CO_2 Concentrations in Forests along a Topographic Gradient

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ABSTRACT: CO_2 concentrations and air temperatures were measured at seven levels at 2-hr intervals for 24 hrs at stations along a slope leading from an upland oak forest into a cedar swamp. Skies were clear and the winds light over the period. Although there was evidence for cold air drainage downslope and concentration of CO_2 in low sites during the early evening hours, temperatures tended to become isothermal at all stations along the gradient later in the night while CO_2 concentrations were higher near the ground on the slope but vertically uniform in the swamp. There was little evidence that CO_2 concentrations were significantly higher through most of the night in the swamp than on the upland.

INTRODUCTION

CO_2 concentrations fluctuate in nature because of variation in rates of photosynthesis and respiration, and changes in microclimatic conditions. Investigations have shown that CO_2 concentrations are generally higher in forests than in fields or grasslands (Fuller, 1948; Wiant, 1964), and that concentrations increase markedly near the ground (Huber, 1952; Mitscherlich *et al.,* 1963; Sparling and Alt 1966; DeSelm, 1952). Near the ground, concentrations may vary spatially depending on sunlight penetration or proximity to CO_2-rich sources such as decaying logs (Wiant, 1964). Biological and microclimatic changes associated with the diurnal cycle produce large changes in CO_2 concentrations at all levels, but especially near the ground. Tabulated data presented by Mitscherlich *et al.* (1963) for a 24-hour period showed average maximum changes of 51 ppm at the 1 m level, 32 ppm at 5 to 5.5 m level, and 25 ppm at various heights within tree crowns.

The purpose of this study was to measure topographic influence on concentrations of CO_2. The study was conducted at Cedar Creek Natural History Area, Anoka Co., Minnesota, 48 km north of Minneapolis. The site was on a sandy peninsula nearly surrounded by a peat-filled basin supporting a white cedar (*Thuja occidentalis* L.) swamp forest. Upland vegetation on the peninsula was dominated by northern pin oak (*Quercus ellipsoidalis* E. J. Hill). A narrow "lagg" (marginal fen) community about 20 m wide was located along the sand-peat intersection at the foot of the slope. This community was dominated by black ash (*Fraxinus nigra* Marsh.), American elm (*Ulmus americana* L.) and speckled alder (*Alnus rugosa* (Du Roi) Spreng).

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The topographic transect extending from the crest of the peninsula to 20 m within the cedar swamp was 78 m long and dropped 2.1 m in elevation. Although the gradient was slight, it was obvious from experience that on calm evenings, cold air drained from the upland to the lagg and swamp. Since cold air drains down from radiating foliage surfaces at night, presumably considerable amounts of CO_2 resulting from leaf respiration move towards the forest floor with this drainage. Also, since large amounts of CO_2 are released from the forest floor, it would seem that cold air moving downslope and collecting in basins would be particularly enriched in CO_2. This study was designed to measure the degree of this enrichment along the topographic gradient.

Acknowledgments.—This study was supported by N.S.F. grant No. GB-3636 and the Graduate School of the University of Minnesota. Special appreciation is due Dr. William H. Marshall, Director of Cedar Creek Natural History Area, for services and use of the area.

METHODS

Four 6.1 m poles of electrical conduit were located along the topographic gradient. One was located on the peninsula crest (A), the second midway downslope in the oak forest (B), the third in the lagg (C), and the fourth in the cedar swamp (D). The tops of these "towers" reached into the lower portions of the oak forest and lagg canopies, and about midway into the cedar canopy. Pulleys were arranged at the top of each of these towers so that a thermocouple and ¼-inch ID polyvinyl chloride tubing could be raised to desired levels.

Every two hours for a 24-hr period, CO_2 concentrations and air temperatures were measured at each tower at 0.06, 1.0, 2.0, 3.0, 4.0, 5.0, and 6.0 m levels. Temperatures were measured with 24-gage copper-constantan, shielded thermocouples and recorded by a temperature-compensated Leeds and Northrup potentiometer. CO_2 concentrations were measured by drawing air through the tubing to a Beckman model 15-A infrared gas analyzer. The analyzer was recalibrated at least every two hours. Temperatures were accurate to 0.5 C. The accuracy of CO_2 concentration measurements varied with concentration. Approximate accuracies are 2 ppm between 280 and 380 ppm, 10 ppm between 381 and 480 ppm, and 20 ppm at concentrations greater than 480 ppm.

The first 2-hr period began at 0900 hr CST, 25 Aug. 1966, and the last period ended at 0847 hr, 26 Aug. Sunset on 25 Aug. was 1903 hr CST, sunrise on 26 Aug. was 0528 hr. Skies were clear over the entire period. Breezes up to 11 km/hr developed during daylight hours but dropped to 3-5 km/hr between 1900 and 0800 hrs. Air speeds were measured by a cup-anemometer at 18.2 m, 4.5 m above the canopy at Cedar Creek weather station, 0.4 km from the study site. No air movement during night hours was registered by a similar anemometer located at 1.5 m above the ground in an open field. It is probable that inversion conditions occurred over the night hours. A

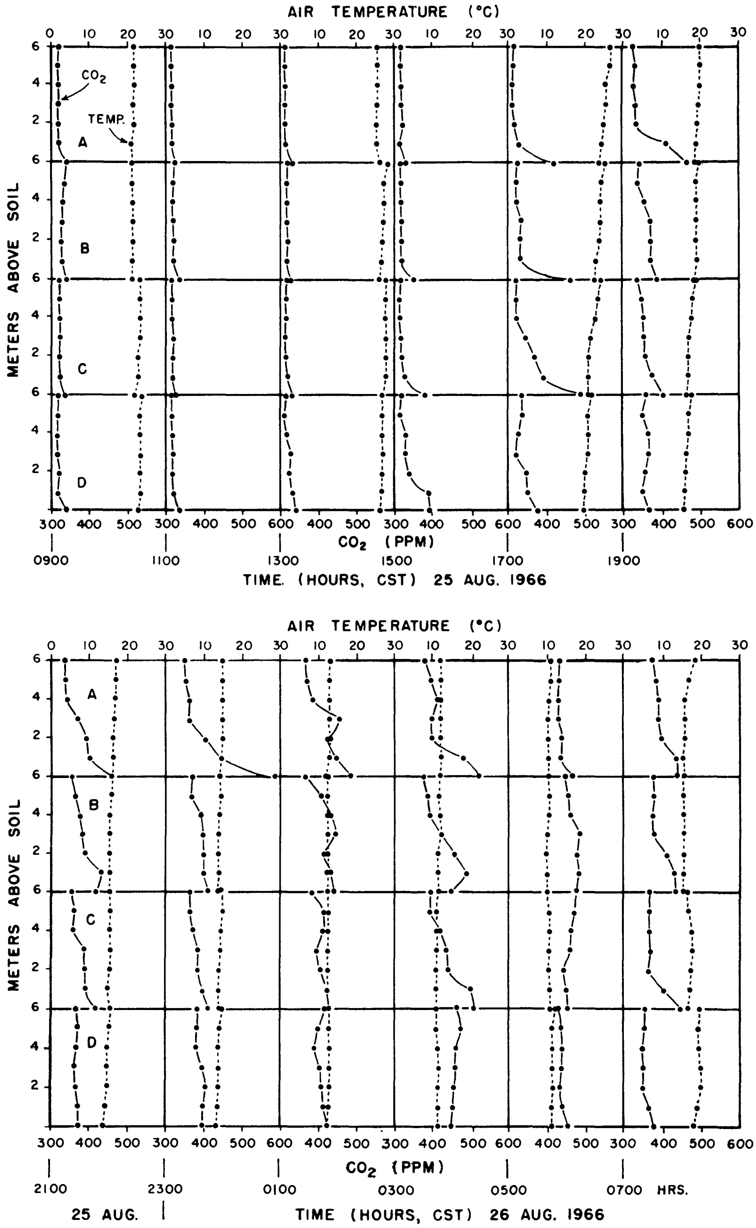

Fig. 1.—CO_2 and temperature profiles for four stations (A, B, C, D) for 12 two-hour periods. Values for the temperature curves are given above the graphs, values for CO_2 curves given below the graphs.

pronounced inversion was measured over St. Cloud, Minnesota, at 0500 hr., 26 Aug. 1966. Straight-line distance from Cedar Creek to St. Cloud is approximately 80 km.

RESULTS

TEMPERATURE

Temperature and CO_2 data are plotted together in Fig. 1. Temperature data are lacking for the 1100 and 1500 hr periods. Temperature profiles were very nearly isothermal in the 0900 and 1300 hr periods and temperatures were slightly higher, ca. 1 to 2 C, at C and D compared with upslope position A and B.

At 1700 hr, temperatures were 2 to 3° lower near the ground than at 1 m at all stations and distinctly lower at all levels than at 1300 hr. Temperatures at all levels tended to decrease downslope. The same characteristics were measured at 1900 hr except that temperatures were still lower.

Although temperatures continued to decline at all levels at all stations for the remainder of the night, differences between stations diminished until by 0100 hr air at all stations was at nearly equal temperature. Conditions at all stations were isothermal between 0100 and 0700 hr.

By 0700 hr temperatures began to rise rapidly, with the C and D stations apparently warming more quickly than the A and B stations.

CO_2 CONCENTRATION

CO_2 concentrations decreased slightly in the A, B, and C stations from 0900 to 1300 hr. Concentrations were nearly uniform at all levels except for slightly higher values of 10 to 20 ppm between 1 m height and 6 cm. The minimum concentration throughout the entire period was 312 ppm at 4, 5, and 6 m heights at station A at 1700 hr.

At 1500 hr a distinct increase in CO_2 occurred near the ground in stations B, C, and D. This trend continued at 1700 hr but included station A. At 1900 hr CO_2 increased significantly at upper levels at all stations while it remained the same or even decreased slightly at levels near the ground.

CO_2 continued to increase at nearly all levels through the 0500 hr period. In general, concentrations tended to become vertically uniform later in the night, this tendency beginning first in the C and D stations, then spreading to B and A stations. By 0500 hr profiles for all four stations were reasonably uniform vertically but more regular in C and D. The tendency for concentrations to be higher near the ground persisted longest at the A and B stations. The average CO_2 concentration in ppm at 0500 hr, the period of generally highest values, was 439 for A, 469 for B, 460 for C, and 439 for D. The highest concentration recorded over the entire 24-hr period was 584 ppm at 6 cm, station A, at 2300 hr.

At 0700 hr CO_2 began to decline at all stations but apparently most rapidly at C and D. Concentrations decreased more rapidly at upper levels than lower levels.

DISCUSSION

As temperatures dropped between 1300 and 1700 hr, and then rose again between 0500 and 0600 hr, it appeared that changes occurred earliest in the lagg and swamp stations (C, D). While this may have been true, it should be recognized that the measurement periods were two hours long and the stations were measured in a downslope order. Since large changes in microclimate can occur in two hours, it should be expected that the changing characteristic would be more advanced at the end of the period. The ends of periods coincided with the times downslope stations were measured. A lack of absolute synchrony must be considered in interpreting these results.

As temperatures decreased and CO_2 concentrations increased between 1300 and 2400 hr, the levels nearest the ground were both lowest in temperature and richest in CO_2. This indicated that cold, CO_2-rich air was lying on the ground surface and one would expect this denser air to move downslope, creating deep, cold pools of air in the swamp and lagg. To some extent this seems to be the case. For example, CO_2 concentrations were highest near the ground and higher at 1 m level in D than C at 1500 hr, and temperatures were steadily lower downslope at 1700 hr. That these gradients represented evidence for downslope air movement is disputable because of the problem of non-synchronous measurements discussed above.

It is quite clear that by 2100 hr temperatures were no lower in the lagg and swamp than on the oak-forested slope. This was true through the rest of the night. Furthermore, temperature profiles were essentially isothermal, indicating that on this particular night no cold-air pools were peculiar to low-lying communities. The fact that A and B CO_2 profiles continued to show higher concentrations between the ground and 2 m for most of the time between 2300 and 0700 hr, may be evidence of continued downslope movement of slightly denser, CO_2-rich air. Yet the CO_2 profiles in the lagg and swamp are nearly uniform vertically. If downslope movement of CO_2-rich air did occur, it would seem that CO_2 concentrations at C and D would either be very high near the ground, or, if the pool were fairly deep, concentrations would be higher throughout the C and D profiles compared with upslope stations. Neither case was true.

This situation may have resulted from one of several factors. Diffusion may have accounted for some loss of CO_2 stratification but could not have been entirely responsible. A slight amount of forced convection was recorded over the night and may also have contributed to mixing. Occasional gusts were reported by De Selm (1952) as having disrupted nighttime stratification in a beech forest. It is difficult to understand, however, why such light breezes as recorded in this study might have affected the lower, denser, swamp forest more than the upland forest.

A third factor may have been the minimization of downslope air movement after early evening hours because of evenly distributed cold air resulting from the deep inversion. Under these conditions, the more prolonged concentration of CO_2 near the ground at A and B may have developed from higher CO_2 evolution rates from forest floors in the oak forest than in the lagg and swamp and may have been unrelated to downslope movement. On the basis of extensive measurement of CO_2 evolution from forest floors in this area, however, it would be expected that nighttime CO_2 evolution rates from the oak forest floor would be less, not greater, than in the lagg and swamp communities.

A fourth possibility is that a deep pool of CO_2-rich air may have developed in the swamp, but under the meteorological conditions of the night became so deep that the top of the pool exceeded the highest measured level, 6 m. This hypothesis is weakened by the fact that if such a deep pool of CO_2-rich air did develop, and if it did have a level top, the top would have intersected the slope of the peninsula at some well-defined levels of stations A and B. No such intersection is obvious. It is possible that the pool may have been much deeper than 6 m, the top of the tower in the swamp, but if so, it would have entirely overridden the entire peninsula and not represented a result of the topographic gradient.

The fifth hypothesis is that downslope air movement may have occurred but, rather than producing a stagnant pool of cold air in the swamp, this movement produced a somewhat cyclic pattern of air flow as described by Van Arsdel (1965, 1967). According to Van Arsdel, under calm conditions, cold air flows downslope to swamps but is pushed upward into the swamp canopy by constantly underriding air. This rising air then may circulate a short distance aloft depending on the height of the shallow inversion ceiling, sinking over upslope sites, flowing down to the soil, and then downslope again, completing the cycle. Such circulation patterns have been observed by Van Arsdel with the use of smoke bombs.

At present, this last hypothesis may present the best explanation for the fact that although CO_2 profiles at C and D were nearly uniform vertically between 2300 and 0700 hr, profiles at A and B showed higher concentrations along the ground. Rising air in the lagg and swamp would produce vertically uniform CO_2 profiles. Unfortunately, temperature profiles at A and B do not indicate colder air along the ground, which would be better evidence for downslope movement and support the hypothesis that cyclic patterns existed.

The distribution of CO_2 described in this study is incompletely understood but with better instrumentation might be better explained. Collection points located well above the canopy, and smoke bomb devices would be helpful in understanding this phenomenon. Automated data collecting and recording devices would be extremely useful, allowing replication of these observations over longer periods and diverse conditions.

Whatever the explanation, results from this study did not show an extraordinary increase in CO_2 concentration in low-lying sites compared with upland sites under clear, calm, nocturnal conditions. Some process tended to maintain CO_2 concentrations at approximately equal values along the topographic gradient. For these conditions, exceptionally abundant CO_2 does not appear to be an important environmental factor for the swamp and lagg communities except for the more rapid accumulation of CO_2 in early evening hours and hence, longer periods of time under a CO_2-rich atmosphere.

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SUBMITTED 14 JUNE 1967 ACCEPTED 13 JULY 1967