundle sheath thereby allowing limited expression of Rubisco discrimination (b_3). The leakiness may also be thought of as a measure of "overcycling" by PEPC that occurs in the mesophyll cells, raising c_i in the bundle sheath cells (Farquhar, 1983). The sum $(b_4 - b_3 f - a)$ is a small number, further reduced by its product with the c_i/c_a ratio. As a consequence, $\delta^{13}C$ values of C_4 plants reflect the $\delta^{13}C$ of air with limited physiological influences.

Given this, it is likely that, at least within a species, the $\delta^{13}C_{plant}$ value of C_4 plants can be used to estimate $\delta^{13}C_{air}$ if we assume that other parameters in Eqn. 2 are constant. Evans et al. (1986) and Henderson, von Caemmerer & Farquhar (1992) provided initial evidence in support of this assumption. Marino & McElroy (1991) and Marino et al. (1992) have adopted this approach and used it to estimate $\delta^{13}C_{air}$ over historical time periods, although it is possible that some environmental influences could affect carbon isotope discrimination by C_4 plants (Henderson et al., 1992). There is evidence that soil salinity can influence carbon isotope discrimination by C_4 plants (Walker & Sinclair 1992; Sandquist & Ehleringer, 1994, Leffler, Basha & Ehleringer, 1996), but drought does not appear to have any impact (Leffler et al., 1996).

We examined the carbon isotope variation of C_4 vegetation on nonsaline sites at varying distances from one of the burning coal-seam vent sources to examine the possibility that atmospheric CO_2 concentrations

could be reconstructed from C_4 isotopic values and that these vents might serve as a tool for investigating elevated CO_2 effects on ecophysiological activity of C_3 and C_4 species in this desert community. Atmospheric gases were also analyzed with an infrared gas analyzer to compare with isotopic observations.

MATERIALS AND METHODS

Study site

Field observations were made on an isolated, unnamed peak in the Burning Hills of southern Utah, USA (lat. 37° 16', long. 111° 22', 1750 m elevation). The coal seam on this peak had been burning for an extended period (>25 years) and was very near the site described by Gleason & Kyser (1984). We sampled vegetation at varying distances from a series of coal vents burning at the southern end of this peak; each sampling site was approximately 10 m in diameter.

Along the mountain there were occasional large crevices which emitted CO_2 at apparent lower rates than the large vents. The vegetation was cold desert perennial scrub and was dominated by *Agropyron desertorum* (C_3), *Artemisia tridentata* (C_3), *Atriplex confertifolia* (C_4), *Bromus tectorum* (C_3), *Chrysothamnus viscidiflorus* (C_3), *Coleogyne ramosissima* (C_3), *Elymus elymoides* (C_3), *Ephedra nevadensis* (C_3), *Eurotia lanata* (C_3), *Gutierrezia sarothrae* (C_3), *Juniperus osteosperma* (C_3), *Munroa squarrosa* (C_4), *Oryzopsis hymenoides* (C_3), *Opuntia* sp. (CAM), *Salsola iberica* (C_4), and *Sphaeralcea* sp. (C_3).

All sites sampled along this transect, except for the last one, consisted of undisturbed vegetation. The last site was nearest the active vents and had the highest CO_2 concentrations; there were obvious indications that this last site had been previously disturbed in the past by land-management attempts to bulldoze the area and extinguish the burning coal.

Atmospheric CO_2 measurements

Atmospheric CO_2 concentrations were measured with an infrared gas analyzer (LI-6200, Licor, Lincoln, NE, USA). At each site, CO_2 was measured every 1 s for 60 s and averaged to derive a single sample value. This sampling was repeated six to nine times per site to get an overall estimate of the mean CO_2 concentration and variability at a site. During the entire sampling period, the wind was moderate (1-3 m s^{-1}) from the south, which is typical of long-term patterns (Gleason & Kyser, 1984).

Carbon isotope composition of dry leaf matter

Leaf samples were taken from five stems on each of five plants per species at a site. The material from individual plants was bulked to form a single composite sample. All samples were oven dried at 85°C for forty-eight hours. The dried leaves were ground with liquid nitrogen to form a fine powder. Approximately 2 mg of powder was loaded onto an elemental analyzer coupled to an isotope ratio mass spectrometer (C. F. Kitty, delta S, Finnigan-MAT, San Jose, CA, USA). Samples were combusted, CO_2 was isolated, and then this gas was introduced into the mass spectrometer for carbon isotope ratio analysis. The carbon isotope ratio was calculated using "delta" notation as

$$\delta = [(R \text{ sample} / R \text{ standard})] \times 1000\,^0/_{00} , \qquad [3]$$

where R is the molar $^{13}C/^{12}C$ ratio of either the sample or standard (PDB). Units are parts per mil (‰). While the instrument has a repeatability of ± 0.02‰, the long-term, overall precision of sampling, combustion, and analysis is ± 0.11‰. The carbon isotope discrimination (Δ) of plant material (Farquhar, Ehleringer & Hubick, 1989) was calculated as

$$\Delta = (\delta^{13} C_{air} - \delta^{13} C_{plant}) / (1 + \delta^{13}C_{plant}), \qquad [4]$$

where $\delta^{13}C_{plant}$ was derived from $\delta^{13}C$ measurements as described above and $\delta^{13}C_{air}$ was derived as described below.

The δ_{air} value was not directly measured, but instead was calculated as a residual by rearranging the terms in Eqn. 2. Marino & McElroy (1991) had capitalized on the near constant photosynthetic fractionation by C_4 plants (all terms influencing $\delta^{13}C_{plant}$, except $\delta^{13}C_{air}$ in Eqn. 2 by measuring $\delta^{13}C_{plant}$ and assuming a constant photosynthetic fractionation; they calculated $\delta^{13}C_{air}$ as a residual. We calculated the $\delta^{13}C_{air}$ value in this manner. The baseline C_4 discrimination value was calculated using the $\delta^{13}C_{plant}$ value measured in a "clean" site 10 km away from the burning coal seam.

RESULTS AND DISCUSSION

There was no active vegetation in the area immediately adjacent to the most active burning coal vents and ambient atmospheric CO_2 concentrations decreased with distance from this location. The vegetation closest to the primary vents was approximately 50 m distant, and the atmospheric CO_2 concentration surrounding this vegetated site averaged 895 ppm. There was substantial variation about this mean CO_2 concentration associated with shifting wind. Overall the atmospheric CO_2 near this vegetation varied $\pm$ 134 ppm (standard error). At nearby undisturbed sites, the atmospheric CO_2 concentrations were lower than 420 ppm and exhibited substantially less variability. Overall, there was a strong positive correlation between the mean CO_2 concentration at a site and the total range of CO_2 concentrations measured with the IRGA ($r = 0.986$, $n = 7$, $P < 0.01$). At the control site 10 km to the north, the atmospheric CO_2 concentration was 352.1 ± 0.6 ppm.

Carbon isotope ratios of the C_4 vegetation varied substantially in association with changes in atmospheric CO_2 concentration (Fig. 1). *Atriplex confertifolia* and *Salsola iberica* were the most common C_4 species along the gradient and exhibited $\delta^{13}C$ values ranging from -20.7 to -12.6 ‰. *Munroa squarrosa* occurred at three of the microsites sampled and its isotopic composition varied from -15.2 to -13.7 ‰ in a manner consistent with the isotopic changes in the other two C_4 species.

In order to calculate atmospheric CO_2 concentrations, the C_4 discrimination value was estimated from Eqn. 2 using the $\delta^{13}C$ values of C_4 plants from a control site 10 km away.

The $\delta^{13}C_{air}$ for each site near the vent was then calculated by subtracting the C_4 discrimination value from the observed $\delta^{13}C_{plant}$ values of the C_4 plants within these sites.

The atmospheric CO_2 concentrations were then calculated from a linear mixing model using the $\delta^{13}C_{air}$, based on C_4 plants, and the bulk atmospheric air based on observations at the control site. The calculated CO_2 concentration compared favorably with IRGA observations at the different sites ($r = 0.797$, $P < 0.05$, Fig. 2).
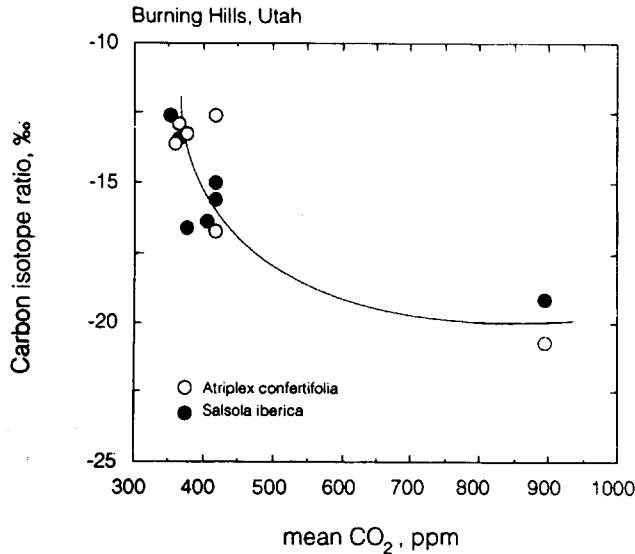

FIG. 1. The carbon isotope ratio of leaves of two C_4 species at different sites near a burning coal vent as a function of the atmospheric CO_2 as measured with an IRGA.

At slightly elevated atmospheric CO_2 concentrations (365-425 ppm), there was very close agreement between predicted and actual CO_2 concentrations. However, at the highest atmospheric concentrations, there was some discrepancy among methods, possibly as a result of turbulence-
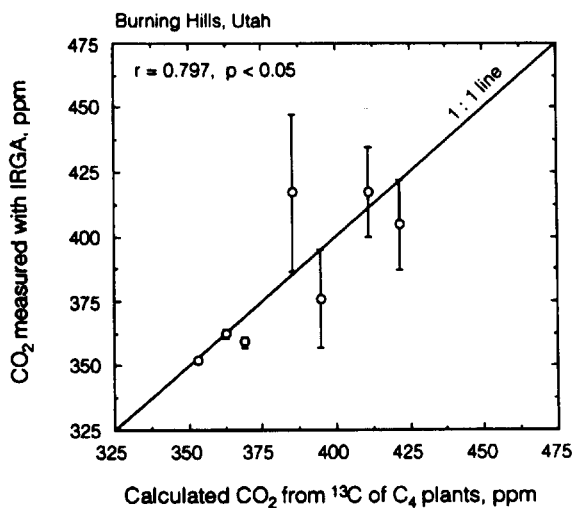
FIG. 2. The correlation between the measured atmospheric CO_2 (IRGA measurements) and the atmospheric CO_2 concentration calculated from the ^{13}C of C_4 plants at this site. Vertical lines indicate the 95 % confidence interval surrounding the IRGA CO_2 measurements.

based variations in the IRGA-measured atmospheric values. On the other hand, a second possibility is that carbon isotope discrimination by C_4 plants had increased at the site with most elevated CO_2 levels as predicted by Farquhar (1983), indicating increased expression of Rubisco discrimination.

Overall the CO_2 concentrations at these locations nearby the burning coal seam were significantly elevated above natural conditions, suggesting that sites in this area might be useful locations for evaluating plant performance under elevated CO_2 levels.

One possible limitation to this system could be complications arising from oxidation of sulfur within the coal seams if baseline sulfur levels were high enough to cause SO_2-induced stomatal closure (Taylor & Pitelka, 1991). Atmospheric SO_2 levels were not directly measured, but from observations in the area, there were no indications of sulfur deposition near the soil surface. The coal seams contained less than 0.8% sulfur and are known to be nearly water saturated (Doelling & Graham, 1972).

It is possible that SO_2 formed during combustion processes was partly

dissolved in deep soil water before these gases could reach the surface, thereby minimizing SO_2 effects. The Burning Hills of southern Utah are distinct from similar burning coal seams in other parts of the world (e.g., arctic Smoking Hills as described by Havas & Hutchinson, 1983) in that the Utah coal seams are substantially lower in sulfur content. While it is not possible to eliminate SO_2 effects from confounding data interpretation, the available evidence suggested that this possible impact would be minimal.

Gutierrezia sarothrae was the only C_3 species distributed continuously along this CO_2 gradient. Leaf carbon isotope discrimination values (Δ) decreased from 20.2 to 13.5 ‰ as atmospheric CO_2 concentrations increased from 352 to 422 ppm (Fig. 3). The changes in the calculated leaf δ values were equivalent to a decrease in the c_i/c_a ratio from 0.70 to 0.40 (Eqn. 1). This change in c_i/c_a ratio was large enough that it should have significant impact on plant gas exchange rates (Farquhar *et al.*, 1989) as well as resulting in a doubling of plant water use efficiency in plants along this gradient (Ehleringer *et al.*, 1992).
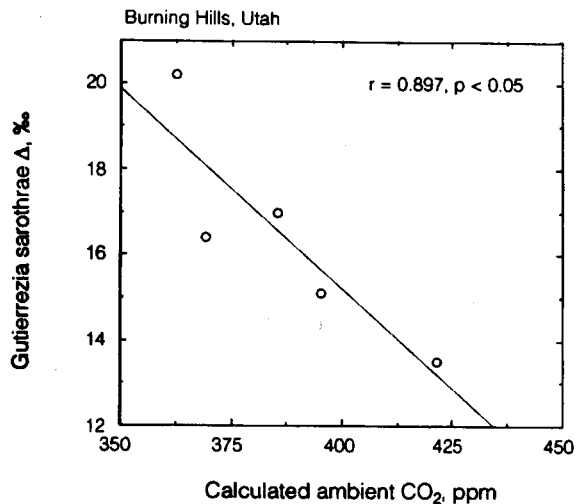

FIG. 3. The relationship between carbon isotope discrimination in *Gutierrezia sarothrae* (a C_3 plant) and atmospheric CO_2 concentration as estimated by the ^{13}C content of surrounding C_4 species at the site.

At the community level, carbon isotope discrimination values decreased as atmospheric CO_2 levels increased. For plants still active at the August sampling period (*Agropyron, Coleogyne, Ephedra, Gutierrezia,* and *Oryzopsis*), leaf δ values were significantly correlated with the CO_2 concentrations at the respective sites. The correlation was highly significant ($r = 0.576$, $P < 0.02$, $n = 18$) despite large differences in the individual values among species.

A reduction in stomatal conductance is typical in leaves of C_3 plants exposed to elevated CO_2 (Cure & Acock, 1986; Bunce, 1993). Such a mechanism could easily account for the observed decreases in the c_i/c_a ratio of *G. sarothrae*. However, some caution may be necessary when interpreting these initial data. These burning coal vents are characterized by an incomplete combustion, resulting in a release of saturated hydrocarbons in addition to CO_2. Using measured vent concentrations from Gleason & Kyser (1984), we calculated that methane and saturated hydrocarbon concentrations at our sampled sites were in the neighborhood of 5 ppm. While we are unaware of any studies indicating that methane and other hydrocarbons at these concentrations have an adverse effect on stomatal activity, direct experimentation is necessary to test the possibility.

The significant decreases in the c_i/c_a ratio among all species as atmospheric CO_2 increased suggests that water-use efficiency will also have increased in these plants. Since soil moisture is the primary climatic factor limiting productivity in aridland ecosystems, any mechanism that decreases the rate of soil moisture extraction might provide a growth advantage to plants, most likely perennials, capable of utilizing the remaining moisture later in the season. While we have no data available yet showing that soil moisture is retained longer in this aridland ecosystem, Field *et al.* (1992) have suggested that in semiarid ecosystems stomatal closure associated with elevated CO_2 should result in greater soil moisture retention at depths not subject to surface evaporation and thus possibly extend productivity to later periods in the drought.

The burning coal vents of southern Utah have the potential to serve as a vehicle for examining elevated atmospheric CO_2 effects on aridland vegetation. Given the low productivity and low cover that typically characterize aridland ecosystems, these communities are not

likely to be a high priority agenda item for large-scale elevated CO_2 manipulations, such as free-air-CO_2-enrichment (FACE) studies. Yet aridland ecosystems may be particularly responsive to elevated atmospheric CO_2 if stomatal closure results in a reduced rate of soil moisture loss. Whereas in some natural burning-coal vents, high-sulfur coals result in SO_2-pollution effects that compound interpretation of plant responses (Freedman *et al.*, 1990), this may not be the case for the coal seams of southern Utah.

In the remote Burning Hills of southern Utah, lightning strikes have resulted in several burning seams. Doelling & Graham (1972) reported numerous sites where the coal seam had ignited and later burned out, indicating that this process has been ongoing for extended time periods. More than four large, long-term burns are known to occur at present and other small, unknown burns may exist as well. Of the large burns, at least one is thought to be more than a century old.

Burning coal vents are somewhat analogous to the elevated-CO_2 springs described by Miglietta *et al.*, (1993). These geothermal sources occur throughout the Mediterranean-climate landscape in central Italy and provide a resource for evaluating plant acclimation and adaptation to elevated atmospheric CO_2 conditions. In both systems, atmospheric turbulence will result in fluctuations in the absolute CO_2. While the extent to which stomata can respond to high frequency changes in CO_2 concentration is unknown, carbon isotope ratio values of C_4 plants will provide an estimate of the long-term, assimilation-weighted value of the atmospheric CO_2 concentration.

ACKNOWLEDGEMENTS

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