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CONCENTRATION OF CO_2 IN THE AIR ABOVE A SUGAR BEET FIELD*

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ABSTRACT

The concentration of CO_2 in air sampled above a sugar beet crop was measured during July, August, and early September 1966 at Scottsbluff, Nebr. During July the mean daytime concentration decreased from 310 ppm to 283 ppm as the leaf area index increased from 0.8 to 4.0. Only small deviations from the mean daytime concentration of 283 ppm occurred during the remainder of the season. The mean nocturnal concentration during this period was 320 ppm and was more variable than the daytime concentration. The daily amplitude of concentration averaged 70 ppm and was as great at times as 100 ppm.

Regression analysis revealed strong negative correlation between CO_2 concentration and mean wind speed during the night. Mean concentration was independent of mean temperature, mean incident radiation, and predominant wind direction.

During each day the concentration remained constant between 1½ hr after sunrise and 1 hr before sunset except for a few cases. These were associated with incident radiation below 0.2 cal $cm^{-2} \cdot min^{-1}$ and/or wind speeds at 25 cm above the crop of less than 0.3 m sec^{-1} or more than 3 m sec^{-1}.

Evidence is presented that the concentrations reported here are at least partially dependent on the flux to and from the sugar beet crop.

1. INTRODUCTION

The daytime concentration of CO_2 surrounding the leaves in a field is expected to depend upon the rate of net photosynthesis, the rate of soil respiration, [CO_2] [1] in the bulk air, and the rate of the turbulent transport which conveys CO_2 from the bulk air to the leaves. The same factors regulate the nighttime concentration except that respiration prevails.

The influence of [CO_2] on photosynthetic rates of several species has been reported. For most crops the photosynthetic rate of individual leaves (Gaastra 1959; Bierhuizen and Slatyer 1964) as well as plant communities (Thomas and Hill 1949) depends directly on [CO_2] between 200 and 500 ppm. In order to interpret these results in terms of field responses, information about [CO_2] in the field must be available.

This research was conducted as part of a study of windbreak influences on CO_2 flux and photosynthesis. The results of other phases of the research which were conducted simultaneously will be reported elsewhere.

2. MATERIAL AND METHODS

The 4.2 hectare sugar beet (*Beta vulgaris*) field used for this experiment was located at the Scottsbluff Experiment Station of the University of Nebraska (1225 m above MSL, latitude 40°57′ N., longitude 103°41′ W.). The climate of the area would be classified as "dry middle latitude steppe" in the Köppen system. The field was irrigated, as were all surrounding fields. Most of the land in this part of Nebraska is used for range or dryland wheat except for the intensively cultivated irrigated lands in the valley of the North Platte River, in which the station is located. The predominantly southeast winds traverse several kilometers of irrigated lands before reaching the experimental field. The field was carefully selected to provide the best fetch possible.

The [CO_2] reported here is for samples collected at crop height. The wind speeds were measured at 25 cm and 100 cm above the crop height. During July the air sampling tubes and anemometers (Casella [2] mechanical contact) were raised periodically to adjust for the increase in plant height.

Observations were also made of incident solar radiation (Eppley), net radiation (Fritschen), and air temperature (shielded and aspirated thermocouples) every 15 min. Only the CO_2 measuring system will be described in detail here.

A continuous flow system (fig. 1) was constructed to sample air at six locations. The field lines and mixing chambers were purged continuously except when subsamples were drawn for analysis. Purge rate and sample rate were identical; thus a constant flow rate was maintained in the field lines and mixing chambers at all times. During a measurement cycle, samples were drawn from each mixing chamber in turn. The samples were dried and enough time allowed for the analyzer to equilibrate before the signal was recorded.

The air to be analyzed was sampled in the field by drawing it through a .635-cm (¼-in.) OD copper tube.

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[1] [CO_2] will be used as an abbreviation for the concentration of CO_2.

[2] Mention of commercial products does not constitute endorsement.

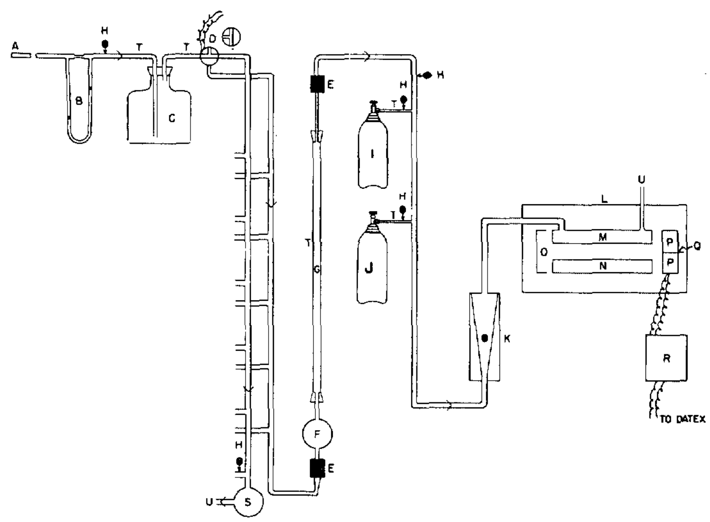

FIGURE 1.—Schematic diagrams at the CO_2 sampling system. All lines on the recorder side of the manometer were kept as short as possible. The lines were $\frac{1}{4}$-in. OD copper tubing except those labeled T which were $\frac{1}{4}$-in. ID tygon tubing. The letter A represents a nylon stocking filter; B, the flow rate manometer; C, the mixing bottle; D, the three-way solenoid valve; E, the dust filter; F, the diaphragm sample pump; G, the desiccant column; H, the needle valve; I, the upscale standard gas tank; J, the downscale standard gas tank; K, the rotameter; L, the infrared gas analyzer; M, the sample cell; N, the reference cell; O, the infrared source; P, the detector; Q, the diaphragm; R, the amplifier; S, the impeller purge pump; T, the tygon tubing; and U, the exhaust.

Ends of the tubes were covered with several layers of fine nylon mesh (stockings) to prevent insects and dust from entering. The field lines, which were as long as 122 m, were assembled from 6.1-m rigid copper tubes. The lines were suspended on fence posts and the soldered junctions were checked periodically for leaks. Repeated tests during both day and night did not indicate the presence of water in the lines except during short periods after heavy rains. The well-exposed lines were heated sufficiently by the sun to prevent internal condensation during the day. Flow manometers were used in each of the six field lines to allow for periodic checks of flow rate. Samples flowed through 3.78-liter (1-gal) containers at the rate of 4 liters min^{-1}. This arrangement produced a time constant of 57 sec. Three-way solenoid valves (Skinner Model V5) were activated by a signal from the recorder. When a sampling cycle was initiated, the first solenoid was switched from the purge manifold to the sample manifold. The analyzer signal for the first sample was recorded 10 sec later. After recording, the first solenoid was switched back to the purge position and the second solenoid was switched to the sample position. Subsequent recording and switching was done at 6-sec intervals. While samples were being analyzed, the purge pump (Gast Model D321–V3–G180B) drew air through five lines instead of the usual six. Only a fraction of the purge pump capacity was used. Consequently, the switch from six to five lines did not alter the purge flow rate significantly.

Porous metal dust filters (Hoke, B541) were used in the line before both the sample pumps and the infrared gas analyzer. A positive displacement diaphragm pump (Cole-Parmer Model 7060) was selected to pump the gas through the analyzer. Anhydrous calcium sulphate (Drierite) with an indicating dye in a 75-cm length of 1.27-cm ID tygon tube was used as a dessicating column. The dessicant was changed frequently.

A needle valve was included in the system to allow adjustment of flow rate and to isolate the sample line during calibration. Two tanks of standard gas were used for the frequent calibrations required. A rotameter was included in the line between the pump and the analyzer. The flow rate was maintained at 4 liters min^{-1} during all sampling periods as well as during analyzer calibration.

The concentration of the standard gases used to calibrate the infrared gas analyzer (Beckman Model 315) were determined by a gravimetric technique given by Brown and Rosenberg (1968).

The analyzer was recalibrated approximately every 4 hr during the day. The standard deviation of drift before the 187 calibrations conducted during the 1966 season was 13.6 ppm. The fact that drift was directly related to length of time between calibrations led to the use of the assumption that analyzer drift was linear between calibration times. Concentration data recorded in the period between calibrations were corrected for both downscale and upscale drift as a function of time. These corrections are insignificant in calculating concentration differences measured within a short period of time. Had the corrections not been made, however, absolute concentration values would occasionally have been in error by as much as 20 ppm.

3. RESULTS

ANNUAL CYCLE OF [CO_2]

The rate of biological activity changes with season. Therefore [CO_2] in air should show a seasonal dependency. In order to characterize the cyclical variation in [CO_2], mean day and night concentrations were calculated between 0800 and 1600 and between 2000 and 0400 hr, respectively. These times were selected to avoid transition periods and to eliminate the necessity of adjustments for changes in sunrise and sunset times. The resulting averages are presented in figure 2. Although data were taken for only $2\frac{1}{2}$ mo, during the growing season a portion of the annual cycle of mean [CO_2] is evident. The decrease in mean daytime concentration during July is highly correlated with the increase in leaf area index during this month. The field appeared to be nearly covered with leaves by July 15. However, mean daily concentration did not reach its minimum until August 1, by which time leaf area index (LAI) had reached 4. Between August 1 and September 12, the mean daily concentration was nearly constant at 283 ppm.

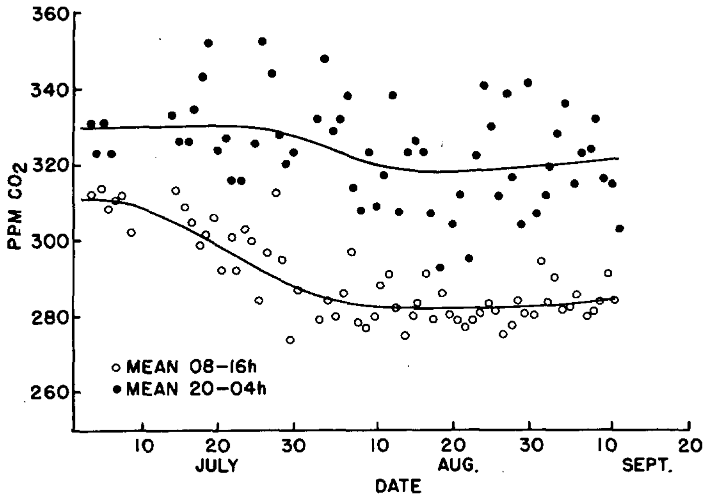

FIGURE 2.—Mean daytime (open circle) and nocturnal (solid circle) concentration of CO_2 in air sampled at plant height over a sugar beet crop.

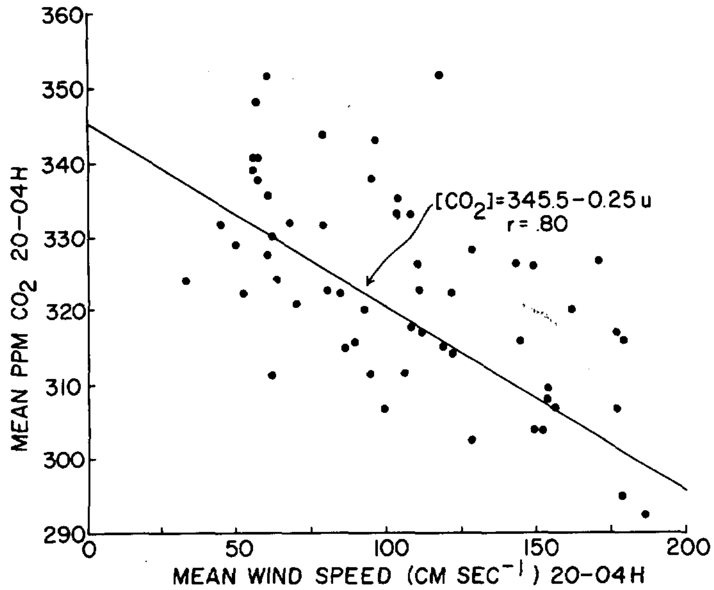

FIGURE 3.—Mean nocturnal concentration as a function of mean wind speed.

The mean nocturnal concentration also decreased during the period of the study. The decrease lagged behind the mean daytime decrease by about 15 days. Nocturnal [CO_2] decreased by only 10 ppm as compared to the 28 ppm decrease in mean daytime [CO_2]. Between August 1 and September 12, the mean nocturnal concentration was 320 ppm.

DIURNAL CYCLE OF [CO_2]

The diurnal cycle of biological activity caused amplitude of the mean diurnal concentration cycle to increase from 20 ppm during early July to 70 ppm during August and September (fig. 2). The day-to-day variation in the mean daytime concentration is only about one-fourth of that which occurred during the night.

A regression analysis of independent environmental parameters against dependent mean daytime and nocturnal [CO_2] was conducted for data collected between August 1 and September 12. The parameters included as independent variables were: mean incident solar radiation (daytime only), mean wind speed, predominant wind direction, mean air temperature, and soil water potential.

The greatest share of the variance in mean daily concentration was associated with changes in mean wind speed and soil water potential. Increases in mean wind speed and decreases in soil water potential were associated with increases in the mean concentrations. The mean incident radiation was not significantly related to the concentration. This probably occurred because during the experimental period a large portion of the days were nearly clear providing, thereby, a very limited range of light intensity for study. During clear calm days the concentration was 2 ppm lower than average. On clear days with mean wind speeds greater than 2 m sec^{-1} at 25 cm above the crop the concentration was 7 ppm greater than average.

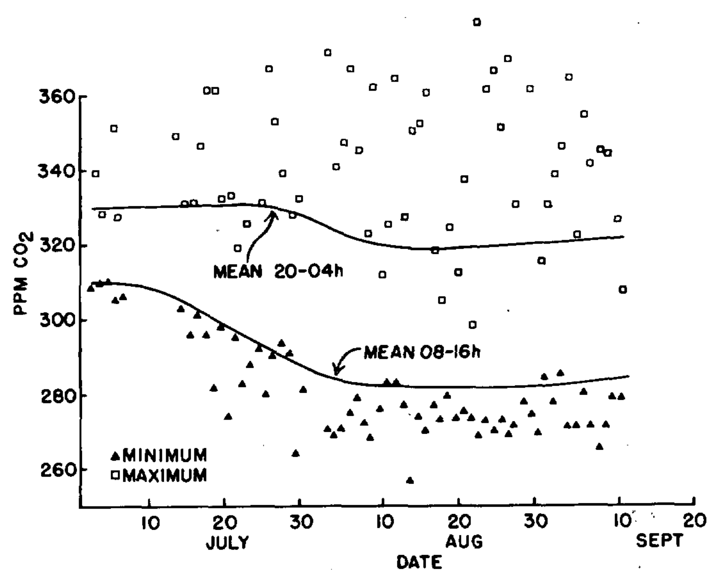

FIGURE 4.—Highest and lowest hour average concentration of CO_2 during the day and the night. The air was sampled at crop height in the open field. The curves are the daytime and nocturnal means which are repeated here from figure 2.

As can be seen in figure 3, mean nocturnal concentration is dependent on wind speed.

The extreme hourly average concentration for each day is plotted in figure 4. The amplitude of the daily cycle of concentration during August and September averaged 70 ppm with a maximum of 100 ppm and a minimum of 27 ppm. The maximum concentrations generally occurred at 0400 or 0500 hr and the minimum between 1200 and 1500 hr.

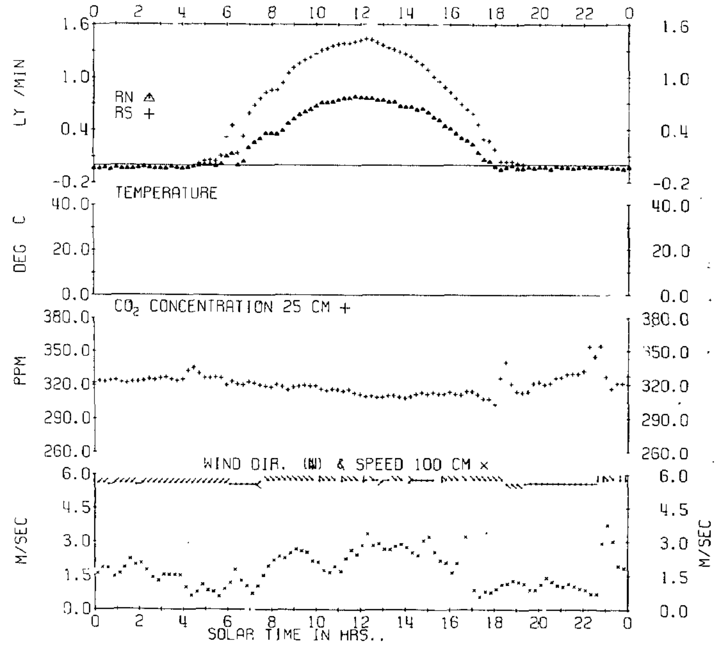

FIGURE 5.—Microclimatic data for July 4, 1966, recorded above an open sugar beet field. RS and RN represent incident solar radiation and net radiation, respectively.

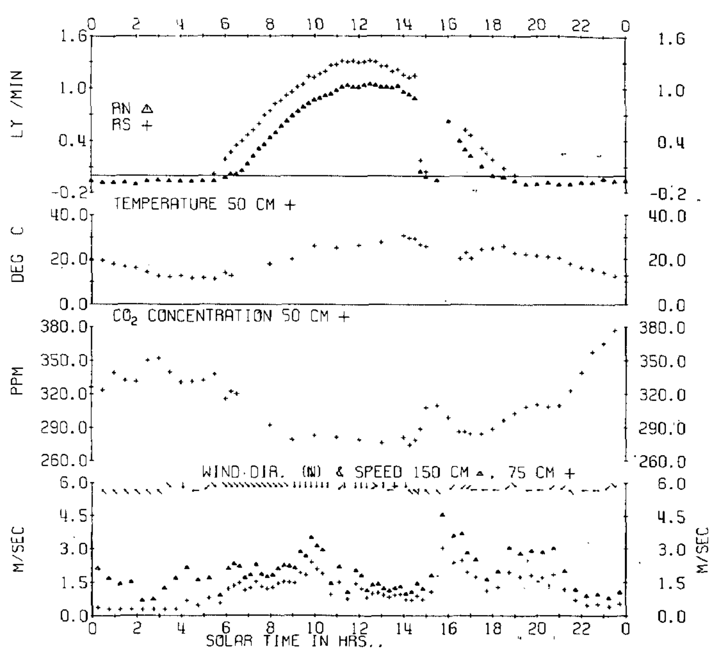

FIGURE 6.—Same as figure 5 for Aug. 6, 1966.

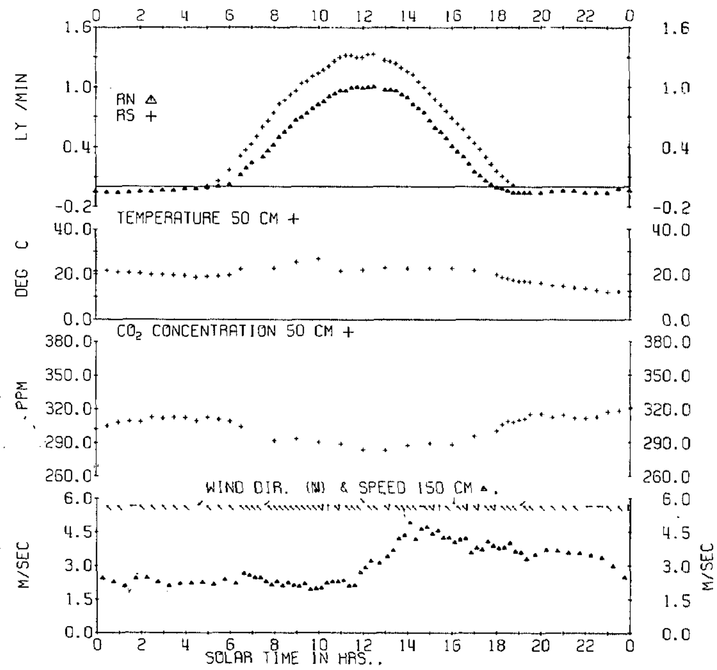

FIGURE 7.—Same as figure 5 for Aug. 11, 1966.

It is impractical to present in detail all data taken during the 63 days of this experiment. For this reason, average concentration and associated parameters were used above in an attempt to generalize our results. Averaging, however, tends to obscure interesting relationships. Data for several selected days are given to demonstrate certain of these.

July 4 (fig. 5) was a clear day with moderate wind speed. The LAI was 0.8 and only a small fraction of the ground was covered. Approximately half of the fields surrounding the experimental site were covered with lush alfalfa. The only major deviations from a nearly steady [CO_2] occur at 1830 and at 2230 when wind speed was low.

August 6 (fig. 6) was clear except for dense cumulus which occurred between 1445 and 1630. The wind speed fluctuated early in the day but had calmed by 1430. The wind speed increased sharply after this time and decreased again after the clouds had passed. The simultaneous occurrence of low radiation and high wind speed caused an increase in [CO_2] from 278 to 310 ppm in about 45 min. The concentration decreased again to 285 ppm after the passage of the clouds and the abatement of the wind. On only a few occasions during the experiment did [CO_2] increase more than 10 ppm above the daytime average. All of these cases were associated with frontal passages as described above. The correlation between wind speed and nocturnal [CO_2] can readily be seen on this day. The concentration of 378 measured in the open plot at 2330 was among the highest recorded.

August 11 (fig. 7) was a clear day with wind speeds greater than 2 m sec^{-1} at 100 cm above the crop. The wind was strong enough to prevent the nocturnal buildup of [CO_2] and to keep the daytime concentration 5 ppm above the average. On this day the change in [CO_2] from day to night was very smooth. The increase in wind speed from 2 m sec^{-1} at 1145 to 5 m sec^{-1} at 1400 was accompanied by an increase in [CO_2] of less than 4 ppm.

August 27 (fig. 8) was cloudy during the morning and very calm before sunrise and again after 1600. The low

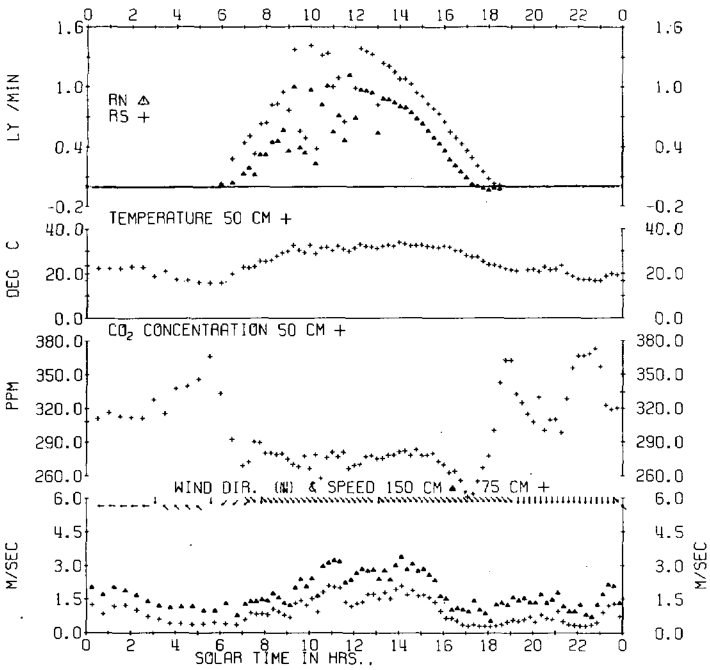

FIGURE 8.—Same as figure 5 for Aug. 27, 1966.

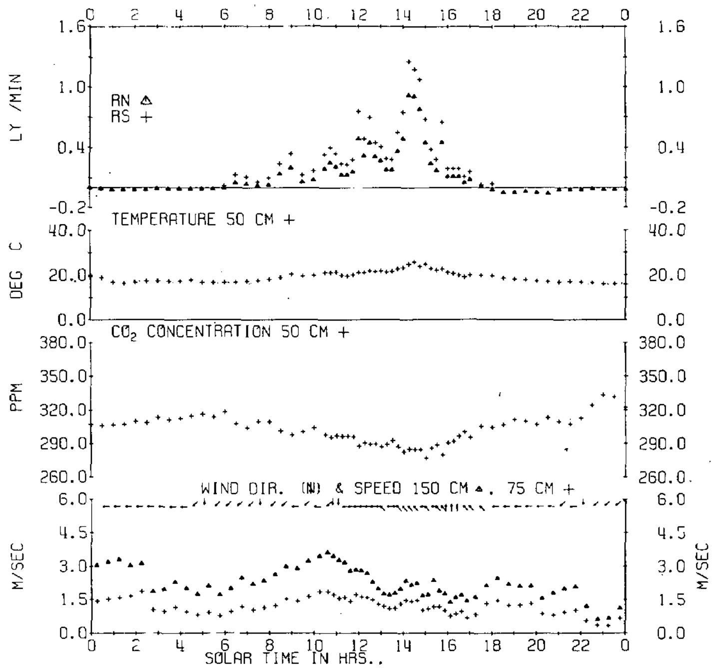

FIGURE 10.—Same as figure 5 for Sept. 1, 1966.

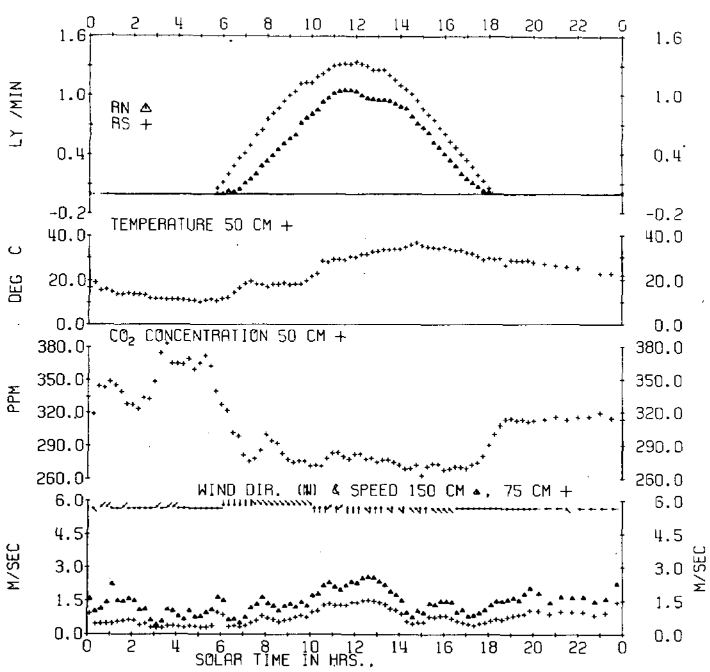

FIGURE 9.—Same as figure 5 for Aug. 28, 1966.

wind speeds at sunrise and sunset resulted in sharp changes in concentration at these times. At both times concentration changes of 100 ppm occurred in less than 90 min. The occurrence of scattered clouds during the morning was associated with only small fluctuations in [CO_2]. The existence of calm conditions after 1600 resulted in a decrease in [CO_2] to 238 ppm. This was the lowest concentration recorded during the study. The correlation between nocturnal wind speed and concentration is again evident.

August 28 (fig. 9) was a clear day with low wind speeds. The concentration fell off rapidly between sunrise and 0700 hr. Between 0700 and 0800 the wind speed increased from 0.3 to 0.6 m sec^{-1}. The [CO_2] increased by 24 ppm during this period. Between 0800 and 0900, the winds decreased again to nearly their original speed. The [CO_2] also decreased during this period. A similar fluctuation of wind speed around 1600 did not cause a similar change in [CO_2]. Calculations of the flux of [CO_2] from gradient measurements yielded nearly identical flux rates at 0800 and 1600. This indicates that the increase in concentration observed at 0800 was a result of increased mixing with the bulk air, which had a greater [CO_2] at this time, than at 1600.

September 1 (fig. 10) was a heavily overcast day with wind speed averaging 1 m sec^{-1}. The amplitude of the diurnal [CO_2] cycle was small. Instead of the usual rapid decrease and increase associated with sunrise and sunset, the transition periods were very long. The minimum concentration was reached after 1400 when the sun shone through a gap in the clouds.

In no case was any increase in [CO_2] found during the day which cannot be associated with either a change in the wind speed, the light intensity, or both. During the day when the wind speed and incident radiation were nearly constant [CO_2] remained nearly constant.

The nocturnal [CO_2] was highly dependent on the wind speed. Once the crop covered the ground, the concentration was found to be greater than 320 ppm when the wind

TABLE 1.—*The mean and extreme day and night concentration of CO_2 in the field air in and above various crops*

Crop	Crop height (cm)	Measurement height (cm)	Dates	No. of days	Concentration CO_2 (ppm) Day (08–16 hr) Min	Day Ave	Day Max	Night (20–04 hr) Min	Night Ave	Night Max	Author
Alfalfa (*Medicago sativa*)	h	h–5	Clear days in open	4½	......	305	......	......	......	......	Ruesch (1955)
Rice (*Oryza sativa*)	75–90	100	July 27–28 & Sept. 2–3	4	......	240	......	......	325	......	Horibe (1964)
Wheat (*Triticum vulgare*)	?	100	......	1	......	315	......	......	425	......	Huber (1960)
Timothy (*Phleum pratense*) & Fescue (*Festuca elatior*)	85	85	May 24–25	1	......	290	......	......	360	......	Monteith (1962)
Corn (*Zea mays*)	25–85	50–100	July	21	266	294	324	290	372†	430	Allen (1968)
	85–200	150–200	Aug	11	260	279	300	308	370†	453	
	200	200	Sept. 1–12	10	280	293	302	322	367†	399	
Corn (*Zea mays*)	?	100	July 15	1	......	254	......	......	356*	......	Chapman et al. (1954)
Corn (*Zea mays*)	190	190	July 23–Sept. 2	11	268	280	307	281*	302*	341*	Tamm & Krzych (1961)
Sugar beets (*Beta vulgaris*)	50	50	Sept. & Oct	?	261	274	294	302*	363*	439*	Tamm & Krzych (1961)
Sugar beets (*Beta vulgaris*)	25–40	25–40	Open July	22	274	301	314	316	330	352	Measurements reported here
	50	50	Open Aug	29	275	283	297	293	320	348	
	50	50	Open Sept. 1–12	12	280	285	294	303	320	336	

†Average of minimum and maximum
*Partial record

speed at 25 cm above the crop was 0.75 m sec^{-1} or less. When the wind speed was between 0.75 and 2 m sec^{-1}, the concentration was generally about 320 ppm, and less than 320 ppm when the wind speed was greater than 2 m sec^{-1}. On several occasions when high speeds occurred at night, turbulent exchange was strong enough to reduce [CO_2] to 290 ppm.

The [CO_2] during most days decreased to very near the 0800 to 1600 average within 1½ hr after sunrise. Between this time and about an hour before sunset, the concentration deviated from this value occasionally by more than 10 ppm. Such deviations were associated either with levels of incident radiation below 0.2 cal cm^{-2} min^{-1} resulting from the presence of dense clouds, with wind speeds of less than 0.3 m sec^{-1}, or with a rapid increase in wind speed to greater than 3 m sec^{-1} at 25 cm above the crop. The majority of these deviations were caused by a combination of low radiation with high wind speed.

4. DISCUSSION

Measurements of mean [CO_2] in the atmosphere are complicated by both diurnal and annual cyclical phenomena. Despite these difficulties, several upper atmospheric sampling programs have produced enough information to permit definition of the mean global [CO_2]. A survey of literature by Allen (1968) reveals that the mean concentration during 1962 was 315 ppm. Pales and Keeling (1965) and Bischof and Bolin (1966) report that atmospheric [CO_2] is increasing at the rate of 0.7 ppm per year. Extrapolation from this data yields a mean concentration during 1966 of 318 ppm. The mean of our data during the 2½ mo of this experiment was 307 ppm. The difference between these two concentrations is not unexpected since the present research was conducted during the summer when net flux of CO_2 at the crop surface is downward.

A summary of available data on [CO_2] at or near crop height is given in table 1. The data were collected above fields in many of the agriculturally important areas of the world. Not all of the data were recorded at the height of the crop. Profiles of [CO_2] in and above various crops (see Tamm and Krzych 1961, Monteith 1962, Long et al. 1964, and Lemon 1967) reveal that midday differences between two levels are about 4 ppm $(25\ cm)^{-1}$ above most crops and within tall open crops. The concentration differences within short dense crops may be as great as 10 ppm $(25\ cm)^{-1}$.

Interpretation of much of the data presented in this table is made difficult by the lack of relevant meteorological data. Nonetheless, it is evident that most of the mean daily concentrations are in close agreement with the 283-ppm mean daily concentration reported here. Those reported means which deviate greatly from this value were generally derived from limited observations. We may, therefore, conclude that the mean daily [CO_2] in air at the height of field-grown crops is of the order of 280 ppm and is nearly independent of the crop and the location of the field. Mean daily concentrations may be expected to range between 260 and 300 ppm. These observations are in good agreement with theoretical calculations of Monteith et al. (1964).

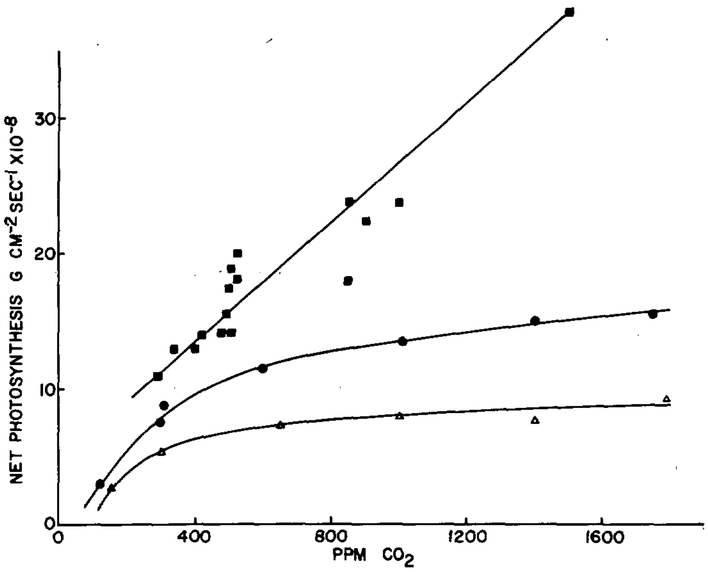

FIGURE 11.—Dependence of the net photosynthetic rate [gm(CO_2) cm^{-2} sec^{-1}] of sugar beets on the concentration of CO_2 in the air. The net photosynthetic rate of a field-grown crop per unit ground area presumably at full sunlight (1.2 cal cm^{-2} min^{-1}) after Thomas and Hill (1949) (solid square) and of isolated leaves per unit leaf area at 1.2 cal cm^{-2} min^{-1} (solid circle) and at .36 cal cm^{-2} min^{-1} (open triangle) after Gaastra (1959).

The concentrations encountered in this experiment ranged from 238 ppm to 382 ppm. Field concentrations as low as 210 ppm have been reported by Chapman et al. (1954) in a corn crop and by Tamm and Krzych (1961) above a sugar beet field. Allen (1968) reported nocturnal field concentrations in excess of 500 ppm.

The dependence of the photosynthetic rate of a sugar beet crop and of isolated sugar beet leaves on [CO_2] is shown in figure 11. From these data, it is evident that at light intensities and [CO_2] encountered in the field the photosynthetic rate of the crop approximates a linear function of [CO_2] in the air.

The question often arises as to whether [CO_2] in the field air limits the rate of photosynthesis. In order for a factor to be rate-limiting in a process, the rate of the process must be independent of all other factors. Therefore, the [CO_2] does not limit the rate of photosynthesis but is one of the factors which regulates it. The slope of the straight line in figure 11 indicates that the rate of photosynthesis increases four times for a five-fold increase in [CO_2].

Assuming mean atmospheric [CO_2] to be 318 ppm and using a mean station pressure of 880 mb, our calculations show that all the CO_2 in a layer of air 30 m thick would be required to support the mean photosynthetic rate of 1.5×10^{-3} gm (CO_2) cm^{-2} day^{-1} which was measured in this field. More realistically, if the concentration is assumed to be reduced uniformly from 318 to 283 ppm, a layer of air 276 m thick must be available to the crop daily. Chapman et al. (1954) reported that [CO_2] differences were only 20 ppm between the surface and 152 m. Thus, since [CO_2] is not reduced uniformly in the layer of air above the surface, it is evident that the crop extracts CO_2 from a very large volume of air each day. The magnitude of the volume of air involved indicates that the natural vertical turbulent transport is a vigorous process. This also suggests that it would be difficult to artifically increase [CO_2] in field air sufficiently to significantly influence photosynthetic rates, because the released CO_2 would be quickly swept away.

Mean nocturnal [CO_2] is much more variable. The dependence on wind speed reported here is in agreement with that reported in the literature (Allen 1968). The mean nocturnal concentration of 320 ppm reported here is lower than is reported by most researchers. Two reasons may be given for this difference. First, certain fields for which data were reported by others were surrounded by trees or by tree-covered hills. For example, the field used by Allen (1968) lay in a valley surrounded by heavily wooded hills. Possibly [CO_2] resulting from respiration by surrounding vegetation may have settled in the valley during the night, resulting in the high concentrations reported. We have found that even a small windbreak in a nearly flat field can act to trap CO_2 which is evolved during the night. Second, the general level of biological activity of the dry plains which surrounded the valley in which this research was conducted was perhaps lower than that found at the other locations where the research was done. It appears, therefore, that nocturnal [CO_2] is much more dependent on the topography and vegetation of the surroundings than is [CO_2] during the daytime.

The ecological significance of nocturnal [CO_2] is not clear. It is doubtful that the nocturnal buildup would significantly decrease the respiration rate. The increased concentrations which occur on calm mornings immediately before sunrise may increase the photosynthetic rate by as much as 10 percent during the first hour after sunrise. The photosynthetic rate during this period is expected, however, to be less than 5 percent of the daily total. Therefore, the maximum increase due to the greatest measured nocturnal buildup of CO_2 would be only of the order of 0.5 percent of the total daily fixation.

The mean daytime [CO_2] reported here were correlated with factors which would be expected to influence CO_2 exchange of the sugar beet field. It was not possible, however, to separate the influence of the experimental field from that of the adjoining fields, or of all the upwind surface on the measured values of [CO_2].

The correlation with leaf area index, at a time of the year when the large expanse of land surrounding the field was already well covered with photosynthesizing vegetation, suggests that the flux to and from our field was important in determining [CO_2] above the sugar beets. The correlation with soil moisture potential in the sugar beet field, which was irrigated at different times than were the surrounding fields, even more strongly suggests that the concentrations reported here are at least partially dependent on the flux to and from the underlying surface.

ACKNOWLEDGMENTS

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