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# SEASONAL VARIATIONS OF CARBON DIOXIDE CONCENTRATIONS IN STONY, COARSE-TEXTURED DESERT SOILS OF SOUTHERN NEVADA, USA

C. L. TERHUNE[1,2] AND J. W. HARDEN[1]

**Knowledge of carbon dioxide concentration in desert soils is required in theoretical models of the development of pedogenic and ground-water calcium carbonate. Most studies have concentrated on medium- to fine-textured soils in temperate to humid environments. Very little data exist for $CO_2$ concentrations in stony, coarse-textured deposits such as those making up alluvial fans and fluvial terraces. The purpose of this study was to obtain $CO_2$ concentration data in stony, coarse-textured, uncultivated soils in a desert environment.**

**Soil gas samples were collected from two sites—Yucca Wash and Rock Valley—at the Nevada Test Site in southern Nevada between June 1985 and June 1986 to determine soil $CO_2$ concentrations and their seasonal and depth variations in the soil profile. Soil $CO_2$ concentrations ranged from 0.03 volume percent in winter and summer to 0.25 volume percent in spring. During the summer, fall, and winter, $CO_2$ concentrations were close to atmospheric levels and varied randomly with depth. In spring, $CO_2$ varied with root density, highest concentrations occurring between 40 and 80 cm of depth. Maximum $CO_2$ values decrease and occur at progressively deeper levels toward the end of spring. Biological activity appears to be limited throughout the year because of the arid climate. During the winter and spring, soil $CO_2$ appears to be more dependent on temperature than moisture, whereas in the summer and fall it appears to be dependent on moisture.**

**Soil gas samples were also collected during the spring from three sites in the Kyle Canyon area in southern Nevada to determine the variation of soil $CO_2$ levels with changes in elevation and vegetation. Soil $CO_2$ values increased from 0.04 to 0.24 volume percent with increasing elevation. The increased elevation is associated with increasing precipitation, greater vegetation density, and decreasing temperature. The $CO_2$ values at the mid-elevation of 1400 m in Kyle Canyon were similar to $CO_2$ values at Yucca Wash at 1266 m in elevation for the spring of 1986.**

[1] U.S. Geological Survey, 345 Middlefield Rd.-MS 975, Menlo Park, CA.

[2] Present address of author: 10500 Malaguena Lane, NE, Albuquerque, NM 87111.

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The carbon dioxide content of the soil atmosphere is a controlling factor in the dissolution and precipitation of calcium carbonate in sediments and soils. Seasonal and/or depth variations of soil $CO_2$ in nonstony coarse-to fine-textured soils in arid to humid environments have been studied in relation to agriculture, ground-water movement, and karst topography (Miotke 1974; Reardon et al. 1979; Buyanovsky et al. 1982; Parada et al. 1983).

Brook et al. (1983) used soil $CO_2$ measurements from 19 localities with sand to clay soil textures to develop a world model of soil $CO_2$ during the growing season. This model uses climatic data to predict soil $CO_2$ levels in the varying climates. The model predicts soil $CO_2$ concentrations below 0.25% for the southern Nevada region. In the arid to semi-arid climate of southern Nevada, many soils are developed in fluvial deposits and alluvial fans that have coarse textures. Coarse-textured soils with higher porosity and permeability most likely have better gas exchange with the free atmosphere than fine-textured soils. Consequently, we expected to see lower $CO_2$ values.

Published data on soil $CO_2$ for this environment in stony soils is scarce. Buyanovsky et al. (1982) studied stony slopes in the arid environment of the Negev desert (elevation 400 m to 610 m) and measured concentrations of $CO_2$ from 0.03 to 0.16%. Miotke (1974, p. 41) collected data from a wide range of soil types all over North and South America and documented $CO_2$ concentrations ranging from 0.01 to 7.0%; however, most of his samples were from tropical and arctic areas. Parada et al. (1983) sampled

$CO_2$ in the semiarid soils (sandy loam to clay loam textures) of southern Arizona and documented a seasonal fluctuation of low $CO_2$ values during the winter, rising $CO_2$ values in the spring, and decreasing values in the summer. Soil $CO_2$ concentrations for their three long-term sites ranged from about 0.1 to 0.5%. Last, Amundson et al. (1988) and Quade et al. (1989) measured $CO_2$ concentrations in soils near the Spring Mountains (Fig. 1) and found values ranging from 0.04 to 0.45% at elevations of 840 to 2150 m during spring months.

Our objective was to determine the seasonal variations of soil $CO_2$ with depth in stony, coarse-textured soils in an arid environment. Variations of soil $CO_2$ between fine- and coarse-textured soils and variation with elevation and vegetation density were secondary objectives.

## SAMPLE SITES

We sampled soil $CO_2$ at sites of various ages and elevation in the arid to semi-arid climate of southwestern Nevada (Fig. 1). Pedon descriptions and soil properties are summarized in Table 1.

The Yucca Wash site is approximately 160 km (100 miles) northwest of Las Vegas at an elevation of 1266 m (4155 feet). The mean annual temperature (MAT) is approximately 16° C, and the mean annual precipitation (MAP) is 116 mm (Beatty 8N station of National Oceanic Atmospheric Administration from Climatological Data of Nevada, 1985–1986). The soil is approximately 10 ka, is formed in a fluvial terrace deposit, and is classified as a sandy-skeletal, thermic typic Torriorthent. The soil texture is

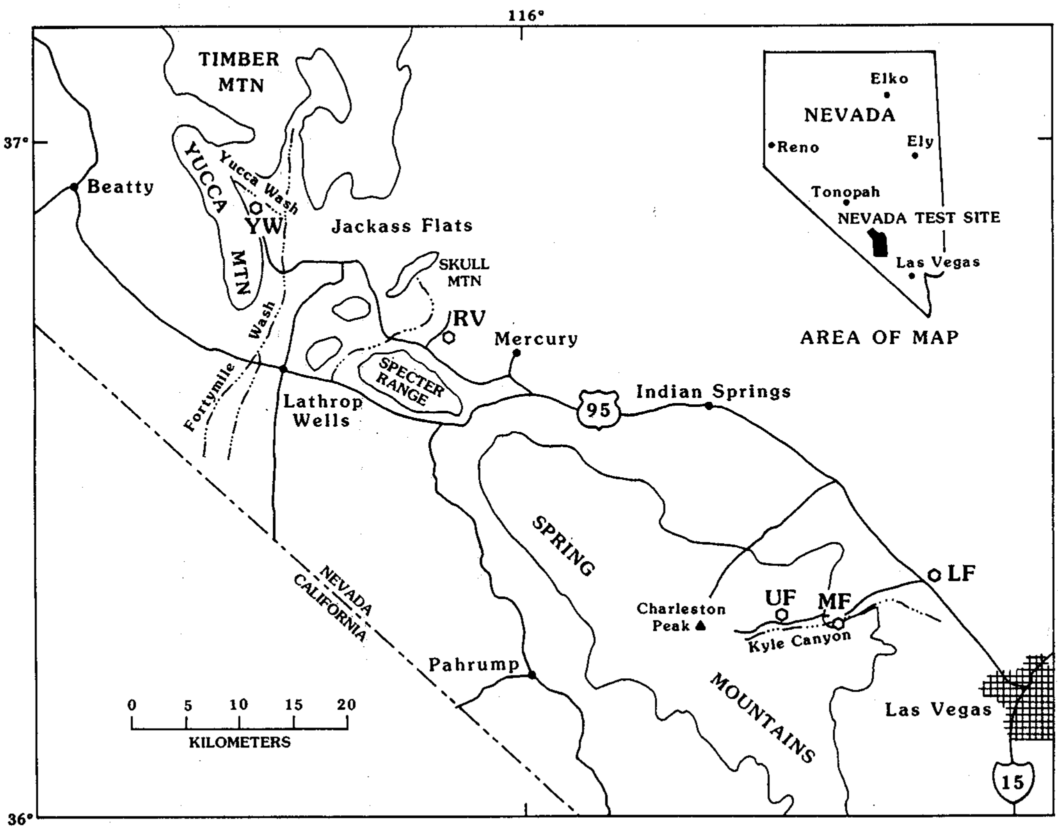


FIG. 1. Location of Sample Sites—Nevada Test sites: YW Yucca Wash site (36°54′ lat., 116°27′ long.); RV Rock Valley site (36°42′ lat., 116°08′ long.); Kyle Canyon sites, LF lower fan site (36°20′ lat., 115°18′ long.), MF mid-fan site, and UF upper fan site.

TABLE 1

*Characterization of soils*

| Profile/ Horizon | Basal Depth (cm) | Dry Color | Density (g/cc) | Gravel (%) | Texture | Sand (%) | Silt (%) | Clay (%) | Organic Carbon (%) | Carbonate Stage | Silica Stage | Structure[a] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Yucca Wash (YW-13), typic Calciorthid, 1400 m, terraces formed in fluvial gravel (Taylor 1986)[b] | | | | | | | | | | | | |
| A | 9 | 10YR5/2 | 1.42 | 53 | LS | 81.75 | 13.78 | 4.47 | 0.61 | 0 | 0 | 3mgr |
| Bw | 21 | 10YR6/2 | 1.42 | 33 | SL | 80.57 | 13.46 | 5.96 | 0.25 | 0 | 0 | 1f-msbk |
| 2Bqj | 73 | 10YR6/3 | 1.61 | 48 | S | 87.56 | 8.18 | 4.26 | 0.12 | 0 | I | sg |
| 2Ckqn | 138 | 10YR6/1 | 1.81 | 67 | S | 93.15 | 4.91 | 1.94 | 0.06 | I+ | I– | sg |
| Rock Valley (RV-2), typic Camborthid, 1220 m, Young fan and wash deposits overly alluvial fan deposits (Yount et al. 1987) | | | | | | | | | | | | |
| Av | 9 | 7.5YR8/4 | – | 20 | SL | 70 | 19 | 11 | – | 0 | – | m,v1vf-msbk |
| 2Bk | 44 | 7.5YR7/4 | – | 15 | SL | 66.1 | 21.4 | 12.5 | – | I | – | m,v1vf-msbk |
| 3Btkb1 | 60 | 7.5YR7/4 | – | 20 | fSL | 58.3 | 23.2 | 18.5 | – | I | – | 2f-coabk |
| 3Btkb2 | 83 | 7.5YR7/4 | – | 20 | SL | 68.7 | 22.3 | 9 | – | I | – | m,1vf-mabk |
| 4Kqb | 113 | 7.5YR8/2 | – | 30 | LS | 80.9 | 11 | 8.1 | – | III | – | m,1m-vcopl |
| Kyle Canyon 1, typic Torriorthent, 823 m, alluvial fan lobe of fluvial gravels (upper 15 cm eolian additions) (Amundson et. al. 1989) | | | | | | | | | | | | |
| Avk | 4 | 10YR7/4 | – | 15 | fSL | – | – | – | – | 0 | 0 | 2cosbk |
| Bwk1 | 15 | 10YR6.5/4 | – | 65 | fSL | – | – | – | – | II– | 0 | 1msbk |
| 2Bwk2 | 32 | 10YR7.5/3.5 | – | 75 | fSL | – | – | – | – | II | I? | 1msbk |
| 2Bwk3 | 51 | 10YR7.5/3 | – | >80 | SL | – | – | – | – | I+ | 0 | sg |
| 2Bwk4 | 73 | 10YR7/2 | – | >80 | fSL | – | – | – | – | II– | 0 | sg |
| 2Bwk5 | 120 | 10YR7.5/4 | – | >80 | SL | – | – | – | – | II | 0 | sg |
| 3Bwk6 | 168 | 10YR7/3.5 | – | >80 | fSL | – | – | – | – | II | 0 | sg |
| 4Bkqb | 237 | 10YR7/4 | – | >80 | SL | – | – | – | – | II | II | sg |
| 5Bkb | 252 | 10YR8/4 | – | >80 | fSL | – | – | – | – | II+ | II | sg |
| Kyle Canyon 5, typic Calciorthid, 1400 m, alluvial fan lobe of fluvial gravels and sheetwash (upper 8 cm eolian) (Amundson et. al. 1989) | | | | | | | | | | | | |
| Av | 8 | 10YR6/3 | 1.28 | 56 | L | – | – | – | – | I– | 0 | 2fsbk,1fpl |
| Bktj | 22 | 10YR6/4 | 1.36 | 56 | L | – | – | – | – | I | 0 | 2m-cosbk |
| 2Btk | 40 | 7.5YR6/5 | 1.38 | 65 | SCL | – | – | – | – | I | 0 | 1f-msbk |
| 2Bktj | 61 | 10YR6/5 | – | 84 | SL+ | – | – | – | – | I+ | 0 | sg |
| 3Bk(m) | 108 | 10YR7/3 | 1.96 | 85 | – | – | – | – | – | II+ | I– | 2coabk |
| 3Bkq | 163 | 2.5Y7/2 | 0.77 | 78 | LS | – | – | – | – | II | I | sg |
| 3Bk1 | 223 | 10YR7/2 | 1.14 | 82 | SL– | – | – | – | – | II | I– | sg |
| 3Bk2 | 284 | 2.5Y7/2 | 1.67 | 74 | LS | – | – | – | – | I– to II– | 0 | sg |
| 4Bkmb | 350 | 7.5YR7/2 | 1.36 | 64 | SiCL | – | – | – | – | III | 0 | m,3m-coabk |
| Kyle Canyon Upper, aridic Ustochrept, 1750 m, alluvial fan lobe of fluvial gravels (Amundson et. al. 1989) | | | | | | | | | | | | |
| A1 | 3 | 10YR6/4 | – | 20 | grfSL+ | – | – | – | 0.72 | – | – | 3fpl |
| A2 | 10 | 10YR6/4 | – | 20 | grSiL | – | – | – | 0.27 | – | – | 1fsbk |
| 2Bw | 39 | 10YR6/3 | – | 45 | vgrfSL | – | – | – | 0.06 | – | – | 1msbk |
| 2Bk | 67 | 10YR6/3 | – | 60 | vgrSL | – | – | – | 1.08 | – | – | m |
| 3Bkm | 79 | 10YR7/2 | – | 50 | vgrSL | – | – | – | 0.66 | – | – | m |
| 3Bk | 89 | – | – | – | – | – | – | – | 1.38 | – | – | m |
| 4Bkm | 89+ | 2.5Y7/2 | – | 65 | vgrSL | – | – | – | 0.36 | – | – | m |

[a] 1, very weak; 1, weak; 2, moderate; 3, strong; vf, very fine; f, fine; m, medium, co, coarse, sg, single grain; gr, granular; pl, platy; sbk, subangular blocky; abk, angular blocky.

[b] E. M. Taylor, 1986, Impact of time and climate on quaternary soils in the Yucca Mountain area of the Nevada Test Site, Masters thesis, Univ. of Colorado.

sand to sandy-loam, with 30–70% by weight gravel (Taylor 1986) (Table 1). The surface is moderately vegetated, with *Artemesia tridentia* (sagebrush), *Ephedra sp.* (mormon tea), and other desert shrubs and small cacti. Approximately 80% is bare ground (as estimated by grid on a scaled drawing of the surface). Grasses in the spring reduce the bare ground to approximately 60%. Roots penetrate to a depth of at least 150 cm and are most abundant in the 20 to 50 cm zone.

Rock Valley, the second site on the Nevada Test Site (NTS), is located approximately 40 km (25 miles) southeast of the Yucca Wash sites at an elevation of 1220 m (4000 feet). The soil is slightly older than the Yucca Wash soil (Taylor 1986, and Yount et al. 1987), is formed in an alluvial fan deposit, and is classified as a loamy, thermic, typic Camborthid. The soil texture is loamy-sand to loam, with about 15–50% by volume of gravel (Yount et al. 1987) (Table 1).

The third area is at Kyle Canyon, located approximately 32 km (20 miles) west of Las Vegas. Three sites at different elevations and in different vegetation zones were sampled on an extensive Late Wisconsin to Early Holocene alluvial fan (surface 3 of Sowers 1985).[2] The first site is located at the toe of the fan at an elevation of 823 m (2700 ft), with a MAT of 18°C and MAP of 175 to 250 mm (Sowers 1985). The soil is classified as a sandy-skeletal, carbonatic, thermic typic Torriorthent. The soil texture is sandy-loam, with an estimated 15–80% by volume gravel (Amundson et al. 1989) (Table 1). The vegetation is sparse, consisting of scattered *Larrea divaricata* (creosote bush), *Franseria dumosa* (burro bush), and *Yucca schidigera* (Mojave yucca) (Sowers, personal communication, 1987). The second site, midway up the same remnant surface, is at an elevation of 1400 m (4600 ft). The soil is classified as a loamy-skeletal, carbonatic, thermic, typic Calciorthid. The soil texture is sandy-loam and sandy-clay loam, with 55–86% by weight being gravel (Amundson et al. 1989) (Table I). Because of slightly lower temperatures and higher rainfall (MAT = 10°C, MAP = 200–250 mm) vegetation is more abundant (Amundson et al. 1988). The dominant vegetation is *Coleogyne ramosissima* (blackbrush), *Larrea divaricata* (creosote bush), *Yucca brevifolia* (Joshua tree), *Yucca schidigera* (Mojave Yucca), and *Ephedra* (mormon tea) with a few cacti, grasses, and other desert shrubs present. The third site on the upper fan is at 1780 m (5840 ft). The soil is classified as a loamy-skeletal, carbonatic, mesic, Andic Ustochrept. The soil texture is sandy-loam, with an estimated 20–65% by volume being gravel (Amundson et al. 1989) (Table I). Higher rainfall (MAP of 557 mm; Kyle Canyon ranger station data, 1979–1986) results in more abundant vegetation than other sites, including *Pinusmonophylla* (pinyon pine), *Juniperus sp.* (juniper), *Artemesia tridentata* (sagebrush), and *Cowania mexicana* (cliffrose) (Amundson et al. 1989).

[2] J. M. Sowers, 1985, Pedogenic calcretes of the Kyle Canyon alluvial fan, southern Nevada: Morphology and development, Ph.D. thesis, Univ. of California, Berkeley.

## METHODS USED

### *Sample Techniques*

Most soil $CO_2$ sampling has been designed for, and performed in, fine-grained soils. The methods used include driving or implanting small-diameter steel or copper tubes to the depth desired (Reardon et al. 1979; Parada et al. 1983). Small-sized tubes are difficult to drive into gravelly soils—especially beyond 40 cm in depth. Methods that use backfilling destroy the original soil profile and probably affect the $CO_2$ concentration. Because of the stony nature of the southern Nevada soils, we inserted ½-in. (inside diameter) copper pipe into the soil. These pipes were either hammered vertically into the ground from the surface, or, as at Yucca Wash, some pipes were hammered horizontally into the resin-treated face of an open soil pit (Fig. 2a). The pipes are initially open at both ends and fill with soil when emplaced in the ground. The exposed pipe ends were covered with a rubber stopper and shaded with tape, in order to slow any deterioration of the stoppers from exposure to the sun. The tubes were left to equilibrate for at least a day.

At each site, pipes were hammered vertically to intended depths of 20, 40, 60, 80, and 100 cm; however, the presence of gravel clasts did not always permit such regular sampling intervals. As a result, the sampling depths at Yucca Wash were 20, 40, 50, 60, 70, and 90 cm; the depths at Rock Valley were 10, 20, 40, and 60 cm; and the

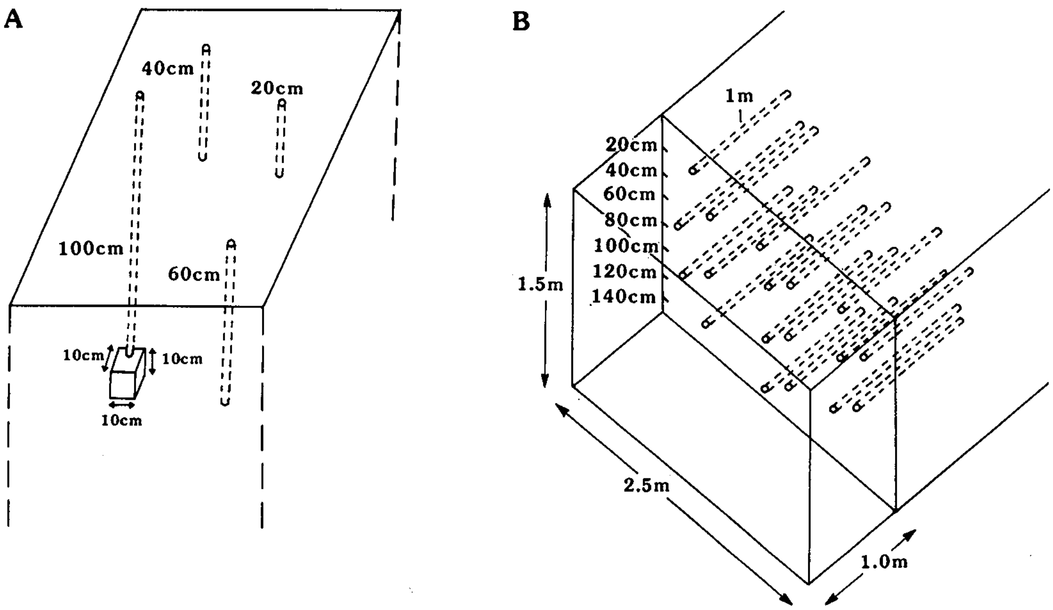


FIG. 2. Sample Site Geometry—(a) surface site: randomly placed copper pipes to variable depths. Box (10 cm by 10 cm by 10 cm) represents the volume sampled; (b) pit site: three transects from 20- to 120-cm depth staggered at intervals of 20 cm.

depths at the Kyle Canyon sites were 20, 40, and a few at 60 cm.

At the Yucca Wash site, a pit was excavated to 2.5-m depth to obtain soil air from depths greater than 100 cm (Fig. 2b). The pit face was covered with a sealing resin (vinyl chloride acetate resin dissolved in acetone) to help prevent an exchange of the soil atmosphere with the free atmosphere through the pit face. In order to determine how far into the pit face the tubes must be driven to prevent atmospheric contamination from the pit face, we hammered 12 pipes from the surface to a depth of 40 cm in a transect perpendicular to the southern pit face. The pipes were placed 20, 40, 60, 80, and 100 cm away from the face and then in increments of 40 cm up to 5 m from the pit face. Results from the transect pipes indicated that, despite the acetate resin, oxygen exchange occurred up to distances of 80 cm from the exposed face (Fig. 3). Therefore, three replicate sets of copper pipes were hammered horizontally 100 cm into the pit face. In order to determine the spacing necessary between pipes to avoid sampling of the same soil area with two different pipes, we calculated the volume of air sampled by a pipe (Fig. 2a). For a pipe 100 cm long with 50% pore space in the

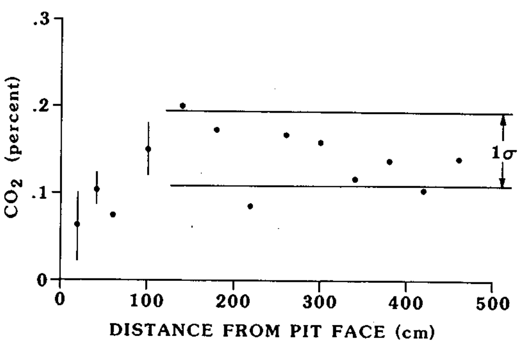


FIG. 3. Yucca Wash Pit Transect—Elevation is 1266 m, sampled April 13, 1985 at a temperature of 21–23 C. Bars represent one standard deviation of transect sites.

soil, the minimum safe distance between pipes is 20 cm. The tubes were placed in increments of 20 cm to a depth of 140 cm (Fig. 2b).

### *Extraction of Soil Air*

Initially, we used Vacutainer brand serum tubes to collect the soil air; however, although sterilized and evacuated when purchased, these tubes were found to contain residual $CO_2$ and were considered unreliable (Table 2). A Draeger

TABLE 2

*Comparison of sample containers*

| | Percentage $CO_2$ ± Standard Error[a] (soil air at 40 cm depth) | | | |
|---|---|---|---|---|
| Sample Tube | Sample 1 | Sample 2 | Sample 3 | Sample 4 |
| Glass | 0.086 ± 0.02 | 0.086 ± 0.01 | 0.104 ± 0.004 | 0.188 ± 0.006 |
| Reevacuated Vacutainer | 0.109 ± 0.03 | 0.197 ± 0.10 | 0.107 ± 0.007 | 0.199 ± 0.02 |
| Vacutainer[b] | 0.76 ± – | 0.605 ± 0.03 | 0.115 ± 0.04 | 0.173 ± 0.04 |

[a] Standard Error $= \frac{x^2 - (x)^2/n^{-2}}{n-1}$ where x is the measured value and n is the number of measurements.

[b] All values corrected for 0.202 ± 0.08 percentage $CO_2$ blank Vacutainer tube (Vacutainer has residual $CO_2$ upon purchase).

tube (Miotke 1974) used to measure the soil $CO_2$ directly in the field was also tried in the spring; however, the percentage of $CO_2$ registered was 0.01%, which is below concentrations of the free atmosphere. From June 1985 to the end of the study, we used Wheaton serum bottles with grey-butyl stoppers and aluminum seals (volume was 24.8 mL when sealed). According to Miotke (1984), the normal $CO_2$ content of the free atmosphere ranges from 0.02 to 0.04% depending on weather and elevation (very slight change). We tested free-atmosphere samples using Wheaton serum bottles and obtained a range of 0.03 to 0.04% $CO_2$ during the year, a reasonable figure for an arid climate at an elevation of 1 to 2 km.

The bottles were sealed and evacuated to $10^{-6}$ atmospheres using a vacuum pump. The bottles were kept in a freezer or ice chest from the time of evacuation to the time of analysis in order to reduce the production of $CO_2$ by decomposition of rubber stoppers or by growth of micro-organisms within the bottle after sampling.

We sampled once every other month during the summer, fall, and winter and once every other week during the spring. Before each sample was collected, a syringe was used to remove contaminated air from one volume of the tube. If a blockage was present (the tube could not be cleaned) the sample was not taken. Samples were collected by using a double-ended needle. The needle was pushed part way into both the stopper on the pipe and the stopper on the bottle and then pushed all the way through the pipe stopper first. The bottle was then left to fill for 5 minutes and removed.

*Sample Analysis*

Samples were analyzed with a gas chromatograph (Carle AGC series 100). The soil air (0.25 mL) was injected into a column with He as the carrier gas. The peaks were measured to 0.5 mm and converted to percentage $CO_2$ by using either a purchased standard of 1.04% $CO_2$ or a prepared standard. Concentration curves on the gas chromatograph are linear for concentration ranging over five orders of magnitude (McNair and Bonelli 1969), making only one standard necessary. The prepared standard was made by using a free-atmosphere sample, collected in the field, with 0.248 mL of 100% $CO_2$ injected into the 24.8-mL bottle giving a 1.03–1.04% $CO_2$ standard. The average peak area of the free-atmosphere sample subtracted from the peak area of the standard was used to obtain the constant by which the peak areas were converted into percentage $CO_2$.

## RESULTS

From late June through about January, the concentration of $CO_2$ in soils at Yucca Wash is low (0.05 to 0.09%); these concentrations are close to that of the free atmosphere. During the spring, $CO_2$ concentrations become 3 to 6 times that of the free atmosphere (Fig. 4). The seasonal variation appears to be due to biological activity responding to changes in both moisture and temperature, as found by Miotke (1984). During late spring, the soil dries enough to decrease both vegetation and microbial respiration significantly. In the early winter, despite increased precipitation, temperatures apparently

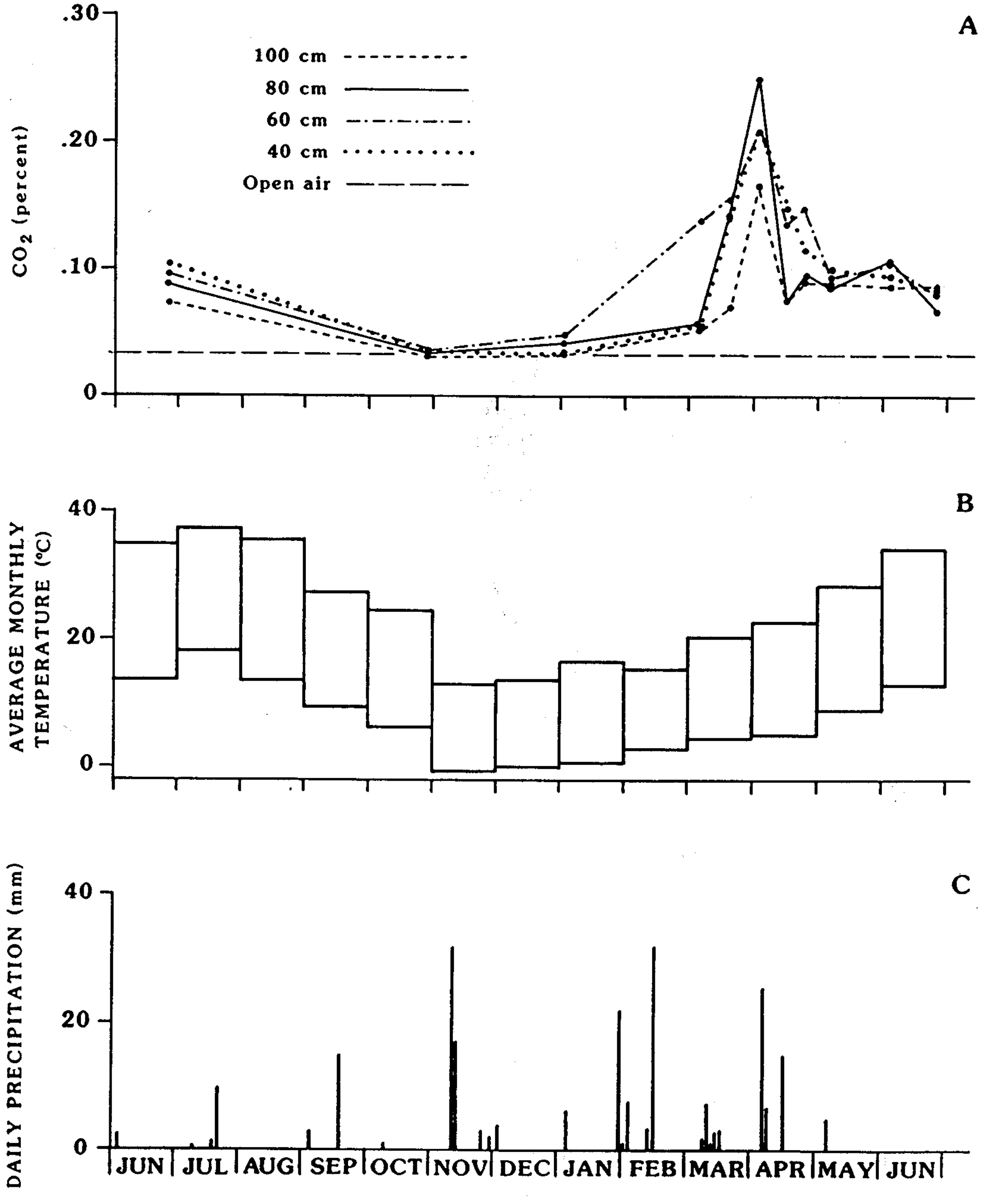


FIG. 4. Seasonal Variation of (a) percentage $CO_2$ (elevation of 1266m), (b) temperature (boxes indicate maximum and minimum), and (c) precipitation (vertical lines represent precipitation in one event) for Yucca Wash (precipitation and temperature data from Beatty 8N station, NOAA, 1985–1986).

are too low for marked biological activity until sometime between late February and March (Fig. 4).

Soil $CO_2$ varies systematically with depth at Yucca Wash during the spring when $CO_2$ concentrations are greatest. Variations of $CO_2$ with depth appear random or mixed with atmosphere during non-Spring seasons (Fig. 5). Soil $CO_2$

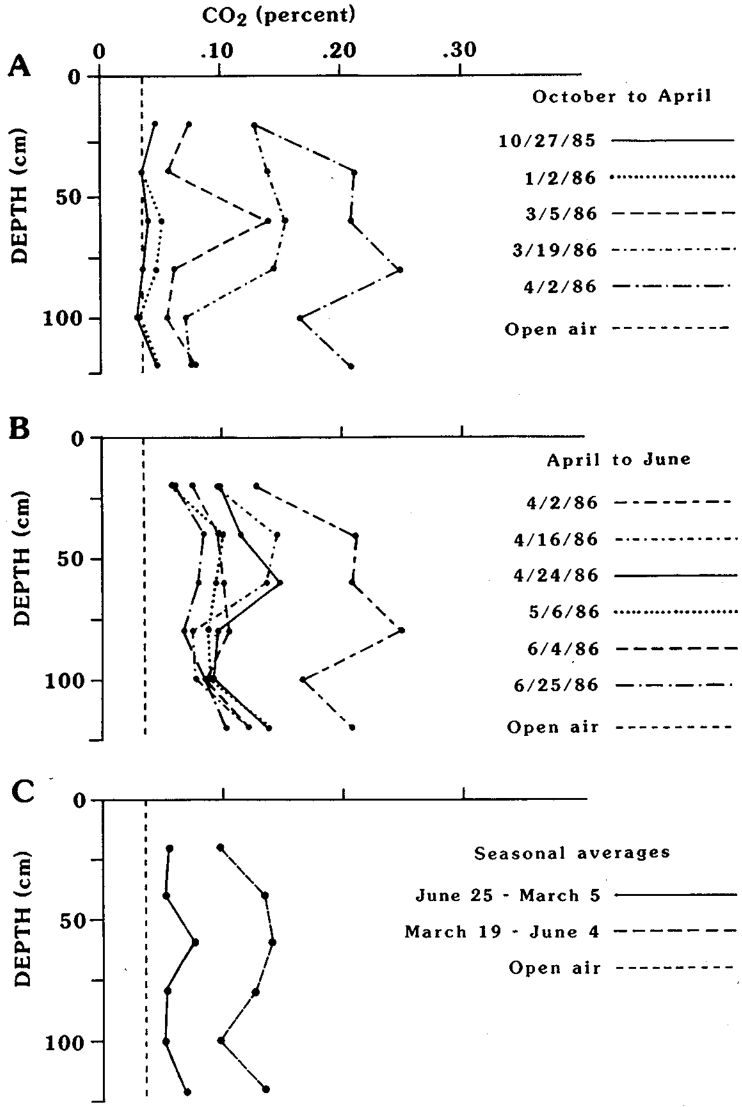


FIG. 5. Seasonal Change of $CO_2$ with Depth for Yucca Wash. (a) October to April; (b) April to June; (c) seasonal averages.

increaes first in the upper profile in mid-March, extending to the full profile (40–140 cm) by the beginning of April. As evapotranspiration removes moisture from the upper horizons, the depth of maximum $CO_2$ concentration increases from April to early June. During this season, increasing temperatures and decreasing moisture content of the upper soil profile possibly forces roots and other micro-organisms to get water from deeper in the soil profile. This change may result in the small but pronounced $CO_2$ peak in the lower soil profile at the end of June. Investigators de Jong and Schappert (1972) found a similar trend in a Canadian soil.

The low concentrations of $CO_2$ led us to hypothesize that soil $CO_2$ might be readily exchanged with the free atmosphere because of the coarse texture and large pore sizes at Yucca Wash (Taylor 1986). We collected data at Rock Valley (Fig. 1) where soils have finer textures (5 to 15% more clay and 5% more silt) and thicker 'vesicular A horizons' that might reduce the exchange of $CO_2$ from soil to air. During the spring, $CO_2$ is lower at Rock Valley than Yucca Wash (Fig. 6), but it is higher during other seasons. Perhaps $CO_2$ production is lower at Rock Valley, but retention during off-seasons (summer, fall, and winter) results in higher

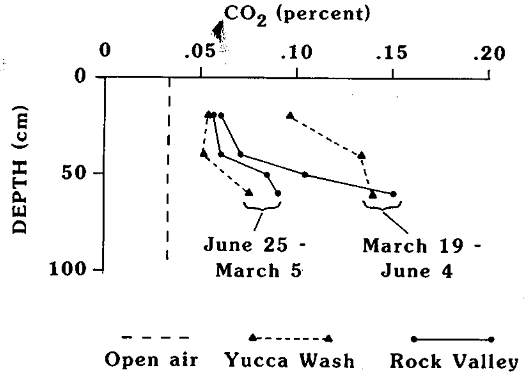


FIG. 6. Comparison of average $CO_2$ Concentrations at Yucca Wash and Rock Valley.

background concentrations. Our conclusion from this comparison is that low $CO_2$ concentrations in soils at Yucca Wash are a result mainly of regionally low concentrations of $CO_2$ production in this climatic environment. Soils that are much finer textured might have higher off-season $CO_2$ concentrations but probably would have comparable concentrations in the spring, especially if vegetation is similar to that at Yucca Wash.

The sites at Kyle Canyon were sampled once during May of 1986 in order to examine the effects of elevation and vegetation on $CO_2$ levels. Soil $CO_2$ increased from the base of the fan to the uppermost sampling site. Soil $CO_2$ is lowest (0.04-0.05%) at the base of the fan at 823 m; here the climate is drier and warmer, and the vegetation is sparser than at the other two sites. Soil $CO_2$ values at mid-fan (1400 meters) ranged from 0.05% $CO_2$ at 20 cm of depth to 0.12% $CO_2$ at 60 cm of depth. This site receives more rain, is slightly cooler, and is better vegetated than sites at the base of the fan. Soil $CO_2$ values at the upper fan site (1780 m) ranged from 0.11% at 20 cm of depth to 0.24% at 40 cm of depth. This site receives much more rain, is cooler, and has denser vegetation than the lower sites. This variation in $CO_2$ levels with increased elevation appears to result from the change of climate and vegetation, which is compatible with the conclusions of Amundson et al. (1988).

## DISCUSSION

In this study we found that concentrations of $CO_2$ in arid soils range from about 0.03 to 0.25% and are low compared to those concentrations in soil microclimates of other studies. The concentrations of this study are similar to $CO_2$ concentrations studied by Buyanovsky et al. (1982), who examined shallow stony soils in an arid region. Comparably low soil $CO_2$ concentrations are restricted to frozen or very cold soils at high altitudes (Miotke 1974, p. 41).

The most critical factors influencing $CO_2$ concentration in soil probably are temperature, moisture, permeability to water and gas, and microbial and macroplant activity (Miotke 1974). Minimal $CO_2$ concentrations result from (1) dormancy of root and microbial respiration during the extreme aridity of summer and the cool temperatures of winter (Miotke 1974) and (2) a generally poor vegetative cover and low amounts of soil organic matter during the most productive spring season. Also, high permeability of the gravelly soils possibly prevents $CO_2$ from accumulating (Miotke 1974, pp. 34–35). The greater $CO_2$ concentrations in Arizona that were documented by Parada et al. (1983) probably result from greater vegetative cover in Arizona (20–30% as compared to 10–20% at Yucca Wash), summer precipitation, and possibly finer textures of the soils (sandy clays to clay; one sandy loam). Greater organic matter may result in higher $CO_2$ production, and finer textures might allow slower diffusion and some accumulation of $CO_2$ in the soil.

The seasonal fluctuations of $CO_2$ concentrations documented by Parada et al. (1983) in Arizona were also observed in this study; however, the $CO_2$ levels in the soils that we studied do not increase in the fall as they do in Arizona. This difference is probably due to lower amounts of rainfall during the summer at Yucca Wash as compared to southern Arizona. The concentrations of $CO_2$ in southern Arizona (Parada 1983) were about 10 times those found in our study area, even in most of Parada's gravelly soils.

As to soil $CO_2$ relation with theoretical models of calcium carbonate accumulation, carbon dioxide in the soil atmosphere is a controlling factor on the solubility of calcium carbonate within the soil. Knowledge of soil $CO_2$ variation is necessary if we are to use theoretical models to determine the rate and depth of pedogenic carbonate accumulation in desert soils. McFadden and Tinsley (1985) and Mayer et al. (1986) used an average yearly value for soil $CO_2$ in such models. Marion et al. (1985) used two series of seasonal values based on data published by Parada et al.

TABLE 3

*Seasonal soil $CO_2$ (percentage) for the Yucca Wash and Rock Valley sites*

| Depth (cm) | N | June 26 | Oct 27 | Jan 2 | March 5 | March 19 | April 2 | April 16 | April 24 | May 6 | June 4 | June 25 | Yearly avg (N = 10) | Seasonal average June 25– March 5 (N = 4) | Seasonal average March 19– June 4 (N = 6) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Yucca Wash: | | | | | | | | | | | | | | | |
| 20 | 3 | 0.124 | 0.045 | 0.043 | 0.075 | 0.129 | 0.129 | 0.095 | 0.096 | 0.057 | 0.074 | 0.059 | 0.080 | 0.055 | 0.097 |
| | | ±0.007 | ±0.013 | ±0.007 | ±0.017 | ±0.025 | ±0.037 | ±0.022 | ±0.035 | ±0.007 | ±0.011 | ±0.005 | ±0.031 | ±0.015 | ±0.029 |
| 40 | 3 | 0.102 | 0.034 | 0.033 | 0.057 | 0.140 | 0.212 | 0.147 | 0.116 | 0.101 | 0.097 | 0.084 | 0.102 | 0.052 | 0.135 |
| | | ±0.043 | ±0.013 | ±0.001 | ±0.018 | ±0.033 | ±0.042 | ±0.001 | ±0.041 | ±0.019 | ±0.035 | ±0.028 | ±0.055 | ±0.024 | ±0.042 |
| 60 | 3 | 0.096 | 0.038 | 0.049 | 0.139 | 0.153 | 0.209 | 0.137 | 0.149 | 0.095 | 0.100 | 0.080 | 0.115 | 0.077 | 0.141 |
| | | ±0.025 | ±0.007 | ±0.010 | ±0.027 | ±0.016 | ±0.066 | ±0.031 | ±0.039 | ±0.040 | ±0.015 | ±0.005 | ±0.052 | ±0.045 | ±0.041 |
| 80 | 3 | 0.095 | 0.035 | 0.046 | 0.059 | 0.145 | 0.250 | 0.076 | 0.097 | 0.088 | 0.103 | 0.067 | 0.097 | 0.052 | 0.127 |
| | | ±0.043 | ±0.013 | ±0.015 | ±0.012 | ±0.000 | ±0.028 | ±0.058 | ±0.070 | ±0.060 | ±0.054 | ±0.013 | ±0.062 | ±0.014 | ±0.065 |
| 100 | 3 | 0.073 | 0.031 | 0.032 | 0.053 | 0.071 | 0.167 | 0.078 | 0.092 | 0.091 | 0.089 | 0.086 | 0.079 | 0.051 | 0.098 |
| | | ±0.014 | ±0.003 | ±0.004 | ±0.008 | ±0.017 | ±0.021 | ±0.021 | ±0.041 | ±0.035 | ±0.030 | ±0.015 | ±0.039 | ±0.026 | ±0.035 |
| 120 | 2 | 0.139 | 0.045 | 0.045 | 0.079 | 0.077 | 0.209 | 0.121 | 0.137 | 0.138 | 0.121 | 0.103 | 0.107 | 0.068 | 0.134 |
| | | ±0.044 | ±0.026 | ±0.023 | ±0.041 | ±0.015 | ±0.066 | ±0.016 | ±0.021 | ±0.011 | ±0.009 | ±0.008 | ±0.049 | ±0.028 | ±0.043 |
| Air | 2 | – | 0.032 | 0.027 | 0.037 | 0.036 | 0.026 | 0.040 | 0.033 | 0.029 | 0.037 | 0.039 | 0.034 | 0.034 | [illegible] |
| | | – | ±0.001 | ±0.001 | – | ±0.005 | ±0.003 | ±0.011 | ±0.000 | ±0.002 | ±0.009 | ±0.019 | ±0.005 | ±0.005 | ±0.0[illegible] |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Avg Depths | 6 | 0.104 | 0.038 | 0.041 | 0.077 | 0.119 | 0.196 | 0.109 | 0.115 | 0.095 | 0.097 | 0.080 | 0.097 | 0.059 | 0.122 |
| | | ±0.023 | ±0.006 | ±0.007 | ±0.032 | ±0.036 | ±0.042 | ±0.030 | ±0.024 | ±0.026 | ±0.015 | ±0.015 | ±0.045 | ±0.011 | ±0.019 |
| Avg 40–80 cm | 3 | 0.098 | 0.036 | 0.043 | 0.085 | 0.146 | 0.224 | 0.120 | 0.121 | 0.095 | 0.100 | 0.077 | 0.105 | 0.060 | 0.134 |
| | | ±0.004 | ±0.002 | ±0.009 | ±0.047 | ±0.007 | ±0.023 | ±0.038 | ±0.026 | ±0.007 | ±0.003 | ±0.009 | ±0.054 | ±0.014 | ±0.007 |
| Rock Valley: | | | | | | | | | | | | | | | |
| 10 | 2 | – | – | 0.034 | 0.097 | 0.064 | 0.047 | 0.091 | 0.080 | 0.033 | 0.049 | 0.036 | 0.059 | 0.056 | 0.061 |
| | | – | – | ±0.004 | ±0.026 | ±0.003 | ±0.005 | ±0.037 | ±0.003 | ±0.008 | ±0.003 | ±0.001 | ±0.025 | ±0.036 | ±0.022 |
| 20 | 2 | – | – | 0.035 | 0.109 | 0.071 | 0.086 | 0.110 | 0.060 | 0.047 | 0.053 | 0.039 | 0.068 | 0.061 | 0.071 |
| | | – | – | ±0.003 | ±0.054 | ±0.013 | ±0.021 | ±0.004 | ±0.042 | ±0.017 | – | ±0.025 | ±0.028 | ±0.042 | ±0.026 |
| 40 | 5 | – | – | 0.035 | 0.142 | 0.086 | 0.121 | 0.138 | 0.125 | 0.094 | 0.065 | 0.078 | 0.098 | 0.085 | 0.105 |
| | | – | – | ±0.005 | ±0.040 | ±0.019 | ±0.032 | ±0.037 | ±0.051 | ±0.044 | ±0.027 | ±0.034 | ±0.036 | ±0.054 | ±0.028 |
| 60 | 3 | – | – | 0.034 | 0.141 | 0.109 | 0.159 | 0.188 | 0.164 | 0.140 | 0.144 | 0.098 | 0.131 | 0.091 | 0.151 |
| | | – | – | ±0.007 | ±0.035 | ±0.002 | ±0.012 | ±0.038 | ±0.012 | ±0.006 | ±0.029 | ±0.021 | ±0.045 | ±0.054 | ±0.027 |
| Air | 2 | – | – | – | 0.030 | 0.035 | 0.027 | 0.047 | 0.041 | 0.027 | 0.030 | 0.036 | 0.034 | 0.033 | 0.035 |
| | | – | – | – | – | ±0.002 | – | ±0.003 | ±0.006 | ±0.002 | – | – | ±0.007 | ±0.004 | ±0.008 |
| Avg Depths | 4 | – | – | 0.035 | 0.122 | 0.083 | 0.103 | 0.132 | 0.107 | 0.079 | 0.078 | 0.063 | 0.089 | 0.073 | 0.097 |
| | | – | – | ±0.001 | ±0.023 | ±0.020 | ±0.048 | ±0.042 | ±0.047 | ±0.049 | ±0.045 | ±0.030 | ±0.030 | ±0.017 | ±0.041 |
| Avg 40–60 cm | 2 | – | – | 0.035 | 0.141 | 0.097 | 0.140 | 0.163 | 0.145 | 0.117 | 0.105 | 0.088 | 0.115 | 0.088 | 0.128 |
| | | – | – | ±0.001 | ±0.001 | ±0.016 | ±0.027 | ±0.035 | ±0.027 | ±0.033 | ±0.056 | ±0.014 | ±0.039 | ±0.004 | ±0.033 |

(1983): one for the winter season (November–February) and one for the remaining seasons.

As shown in Table 3, many values are available for use in a theoretical model: monthly averages, yearly averages, seasonal averages, and depth averages. A marked increase in $CO_2$ with depth occurs during the spring, concurrent with maximum leaching; therefore, we recommend that $CO_2$ be specified for depth increments in modeling calcium carbonate movement in stony, coarse-textured desert soils. In addition, for this study area, two seasons are defined by the $CO_2$ content—one in the spring and one not in the spring. As a result, two series of seasonal averages at specified depths may best represent the soil $CO_2$ in arid coarse-textured soils in a theoretical model of calcium carbonate accumulation.

## CONCLUSIONS

Carbon dioxide concentrations in stony coarse-textured desert soils are lower than those reported for other environments. Spring concentrations of soil $CO_2$ range from 0.06 to 0.25%. During the rest of the year, $CO_2$ concentrations range from about 0.03 to 0.11%, the lowest concentrations occurring in winter. Unlike temperate environments where temperature is probably more important than moisture in controlling the soil $CO_2$ (Gunn and Trudgill 1982), the soil $CO_2$ in the arid to semi-arid environment appears to be limited by temperature in the winter and spring and limited by moisture in the summer and fall. Variations of soil $CO_2$ with depth follow root density during the spring but appear to vary randomly with depth in the other seasons. In addition, in early spring soil $CO_2$ is highest in the upper horizons; the peak $CO_2$ values are found at greater depths by early summer. The deepening of the $CO_2$ peak may result from a deepening source of $CO_2$ as the upper profile dries out. Also, water in soil pores may suppress exchange of soil and open atmosphere, and the depth to pore water probably increases through the late Spring.

As found by Amundson et al. (1988) and Quade et al. (1989), soil $CO_2$ increases with increasing elevation and with more abundant vegetation. Areas at approximately the same elevation in the study area tend to have similar soil $CO_2$ concentrations.

Our sampling technique developed through trial and error during the first 6 months of our study. For future work in desert soils, we recommend the following: (1) do not use Vacutainer serum tubes as sample containers, especially in areas of low $CO_2$; (2) use gas collection apparatus that is able to withstand high heat; (3) evacuate sample containers to a pressure that avoids residual $CO_2$ within the bottles (we used $10^{-6}$ atmospheres); (4) if placing sample tubes horizontally into a pit face, drive the tubes in at least 1 m; (5) purge tubes before sampling to rid them of free atmosphere contamination, but do not purge more than the volume of the tube; (6) refrigerate samples after evacuation until analysis to reduce microbial activity or degassing of rubber or vinyl stoppers; (7) if possible, analyze samples within 1 or 2 days of collection; (8) cover sample sites to prevent deterioration of sampling apparatus if rubber or vinyl are used; and (9) if possible, sample the sites at approximately the same time of day to avoid the possibility of diurnal fluctuations.

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