

University of Nebraska - Lincoln

DigitalCommons@University of Nebraska - Lincoln

---

Papers in Natural Resources

Natural Resources, School of

---

1976

## Carbon Dioxide Concentration and Flux in a Large Agricultural Region of the Great Plains of North America

S. B. Verma

*University of Nebraska - Lincoln*

Follow this and additional works at: <https://digitalcommons.unl.edu/natrespapers>



Part of the [Natural Resources and Conservation Commons](#), [Natural Resources Management and Policy Commons](#), and the [Other Environmental Sciences Commons](#)

---

Verma, S. B., "Carbon Dioxide Concentration and Flux in a Large Agricultural Region of the Great Plains of North America" (1976). *Papers in Natural Resources*. 1188.

<https://digitalcommons.unl.edu/natrespapers/1188>

This Article is brought to you for free and open access by the Natural Resources, School of at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Papers in Natural Resources by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

# Carbon Dioxide Concentration and Flux in a Large Agricultural Region of the Great Plains of North America

SHASHI B. VERMA AND NORMAN J. ROSENBERG

*University of Nebraska, Lincoln, Nebraska 68503*

Results of observations of CO<sub>2</sub> concentration [CO<sub>2</sub>] and flux in an area of typical agricultural land use in the east central Great Plains of North America (Mead, Nebraska) are reported. The observations were made at sufficient heights to represent an integration of CO<sub>2</sub> fixation and release due to all types of land use in the region (pasture, alfalfa, annual crops). Minimum daytime [CO<sub>2</sub>] ranges from about 295–300 ppm in late July to early August (the time of apparent maximum photosynthetic activity) to 328–332 ppm in winter. The shape of the annual CO<sub>2</sub> concentration cycle at Mead is described and compared with those for Mauna Loa, Hawaii, and Barrow, Alaska. Peak daytime flux of CO<sub>2</sub> (in g × 10<sup>-7</sup> cm<sup>-2</sup> s<sup>-1</sup>) from the atmosphere to the ground varied from about 0.5 in early June to 1.5–2.0 in late July to early August and 0.5 in late September. The net daily CO<sub>2</sub> flux (in grams per square meter), calculated from the downward daytime and upward nocturnal fluxes, is about 10–12 in early June, 18–20 in early August (maximum), 6–10 in September, and 1–5 in early October.

## INTRODUCTION

Carbon dioxide is produced in great quantities in industrial and other combustion processes. Current estimates indicate that the global CO<sub>2</sub> concentration is increasing by about 0.7–0.8 ppm/yr [Pales and Keeling, 1965; Bolin and Bischof, 1970; Newell and Dopplnick, 1970; Cramer and Myers, 1972; Machta, 1972; Goldman, 1974]. This rate of increase is only about one third to one half the estimated input from industrial and other combustion sources [Keeling, 1970; Pales and Keeling, 1965].

Causes and effects of the increase are not fully understood. Landsberg [1970] points out that there are serious gaps in our quantitative knowledge of CO<sub>2</sub> sources, whether of volcanic, fossil fuel, respiration, or organic decay origin. Sawyer [1971] emphasized that to estimate future trends in global CO<sub>2</sub> concentration will require more knowledge than is currently available on how natural carbon is distributed between various reservoirs in the air, oceans, and vegetation and how the balance between them is achieved and maintained.

Analysis of oceanic consumption rates [Keeling, 1970] suggests that the shallow layers of ocean surface waters in good contact with the atmosphere can hold less than 10% of the fossil fuel CO<sub>2</sub> which has been extracted from the atmosphere, and therefore, '... the principal sink for CO<sub>2</sub> must lie in the deep ocean or not be oceanic at all.'

Plant physiological studies, on the other hand, have shown conclusively that for many cultivated crops, net photosynthesis increases with increasing CO<sub>2</sub> concentration of the ambient air [Rosenberg, 1974]. The rates of photosynthetic fixation by terrestrial plants may already have increased in response to the increased CO<sub>2</sub> concentration, although we have no direct way of proving this effect. Greater photosynthetic capture of CO<sub>2</sub> may also lead to increased rates of respiration and decay. Thus it appears likely that a major effect of the increased global CO<sub>2</sub> concentration is an increased vegetative biomass and quantitatively greater CO<sub>2</sub> exchange.

The shape of the annual and diurnal CO<sub>2</sub> concentration curves are known for a few locations remote from major sources and sinks [e.g., Pales and Keeling, 1965]. There are some data available describing the influence of industrial con-

centrations in or near cities [Clark, 1969]. There are little data, however, on the natural patterns of [CO<sub>2</sub>] in agricultural and forested regions where the strongest sinks for CO<sub>2</sub> exist. Some CO<sub>2</sub> concentration and gradient measurements made at elevations very close to various crop canopies are available [e.g., Brown and Rosenberg, 1970; Allen, 1971; Georgiyevskiy and Khalikova, 1971; Pearman and Garratt, 1973]. These results are limited to individual crops and fields of small size.

There is a need for experimental data on the source and sink strengths which terrestrial vegetated surfaces exert for atmospheric CO<sub>2</sub> and the buffering effect of these surfaces on global concentration. Such data are needed to begin a more systematic quantification of the component parts of the carbon cycle. In view of this, an organized program of observation has been developed at a well-instrumented rural site. Measurements were made at elevations (5.6–16 m above ground) such that the CO<sub>2</sub> fluxes calculated should represent an integration of the region generally, rather than of the field in which the instrument mast stands.

## EXPERIMENTAL METHODS

Here we report measurements of CO<sub>2</sub> concentration and flux rates made during the period September 1972 to December 1973 at the University of Nebraska Agricultural Meteorology Laboratory located near Mead, Nebraska (41°09'N; 96°30'W; altitude 354 m above msl). The region in which the station is located is of flat to moderately rolling topography. A general map of land use within a 50-km radius is given in Figure 1. Soil textures in the vicinity vary from silty clay loam on the uplands to sandy loam in terraces of a nearby valley which is one of the ancient courses of the Platte River. Within a radius of 3–4 km the land is farmed largely to maize, sorghum, alfalfa, and soybeans. Consequently, depending upon season, the land may be bare, in crop, or in stubble. Some of the sandier land remains in pasture grass throughout the year.

Profiles of carbon dioxide concentration, mean wind speed, and air temperature were measured simultaneously at various elevations between 2 and 16 m. Wind speed was measured with Casella-Sheppard type cup anemometers. Air temperature was measured with a set of shielded, un aspirated differential copper constantan thermocouples. Concurrent measurements of wind direction and incident solar radiation were also made.

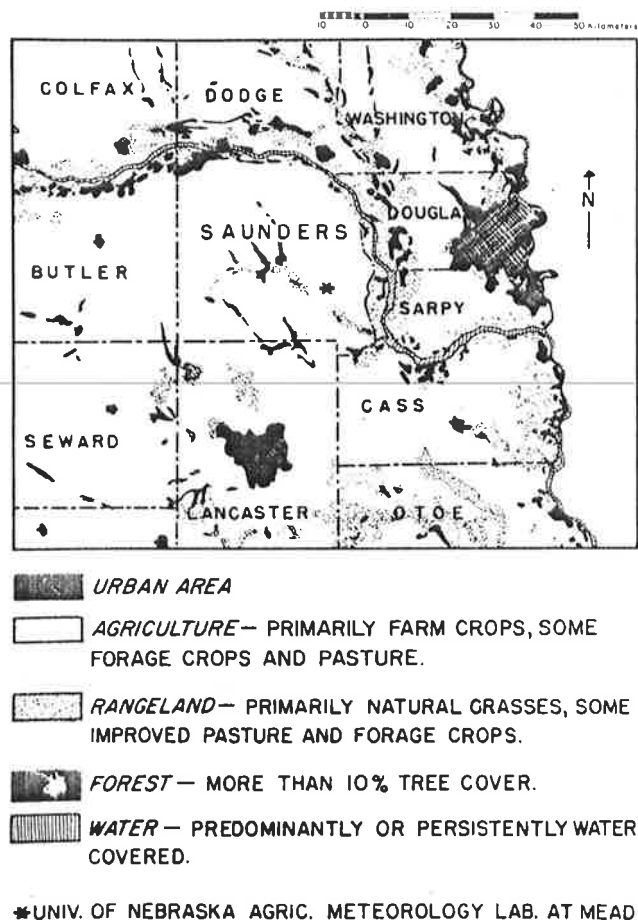


Fig. 1. A general land use map of the region around the University of Nebraska Agricultural Meteorology Laboratory at Mead (41°09'N, 96°30'W; altitude 354 m above ms1).

**CO<sub>2</sub> sampling and analysis system.** A 19.2-m meteorological tower at Mead, Nebraska, is equipped with sampling intakes through which air is drawn into a laboratory building about 60 m away for measurement of CO<sub>2</sub> concentration and gradients. The system has the capacity to sample air at eight locations or elevations. Individual diaphragm pumps, located near the tower (but external to the laboratory), are used for each sample line. These pumps draw air under vacuum and move it into and through the laboratory under positive pressure. The analyzers themselves are purged under a slight positive pressure with CO<sub>2</sub>-free N<sub>2</sub> gas.

The sample lines terminate in the laboratory building at individual rotameters where flow rate into the mixing chambers is controlled. Air from each separate level is continuously mixed in 7.5-l cylinders so as to smooth out the rapid fluctuation in CO<sub>2</sub> concentration. Periodically (usually every 15 min), air samples are drawn in sequence from the mixing cylinders through the infrared gas analyzers (IRGA). Air from the highest elevation samples (say level 1) is passed through a Beckman IRGA model 315A to determine the absolute concentration of CO<sub>2</sub>. Then air from the same source (level 1) is passed through one side of a Beckman IRGA model 315B, used as a differential analyzer, for comparison with air originating at the next lowest level (level 2). The concentration difference between two samples is determined in this way. In the next step, air from level 3 is drawn through the differential

analyzer replacing the sample from level 1. Then the concentration difference between levels 2 and 3 is determined. This process is repeated until all necessary comparisons are made.

A system has been developed to permit automatic hourly calibration of both IRGA's. Analyzer output data during calibration runs are also recorded by the data logging system. Calibration is done in the following way. Once each hour an upscale standard gas of known CO<sub>2</sub> concentration is passed through the absolute IRGA, and the analyzer response is recorded. Then a downscale gas is substituted. At the same time a single standard gas is passed through both sides of the differential IRGA. Zero concentration should be indicated by the IRGA when this is done. The response, whether zero or not, is recorded. Then two different standard gases of known concentrations (differing by a suitable working range) are passed through the two chambers of the differential IRGA to record an upscale response. With the IRGA responses measured and recorded during a calibration cycle the drift of the analyzers can be monitored, and the field observations can be adjusted for changing IRGA calibrations, if any.

A comparison of standard gases of the same nominal concentration, but supplied by different manufacturers, convinced us of the need for an independent calibration of our standard gases. Our primary standard gases were calibrated by the Air Resources Laboratory of NOAA in Boulder, Colorado. The calibrations, based on 59 manometric standards (C. D. Keeling, personal communication, 1975), were accurate to ±0.3–0.5 ppm. Our secondary standards were calibrated against these primary gases by differential gas analysis. The secondary standards were used in the automatic calibration of both analyzers.

It was found that even small pressure differences between the reference and sample sides of the differential IRGA resulted in measurable imbalances and that the error was increased with increasing concentration of CO<sub>2</sub> in the sample gas. Concentration difference errors of the order of 1 ppm were possible. This situation was improved by use of precise pressure regulation devices and flowmeters. It is now possible to maintain the pressure differences between the analyzer tubes at 0 ± 1.0 mbar. These pressure differences are monitored periodically with a water manometer to detect any failures in pressure regulation.

The absorption bands of CO<sub>2</sub> and H<sub>2</sub>O overlap. In order to prevent interference from water vapor a set of optical filters (manufactured by Grubb Parsons and Co. Ltd., Newcastle upon Tyne, England) is incorporated into the path of the infrared radiation stream. These filters transmit only radiation in the 3.8- to 5.7- $\mu$ m wavelength band so that the main water vapor absorption bands are removed. Spectral transmittance of these filters is given by Janac [1971].

Temperatures of the gas samples entering the analyzer cells are monitored (using copper constantan thermocouples embedded in the flow lines) during both data and calibration cycles so that corrections can be made for any significant difference in the temperature of field air samples and laboratory gases.

**Data recording.** All meteorological measurements were made on either a 7- or a 15-min cycle. Data were logged on punch tape with an automatic digital data logging system. Raw data were converted from the digitized emf or count record of individual sensors into parametric forms by computer. All data reported in this paper have been averaged over half-hour periods.

THEORETICAL CONSIDERATIONS

The exchange of CO<sub>2</sub> is a turbulent transfer process. Vertical flux of CO<sub>2</sub>,  $F_c$  (g cm<sup>-2</sup> s<sup>-1</sup>), is given by

$$F_c = f K_c \frac{\partial c}{\partial z} \quad (1)$$

where  $K_c$  (cm<sup>2</sup> s<sup>-1</sup>) is the exchange coefficient for CO<sub>2</sub>,  $\partial c/\partial z$  (ppm cm<sup>-1</sup>) the gradient of CO<sub>2</sub>, and  $f$  the conversion factor for CO<sub>2</sub> from parts per million to specific weight. The exchange coefficient for CO<sub>2</sub> ( $K_c$ ) is assumed to be equal to the exchange coefficient for water vapor ( $K_w$ ). Therefore (1) can be written as

$$F_c = f K_w \frac{\partial c}{\partial z} = f K_m \left( \frac{K_w}{K_m} \right) \frac{\partial c}{\partial z} \quad (2)$$

The exchange coefficient for momentum is given by

$$K_m = \frac{\tau/\rho}{(\partial U/\partial z)} = \frac{u_*^2}{(\partial U/\partial z)} = k^2 z^2 (\phi_m)^{-2} \left( \frac{\partial U}{\partial z} \right) \quad (3)$$

where  $\tau$  is shear stress,  $\rho$  is air density,  $\partial U/\partial z$  is wind speed gradient equal to  $(u_*/kz)\phi_m$ ,  $u_*$  is friction velocity equal to  $(\tau/\rho)^{1/2}$ ,  $\phi_m$  is nondimensional wind shear or diabatic correction factor for the log-law wind profile,  $k$  is von Kármán's constant, and  $z$  is distance measured in vertical direction.

Combining (2) and (3) results in

$$F_c = f k^2 z^2 (\phi_m)^{-2} \left( \frac{\partial U}{\partial z} \right) \left( \frac{\partial c}{\partial z} \right) \left( \frac{K_w}{K_m} \right) \quad (4)$$

Under adiabatic conditions, log-law considerations (i.e.,  $\phi_m = 1$ ) provide good accuracy in predicting momentum transfer. The exchange coefficient for water vapor  $K_w$  (and sensible heat  $K_h$ ) is assumed to be equal to that of momentum  $K_m$ . In nature, however, adiabatic or neutral conditions are seldom realized, and the above assumptions (i.e.,  $\phi_m = 1$  and  $K_w/K_m = K_h/K_m = 1$ ) may lead to significant errors.

Both  $\phi_m$  and  $K_w/K_m$  (or  $K_h/K_m$ ) have been found to vary with atmospheric thermal stability. Stability is usually expressed in terms of the Richardson number ( $Ri$ ) defined as  $Ri = g(\partial\theta/\partial z)\theta^{-1}(\partial U/\partial z)^{-2}$ , where  $\theta$  is the potential temperature,  $g$  is the acceleration due to gravity, and  $\partial U/\partial z$  and  $\partial\theta/\partial z$  are the gradients of wind speed and potential temperature.

Stability correction formulas have been developed in recent micrometeorological investigations. Those of *Pruitt et al.* [1973] are used in this study.

*Model of Pruitt, Morgan, and Lourence (PML), 1973.*

$$\begin{aligned} \phi_m &= (1 - 16 Ri)^{-1/3} \text{ for unstable stratification and } (1 + 16 Ri)^{1/3} \text{ for stable stratification;} \\ K_w/K_m &= 1.13(1 - 60 Ri)^{0.074} \text{ for unstable stratification and } 1.13(1 + 95 Ri)^{-0.11} \text{ for stable stratification;} \\ k &= 0.42. \end{aligned}$$

This model has been tested over an oat field against two other independent methods (namely, the lysimetric and energy balance methods) for measuring CO<sub>2</sub> flux. Results agreed within 10–20% on a short-period basis and within 5–10% on a daily basis (for details see *Verma and Rosenberg* [1975a]). For some periods, when daytime stability (advective inversions) were observed, the fluxes were computed assuming  $\phi_m = 1$  and  $K_w/K_m = 1$ .

Gradients (or derivatives with respect to height) of various profiles ( $c$ ,  $T$ , and  $U$ ) were evaluated using finite differences in the manner suggested by *Panofsky* [1965]. If  $\Psi$  is a profile

variable, then the gradient is given by

$$\frac{\partial \Psi}{\partial z} = \frac{\Psi_2 - \Psi_1}{(z_1 z_2)^{1/2} \ln(z_2/z_1)} \quad (5)$$

where  $z_1$  and  $z_2$  are the heights above the ground. This approximation is, of course, rigorous for logarithmic profiles. Using this approximation, (2) becomes

$$F_c = f k^2 \frac{(U_2 - U_1)(c_2 - c_1)}{(\ln z_2/z_1)^2} \left( \frac{K_w}{K_m} \right) (\phi_m)^{-2} \quad (6)$$

RESULTS AND DISCUSSIONS

*Diurnal course of [CO<sub>2</sub>].* Figure 2 shows a typical diurnal course of [CO<sub>2</sub>] measured at 16 m above the ground. Immediately after sunrise, with the onset of photosynthesis, there occurs a sharp drawdown in [CO<sub>2</sub>]. Concentration levels off between about 0800–0900 hours (solar time) with only slight change until 1600–1700 hours. Later, as photosynthesis ceases, a buildup occurs as the result of respiration from the plant community. *Verma and Rosenberg* [1975b] presented [CO<sub>2</sub>] data measured at various elevations ranging from 0.5 to 16 m above the ground. The diurnal variation in [CO<sub>2</sub>] is considerably greater at an elevation just above the crop canopy (e.g., 0.5 m) than it is at an elevation removed from the canopy (e.g., 16 m). Typically, the amplitude of diurnal [CO<sub>2</sub>] cycles at 0.5 m is 2–4 times that at 16 m. [CO<sub>2</sub>] at night ranges quite widely and may reach 450–500 ppm at 0.5 m and 350–400 ppm at 16 m, especially on calm nights. The diurnal pattern of [CO<sub>2</sub>] and the day-to-day variation is a resultant of the intensity of photosynthesis, which is controlled by ambient light intensity and by wind speed conditions.

*Annual course of [CO<sub>2</sub>].* Figure 3 shows the variation in the diurnal course of [CO<sub>2</sub>] for selected days in the period June–January. The daytime [CO<sub>2</sub>] ranges from a minimum of about 295–300 ppm which occurs during late July and early August to a maximum of about 328–332 ppm during the winter months. The amplitude of the diurnal [CO<sub>2</sub>] cycle varies greatly as the seasons change. The daily amplitude ranges from 20–50 ppm during June, July, and August, from 10–20 ppm during September and October, and from 0.5–2 ppm during the period from November to January.

In curves of diurnal [CO<sub>2</sub>] patterns presented in Figure 3 we note that daytime [CO<sub>2</sub>] is fairly constant during the period 1000–1600 hours. The nighttime concentrations vary quite widely, however, depending upon the thermal stratification and wind speed. Mean daily daytime concentration was obtained by averaging [CO<sub>2</sub>] measured between 0010 and 0016 hours. Plots of these daytime means and of 24-hour means of [CO<sub>2</sub>] measured during September 1972 to January 1973 and June–December 1973 are shown for each day of measurement in Figure 4.

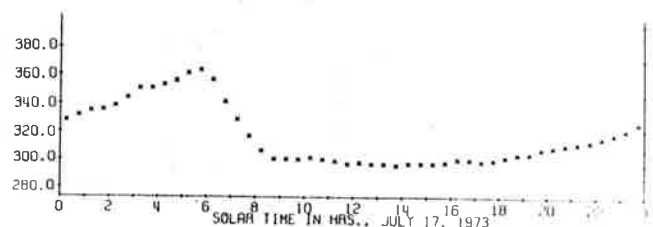


Fig. 2. Typical diurnal pattern of CO<sub>2</sub> concentration at 16 m above ground during the growing season at Mead, Nebraska.

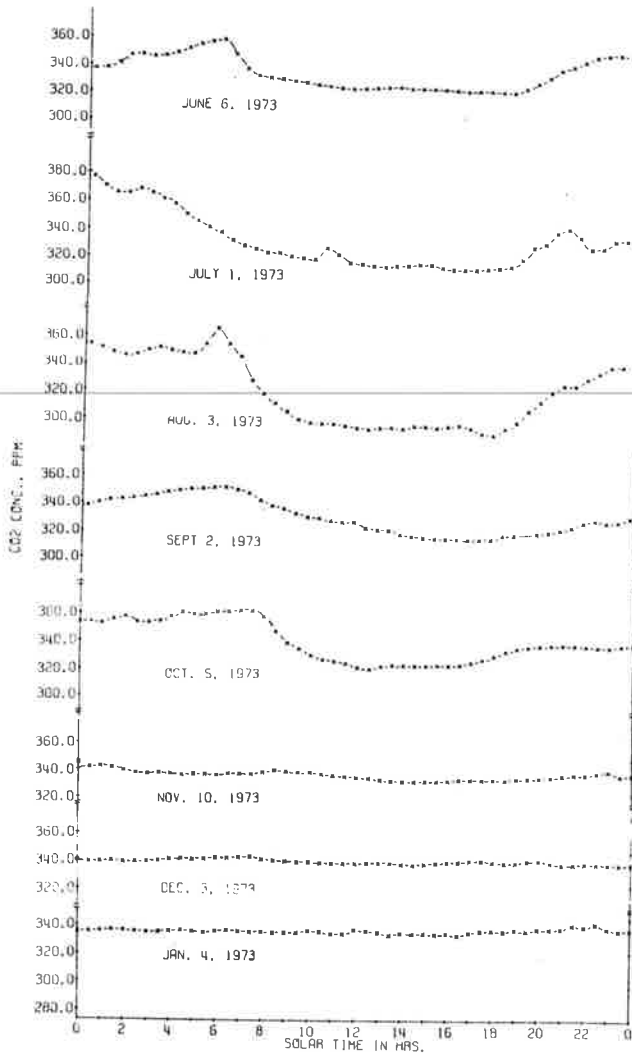


Fig. 3. The diurnal patterns of CO<sub>2</sub> concentration at 16 m above ground at various times of year at Mead, Nebraska.

Seasonal influences on [CO<sub>2</sub>] are evident. In late spring and early summer, mean daytime and 24-hour averages are about 320 and 330, respectively. As crops in the region begin to grow rapidly, [CO<sub>2</sub>] decreases, reaching a minimum at about the end of July or beginning of August. Mean daytime [CO<sub>2</sub>] is about 295–298 ppm at this time of year when photosynthetic fixation rates are most rapid (see below). Later in August, [CO<sub>2</sub>] begins to increase as photosynthetic activity of vegetation in the region declines. By the middle of September most of the vegetation is maturing and leaves of many crops enter senescence. Mean daytime [CO<sub>2</sub>] increases to about 315–325 ppm. During winter months, mean daytime [CO<sub>2</sub>] ranges from about 325 to 335 ppm. The points in Figure 4 were fitted by curvilinear regression (second-degree polynomial) to depict the annual cycle of the mean daytime and 24-hour-averaged [CO<sub>2</sub>]. It should also be noted in Figure 4 that the concentrations observed in the fall and winter months of 1972 and 1973 are in close agreement.

Plots of the monthly averages of the mean daytime and 24-hour [CO<sub>2</sub>] at Mead are presented in Figure 5. For a qualitative comparison, annual cycles of [CO<sub>2</sub>] observed at Mauna Loa, Hawaii (C. D. Keeling, personal communication, 1975), and Barrow, Alaska [Kelley, 1968] are also plotted in this figure. Levels of [CO<sub>2</sub>] at Barrow are lower than those at Mauna Loa and Mead. Barrow data were measured 10 years earlier, and this may account for a difference of about 7–8 ppm, on the average.

A substantially greater buildup of nocturnal [CO<sub>2</sub>] is evident in the 24-hour average data at Mead, as compared to Mauna Loa and Barrow. The [CO<sub>2</sub>] minimum observed during the growing season at Mead is sharper than that at Barrow and Mauna Loa. The vigorous photosynthetic activity in the region may, possibly, result in this substantial drawdown in [CO<sub>2</sub>]. The amplitude of annual [CO<sub>2</sub>] cycle observed at Mauna Loa, biologically a relatively inert location, is smaller than the amplitudes observed at Mead and Barrow. Also the annual minimum occurs later in the year at Mauna Loa than at Mead and Barrow. Bolin and Keeling [1963] have suggested that this lag may be due to latitudinal effects.

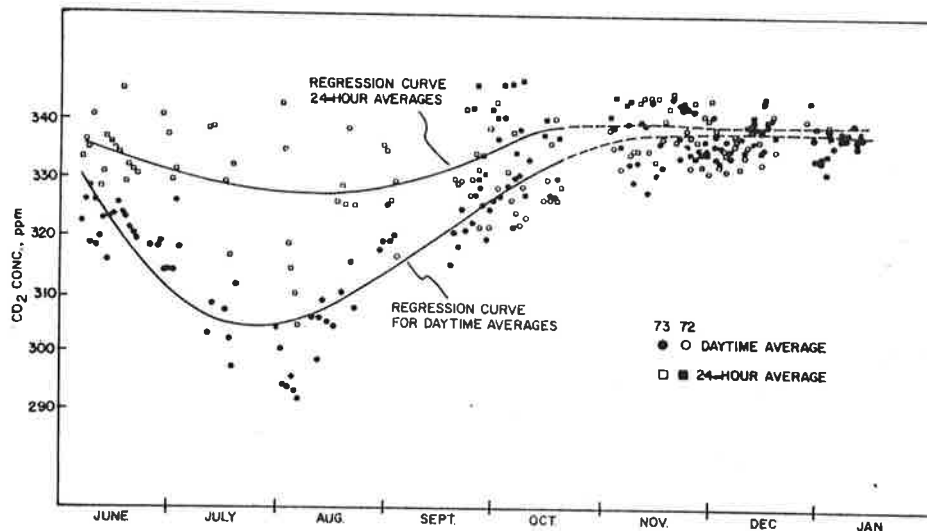


Fig. 4. Daytime and 24-hour means of CO<sub>2</sub> concentration at 16 m above ground during the periods September 1972 to January 1973 and June–December 1973 at Mead, Nebraska. The curvilinear regressions are fitted to the data for only the period of the year shown by the solid lines.

**CO<sub>2</sub> flux.** Rates of CO<sub>2</sub> flux to and away from the ground were computed from the measured profiles of [CO<sub>2</sub>], wind speed, and air temperature. The PML stability-corrected aerodynamic method, outlined in the previous section, was used for this purpose. Measurements were made at elevations (5.6–16 m above ground) such that the CO<sub>2</sub> fluxes calculated should represent an integration of the region generally, rather than of the field in which the instrument most stands. If it is assumed that a fetch to height ratio of 200/1 is required for a fully developed boundary layer in this type of area of flat to rolling topography, the sensors between 5.6 and 16 m should sample air conditioned within an area of about 1- to 3-km radius. To avoid tower wind-shadow effects, only SE-SW winds are considered in this paper. The sign convention adopted here gives CO<sub>2</sub> flux toward the ground as positive and away from the ground as negative.

Figure 6 shows some typical plots of CO<sub>2</sub> fluxes measured during the period June–October 1973. Positive fluxes of CO<sub>2</sub> from the air above to the photosynthesizing crop occur for 11–12 hours daily. The magnitudes of these fluxes depend, primarily, upon solar radiation, wind speed, and air temperature. Average radiation, wind speed, and air temperature for the days depicted in the figure are given in Table 1. The peak daytime fluxes (in  $g \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$ ) ranged from about 0.5 in early June to 1.5 or 2.0 in early August and 0.5 in late September. Negative fluxes measured over the crop at night represent the sum of the soil and crop respiration which depends primarily on the soil and air temperature.

The areas under positive and negative portions of the daily flux curves were integrated, and the results plotted in Figure 7. Lines fitted by curvilinear regression (second-degree polynomial) are shown for both daytime (positive) and nocturnal (negative) fluxes. Scatter in data is partly due to the day-to-day variability of meteorological conditions. A seasonal trend is, however, evident. In early June, daytime and nocturnal fluxes are about  $15\text{--}20 \text{ g m}^{-2}$  and  $-3$  to  $-7 \text{ g m}^{-2}$ , respectively. As the growing season progresses, both fluxes increase, with the daytime maximum of about  $20\text{--}35 \text{ g m}^{-2}$  around late

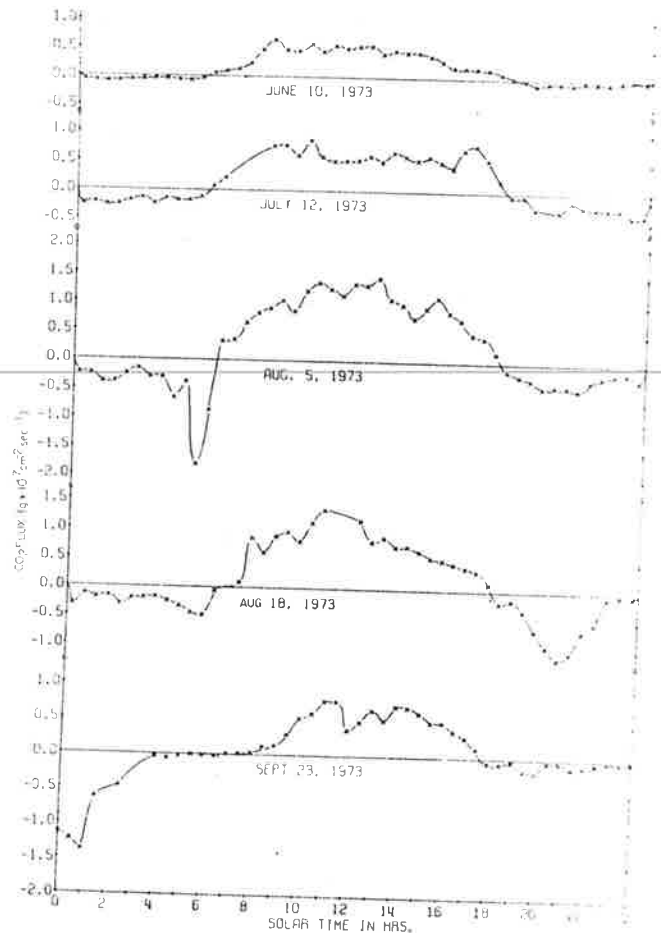


Fig. 6. Typical plots of the diurnal patterns of CO<sub>2</sub> flux during June–October 1973 at Mead, Nebraska.

July and early August. By this time the nocturnal fluxes level off to a value of about  $-10$  to  $-12 \text{ g m}^{-2}$ . Later in the season, as the crops in the area start to mature and photosynthetic activity decreases, the daytime fluxes of CO<sub>2</sub> diminish. The regression lines suggest that during September and October a slight increase in nocturnal flux occurs. If this effect is real, it may be caused by a temporary surge in respiration as plant materials senesce and die.

A curve representing the seasonal variation of net daily atmospheric CO<sub>2</sub> flux is also shown in Figure 7. Photosynthesis is supplied during daylight by downward CO<sub>2</sub> flux from the atmosphere and upward CO<sub>2</sub> flux from the soil and crop itself. The upward CO<sub>2</sub> flux at night is supplied by plant and soil respiration. Thus the difference between daytime and nighttime fluxes above the crop is a rough measure of the amount of CO<sub>2</sub> fixed daily in the biosphere and not necessarily a direct measure of the crop photosynthesis. Net CO<sub>2</sub> fluxes were  $10\text{--}12 \text{ g m}^{-2}$  in early June,  $18\text{--}20 \text{ g m}^{-2}$  in early August (maximum),  $6\text{--}10 \text{ g m}^{-2}$  in September, and  $1\text{--}5 \text{ g m}^{-2}$  in early October.

In Figure 7, peak daytime (downward) CO<sub>2</sub> flux is shown to occur around the period late July to early August. Figures 4 and 5 show that minimum [CO<sub>2</sub>] occurred during the same period. The results of the flux and concentration observations are mutually supportive and suggest, strongly, that the photosynthetic activity is most intense in the east central Great Plains during late July to early August.

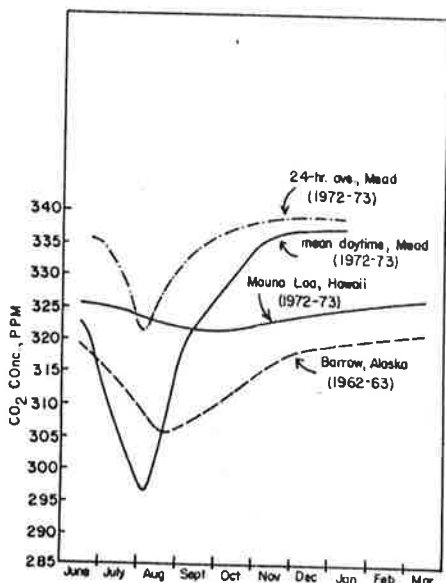


Fig. 5. A part of the annual cycle of CO<sub>2</sub> concentration at Mead, Nebraska. The lines are drawn through monthly means of the daytime and 24-hour concentrations. Comparative data for Barrow, Alaska, and Mauna Loa, Hawaii, are also shown.

TABLE 1. Solar Energy Receipts and Mean Daily Temperature and Wind Speed on Selected Days During 1973 at Mead, Nebraska

| Date    | Solar Radiation, Ly d <sup>-1</sup> | Mean Wind Speed at 5.6 m, m s <sup>-1</sup> | Mean Air Temperature at 5.6 m, °C |
|---------|-------------------------------------|---|-----------------------------------|
| June 9  | 715                                 | 5.04  | 25.6                              |
| 10      | 718                                 | 6.68  | 25.9                              |
| 11      | 715                                 | 4.76  | 26.3                              |
| 19      | 633                                 | 4.14  | 20.9                              |
| 30      | 506                                 | 3.57  | 21.2                              |
| July 11 | 682                                 | 2.46  | 26.0                              |
| 12      | 712                                 | 4.33  | 27.3                              |
| 16      | 691                                 | 3.04  | 21.1                              |
| 17      | 608                                 | 3.96  | 23.3                              |
| 31      | 641                                 | 2.44  | 19.0                              |
| Aug. 2  | 648                                 | 1.57  | 19.9                              |
| 3       | 641                                 | 2.48  | 22.4                              |
| 5       | 631                                 | 4.95  | 23.2                              |
| 6       | 439                                 | 4.61  | 24.4                              |
| 11      | 446                                 | 2.80  | 22.3                              |
| 13*     | 586                                 | 3.59  | 23.1                              |
| 16†     | 593                                 | 3.50  | 24.2                              |
| 18      | 585                                 | 4.06  | 25.3                              |
| 19      | 590                                 | 3.31  | 26.8                              |
| 20      | 588                                 | 2.56  | 23.5                              |
| 22      | 514                                 | 4.51  | 26.5                              |
| Sept. 3 | 536                                 | 3.34  | 19.6                              |
| 23      | 247                                 | 3.73  | 16.6                              |
| 25      | 314                                 | 3.24  | 17.0                              |
| Oct. 2  | 401                                 | 2.86  | 15.8                              |
| 3       | 47                                  | 4.44  | 14.7                              |
| 6       | 74                                  | 2.88  | 13.0                              |
| 7       | 106                                 | 3.02  | 15.7                              |

\*0000-0200 hours missing.

†0000-0700 hours missing.

The greatest receipts of solar radiation in eastern Nebraska occur at the time of the summer solstice, since no anomalous climatic conditions interfere [Rosenberg, 1964]. The maximum of net photosynthetic activity identified above occurs at the same time as the annual peak of air temperature [Neill *et al.*, 1967]. The linkage is probably coincidental since it is respiration rather than photosynthesis which depends directly on temperature. More likely, the occurrence of maximum

photosynthetic activity at Mead is related to the development of the greatest biomass. Most important, annual crops grown in the region reach their full vegetative growth by late July or early August.

Leith [1965], using then available data, attempted to map total worldwide carbon uptake by land plants. He considered his maps a first approximation and emphasized that details were still uncertain. Junge and Czeplak [1968] replotted these maps and integrated the values for each 10° belt of latitude. For such a belt around 41°N latitude they estimate a net uptake of carbon of about  $2.7 \times 10^{16}$  g during the vegetative period of the year. The surface area of the earth for a 10° latitude belt is  $2\pi R^2 \cos \phi d\phi$ , with  $d\phi = 0.175$  and radius  $R = 6.366 \times 10^8$  cm. One gram of carbon yields  $3.67$  g CO<sub>2</sub>. According to Junge and Czeplak's estimates, then, the mean daily net uptake of CO<sub>2</sub> in our latitude should be about  $0.41 \times 10^{-8}$  g cm<sup>-2</sup> s<sup>-1</sup> (average for the summer vegetative period). Our estimates are of the same order of magnitude, although somewhat higher.

Garratt and Pearman [1973] gave a value of the mean daily surface CO<sub>2</sub> flux of  $1 \times 10^{-8}$  g cm<sup>-2</sup> s<sup>-1</sup>. This value represents the net transfer of CO<sub>2</sub> from atmosphere to surface and should apply to a wide range of vegetation. This result was based on Woodwell and Whittaker's [1968] estimates, which range from  $0.4$  to  $1.8 \times 10^{-8}$  g cm<sup>-2</sup> s<sup>-1</sup> for forests and grasslands, and Odum's [1959] estimates of  $0.4$  to  $1.6 \times 10^{-8}$  g cm<sup>-2</sup> s<sup>-1</sup> for many major types of cultivated and uncultivated crops. In some of their own measurements, Garratt and Pearman found a seasonal average value of  $1.4 \times 10^{-8}$  g cm<sup>-2</sup> s<sup>-1</sup> for wheat crop in southeast Australia. Brown and Rosenberg [1971], from dry matter sampling and flux measurements in western Nebraska, found a net CO<sub>2</sub> accumulation rate for sugar beets of about  $2.6$  to  $3.2 \times 10^{-8}$  g cm<sup>-2</sup> s<sup>-1</sup> during the period of peak photosynthetic activity.

Considering an areal average of surface CO<sub>2</sub> flux for length scales upward of 1000 km (corresponding to the time scales of atmosphere surface interaction >1-2 days), Garratt and Pearman suggest a value close to  $1 \times 10^{-8}$  g cm<sup>-2</sup> s<sup>-1</sup> as most appropriate. This value cannot be an underestimate, since the tropospheric vertical gradient of CO<sub>2</sub> concentration in the northern hemisphere [Munn and Bolin, 1971] implies a large-

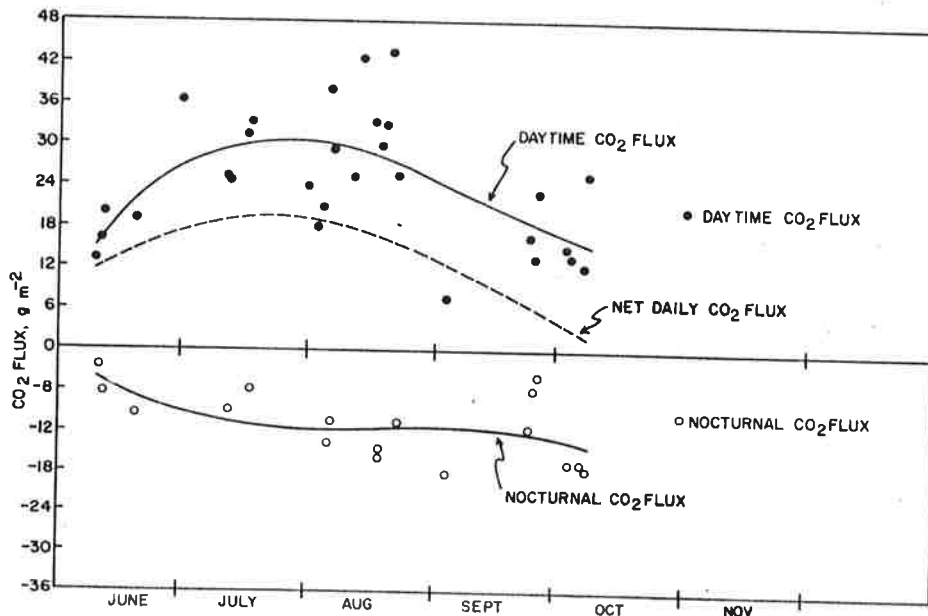


Fig. 7. The seasonal pattern of daytime, nocturnal, and net daily CO<sub>2</sub> flux, June-October 1973 at Mead, Nebraska.

scale CO<sub>2</sub> flux for surface vegetation of the order of  $0.5 \times 10^{-6}$  g cm<sup>-2</sup> s<sup>-1</sup>. Our estimates of mean daily input of CO<sub>2</sub> (in  $10^{-6}$  g cm<sup>-2</sup> s<sup>-1</sup>) are 1.2–1.4 in early June, 2.1–2.3 in early August (maximum), 0.70–1.2 in September, and 0.10–0.60 in early October, values in consonance with others cited in the literature for a wide range of vegetation types.

It may be worthwhile to note that most of the large-area CO<sub>2</sub> flux data available in the literature are based on ecological and other considerations. So far as we know, ours is the first attempt to estimate large-area CO<sub>2</sub> flux using actual measurements of CO<sub>2</sub> gradients and other controlling meteorological variables.

#### SUMMARY

Data are presented on the cycle of carbon dioxide concentration and flux at Mead, Nebraska. Measurements were made at elevations (5.6–16 m above ground) such that the CO<sub>2</sub> fluxes calculated should represent an integration of the region generally, rather than of the field in which the instrument mast stands. Distinct seasonal variations in both concentration and flux of CO<sub>2</sub> were observed.

The daytime [CO<sub>2</sub>] ranges from about 295–300 ppm during late July to early August to 328–332 ppm during the winter months. The peak daytime fluxes (in  $g \times 10^{-7}$  cm<sup>-2</sup> s<sup>-1</sup>) vary from about 0.5 in early June to 1.5 or 2.0 in late July to early August, and 0.5 in late September.

The minimum annual [CO<sub>2</sub>] is observed around late July. CO<sub>2</sub> flux rates reach a maximum during the same period. Together, these data suggest a distinct peak in photosynthetic activity in the region at this time. This peak, we speculate, is due to the coincidence with the achievement of maximum biomass in the annual crops of the region.

The annual cycle of [CO<sub>2</sub>] observed at Mead is compared with that at Barrow, Alaska, and Mauna Loa, Hawaii. The minimum in [CO<sub>2</sub>] at Mead is relatively sharp and intense compared with those at the other locations. The minimum [CO<sub>2</sub>] at Mauna Loa lags those at Barrow and Mead by about 1–2 months.

*Acknowledgments.* This study was conducted with support of the Environmental Data Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, under contract 2-35385. We would like to thank C. D. Keeling of Scripps Institution of Oceanography, La Jolla, California, for providing data on the 1972–1973 carbon dioxide concentration measured at Mauna Loa, Hawaii. Our thanks to Dale E. Sandin, James Hines, and Roberta Sandhorst, who assisted in the field observation and data computation, and to our colleagues Raoul Lemeur, Blaine L. Blad, and Maximo W. Baradas for timely help and suggestions. Published as paper 3844, Journal Series, the Nebraska Agricultural Experiment Station. The work reported was conducted under Nebraska Agricultural Experiment Station Project 20–31 and Regional Research Project 11–33.

#### REFERENCES

- Allen, L. H., Jr., Variations in carbon dioxide concentration over an agricultural field, *Agr. Meteorol.*, 8, 5–24, 1971.
- Bolin, B., and W. Bischof, Variations of the carbon dioxide content of the atmosphere in the northern hemisphere, *Tellus*, 22, 431–442, 1970.
- Bolin, B., and C. D. Keeling, Large-scale atmospheric mixing as deduced from the seasonal and meridional variations of carbon dioxide, *J. Geophys. Res.*, 68, 3899–3920, 1963.
- Brown, K. W., and N. J. Rosenberg, Concentration of CO<sub>2</sub> in the air above a sugar beet field, *Mon. Weather Rev.*, 98, 75–82, 1970.
- Brown, K. W., and N. J. Rosenberg, Energy and CO<sub>2</sub> balance of an irrigated sugar beet (*Beta vulgaris*) field in the great Plains, *Agron. J.*, 63, 207–213, 1971.
- Clark, J. F., A meteorological analysis of carbon dioxide concentrations measured at a rural location, *Atmos. Environ.*, 3, 375–383, 1969.
- Cramer, J., and A. L. Myers, Rate of increase of atmospheric carbon dioxide, *Atmos. Environ.*, 6, 563–573, 1972.
- Garratt, J. R., and G. I. Pearman, CO<sub>2</sub> concentration in the atmospheric boundary-layer over south-east Australia, *Atmos. Environ.*, 7, 1257–1266, 1973.
- Georgiyevskiy, Yu. S., and R. Kh. Khalikova, Seasonal and daily variations in the CO<sub>2</sub> content of the ground layer, *Izv. Akad. Sci. Atmos. Oceanic Phys.*, 7, 656–659, 1971.
- Goldman, M. A., Carbon dioxide measurements and local wind patterns at Mauna Loa Observatory, Hawaii, *J. Geophys. Res.*, 70, 4550–4554, 1974.
- Janac, J., Infra-red gas analyzers and other physical analyzers, in *Plant Photosynthetic Production, Manual of Methods*, edited by Z. Sestak, J. Catsky, and P. G. Jarvis, W. Junk N. V. Publishers, The Hague, 1971.
- Junge, C. E., and G. Czeplak, Some aspects of the seasonal variation of carbon dioxide and ozone, *Tellus*, 20(3), 422–434, 1968.
- Keeling, C. D., Is carbon dioxide from fossil fuel changing man's environment, *Proc. Amer. Phil. Soc.*, 114, 10–17, 1970.
- Kelley, J. J., Carbon dioxide and ozone in the arctic atmosphere, in *Arctic Drifting Stations*, pp. 155–166, coordinated by J. E. Sater, Arctic Institute of North America, Washington, D. C., 1968.
- Landsberg, H. E., Man-made climatic changes, *Science*, 170, 1265–1274, 1970.
- Lieth, H., Versuch einer kartographischen Darstellung der Produktivität der Pflanzendecke auf der Erde, in *Geographisches Taschenbuch*, pp. 72–79, Franz Steiner, Wiesbaden, 1965.
- Machta, L., Mauna Loa and global trends in air quality, *Bull. Amer. Meteorol. Soc.*, 53, 402, 1972.
- Munn, R. E., and B. Bolin, Global air pollution—Meteorological aspects, *Atmos. Environ.*, 5, 363–402, 1971.
- Neild, R. E., N. J. Rosenberg, and R. E. Myers, Temperature patterns and some relations to agriculture in Nebraska, *Misc. Publ. 16*, Nebr. Agr. Exper. Sta., Lincoln, 1967.
- Newell, R. E., and T. C. Dopplick, The effect of changing CO<sub>2</sub> concentration on radiative heating rates, *J. Appl. Meteorol.*, 9, 958–959, 1970.
- Odum, E. T., *Fundamentals of Ecology*, 2nd ed., Saunders, Philadelphia, Pa., 1959.
- Pales, J. C., and C. D. Keeling, The concentration of atmospheric carbon dioxide in Hawaii, *J. Geophys. Res.*, 70, 6035–6076, 1965.
- Panofsky, H. A., Reanalysis of Swinbank's Kerang observations, Flux of Heat and Momentum in the Planetary Boundary Layer, pp. 66–76, Dep. of Meteorol., Pa. State Univ., University Park, 1965.
- Pearman, G. I., and J. R. Garratt, Carbon dioxide measurements above a wheat crop, 1, Observations of vertical gradients and concentrations, *Agr. Meteorol.*, 12, 13–25, 1973.
- Pruitt, W. O., D. L. Morgan, and F. J. Lourence, Momentum and mass transfer in the surface boundary layer, *Quart. J. Roy. Meteorol. Soc.*, 99, 370–386, 1973.
- Rosenberg, N. J., Solar energy and sunshine in Nebraska, *Nebr. Agr. Exper. Sta. Res. Bull.* 213, 31 pp., 1964.
- Rosenberg, N. J., *Microclimate: The Biological Environment*, pp. 211–212, John Wiley, New York, 1974.
- Sawyer, J. S., Possible effects of human activities on world climate, *Weather*, 26, 251–262, 1971.
- Verma, S. B., and N. J. Rosenberg, Accuracy of lysimetric, energy balance and stability-corrected aerodynamic methods of estimating above canopy flux of CO<sub>2</sub>, *Agron. J.*, in press, 1975a.
- Verma, S. B., and N. J. Rosenberg, Vertical profiles of carbon dioxide concentration in stable stratifications, submitted to *Agr. Meteorol.*, 1975b.
- Woodwell, G. M., and R. H. Whittaker, Primary production in terrestrial ecosystems, *Amer. Zool.*, 8, 19–30, 1969.

(Received August 14, 1974;  
revised June 19, 1975;  
accepted July 9, 1975.)