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Annual variation in soil respiration in selected areas of the temperate zone

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ABSTRACT

A 6-year record of soil respiration and CO_2 concentration measurements in various soils with different plant cover is presented. The effect of temperature and soil-moisture content is discussed; for this, ^{222}Rn-flux and concentration measurements are used to trace gas transport in the unsaturated soil zone. The CO_2 production in the soil is strongly correlated with the subsoil temperature. Q_{10}-values vary between 1.4 and 2.7, depending on mean annual temperature and precipitation. Soil respiration is reduced not only by extremely dry but also by extremely wet soil conditions. This is probably due to an evolution adaptation of soil microorganism to the long-time mean meteorological situation. The regional mean annual cycle of soil respiration representative for the Rhine Valley area near Heidelberg is deduced from spot measurements in this region. Minimum soil respiration occurs in February; the maximum CO_2 production is in June and July. A steep increase of the respiration curve in spring is followed by a slow decrease from summer to winter. Even during the coldest winter months, soil respiration does not reach zero, but makes up 10% to 15% of the maximum respiration rate. The regional annual mean value of the soil CO_2 production is 6 mmol m^{-2} h^{-1}; the summer mean value is 9 mmol m^{-2} h^{-1}.

1. Introduction

Carbon dioxide is produced in the soil by microbial decomposition of soil organic matter and by root respiration. The biogenic activity is mainly temperature controlled. The annual cycle of CO_2 production in the soil is thus strongly correlated with soil temperature (Dörr and Münnich, 1980; Witkamp and Frank, 1969; Wiant, 1967). Only in particular cases is soil moisture (extremely wet or dry soil) a controlling factor for CO_2 production (Edwards, 1975; Wiant, 1967).

Soil respiration, i.e., the CO_2 flux at the soil surface, and CO_2 concentration in soil air, depends both on CO_2 production *and* gas transport in the unsaturated soil zone. To study the temperature and soil moisture dependence of soil respiration by direct field measurements, transport and production effects must be distinguished. To trace gas transport, the radioactive noble gas ^{222}Rn is used (Dörr et al., 1983). ^{222}Rn is produced in the soil by radioactive decay of ^{226}Ra, which is distributed rather uniformly in the soil matrix. The ^{222}Rn flux at the soil surface and the ^{222}Rn concentration in soil air are influenced only by soil parameters, which can be determined by measuring flux and concentration gradient at the same site.

Atmospheric CO_2 variations also depend both on varying sources and sinks *and* on atmospheric transport. Here too, ^{222}Rn is a helpful tracer in identifying source/sink-induced CO_2 variations (Levin, 1987; Dörr et al., 1983).

Transport-calibrated soil respiration data will yield a better understanding of the biospheric carbon cycle. Further, more information on the carbonate chemistry of soil- and groundwater can be obtained from reliable CO_2 production data.

2. Experimental

2.1. Sampling and measurement

Soil air samples are taken by driving connectable stainless steel tubes, each 1 m long with 6 mm outer and 2 mm inner diameter, into a present depth into the soil. Gas inlet is through 8 holes of 0.5 mm diameter just behind the cone tip of the probe (Dörr, 1984). Soil gas samples are taken in pre-evacuated 50 ml glass flasks for CO_2 measurement and 1000 ml glass flasks for ^{222}Rn measurement. Direct flux measurements are carried out by Lundegardh's inverted cup method. The gases diffusing out of the soil surface are collected under a tin container and sampled after about 1 h for CO_2 and ^{222}Rn measurement. The flux is calculated from the concentration rise during collection time (Dörr, 1984). For ^{13}C and ^{14}C measurement, soil respiration CO_2 is absorbed in 300 ml 4-normal sodium hydroxide solution (Dörr and Münnich, 1980). Sampling time for ^{13}C and ^{14}C samples of soil respiration is between 2 and 6 weeks (station NU). At station, SA profile and flux measurements are carried out once a week. Other locations are sampled between 2 and 6 times a year. CO_2 concentration is measured with a non-dispersive infrared gas analyzer (NDIR, URAS 1) after diluting the samples with N_2 in a standard manner (Barth, 1980). Absorbed CO_2 is recovered in the lab in a vacuum extraction system by acidification of the sample (Dörr and Münnich, 1980). ^{222}Rn activity is measured in a slow pulse ionisation chamber (Roether and Kromer, 1978; Barth, 1980).

2.2. *Location*

All samples were taken in an area of about 50 km radius around Heidelberg. The two sampling sites, where the long-term records of soil respiration are obtained, are located about 15 km south of Heidelberg in the Rhine valley on a loamy, uncultivated, grass-covered soil (NU) and in a mixed beech-spruce forest on a sandy soil (SA).

3. Results and discussion

3.1. *CO_2 and ^{222}Rn concentration in soil air*

Fig. 1 shows three CO_2 concentration/depth profiles taken in different soils and at different times. The CO_2 increase with depth is determined by the depth distribution of soil organic matter and plant roots; the CO_2 concentration depends on the source strength *and* on soil structure. Profile III shows the highest CO_2 concentration and the lowest CO_2 production. In profile I, the CO_2 concentration is about 4 times lower but the CO_2 production about twice compared to profile III.

This example shows clearly, that there is a necessity for information on gas transport in the unsaturated soil zone, to calculate the CO_2 flux at the soil surface from a concentration profile measurement. Direct (inverted cup) CO_2 flux measurements are disturbed by above-ground vegetation and yield no reliable data for soil CO_2 production, except for measurements on bare soil.

In order to trace gas transport in the unsaturated soil zone, both ^{222}Rn concentration in soil air and ^{222}Rn flux at the soil surface is measured (Dörr et al., 1983). Fig. 1 shows a typical ^{222}Rn depth profile, taken parallel to CO_2 profile No. I. The ^{222}Rn profile increases more slowly with depth than does the CO_2 profile. Assuming a homogeneous distribution of the ^{222}Rn source, and constant diffusion coefficient $D = D_0/k$ in soil air, the scale height $\bar{z}$ can be calculated from $\bar{z} = \sqrt{(D_0/k)\,\tau}$ (Israel, 1962; Dörr et al., 1983) to be $\bar{z} = 180$ cm ($D_0 = 0.1$ cm^2 s^{-1}; $k = \frac{2}{3}$ (Penman, 1940); $\tau = 5.5$ d, mean life of ^{222}Rn).

Gas transport in the unsaturated soil zone occurs through molecular diffusion; thus, the CO_2 and ^{222}Rn fluxes can be calculated from Fick's law no. 1

$$j = -P \operatorname{grad} c \tag{1}$$

where $P = D_0(\varepsilon_0 - F)k$ and,
D_0: molecular diffusion constant of the gas in air;
ε_0: total porosity;
F: soil moisture (by volume);
k: tortuosity, describing the variation of the diffusion cross section in the soil by soil grains and water-filled capillary regions (bottle necks).

The CO_2/Rn flux ratio

$$j_{CO_2}/j_{Rn} = (D_0^{CO_2}/D_0^{Rn})(\Delta C_{CO_2}/\Delta C_{Rn}) \tag{2}$$

does not depend on soil parameters. The ratio of the molecular diffusion coefficients for CO_2 and Radon at a given temperature is constant ($D_0^{CO_2}/D_0^{Rn} = 1.3$ at 15°C (Jost, 1960).

The CO_2 flux at the soil surface is calculated from eq. (2) using measured CO_2 and ^{222}Rn concentration profile data and the ^{222}Rn flux at the soil surface. The direct ^{222}Rn flux measurement is not disturbed by above-ground vegetation or by changes in the natural conditions induced

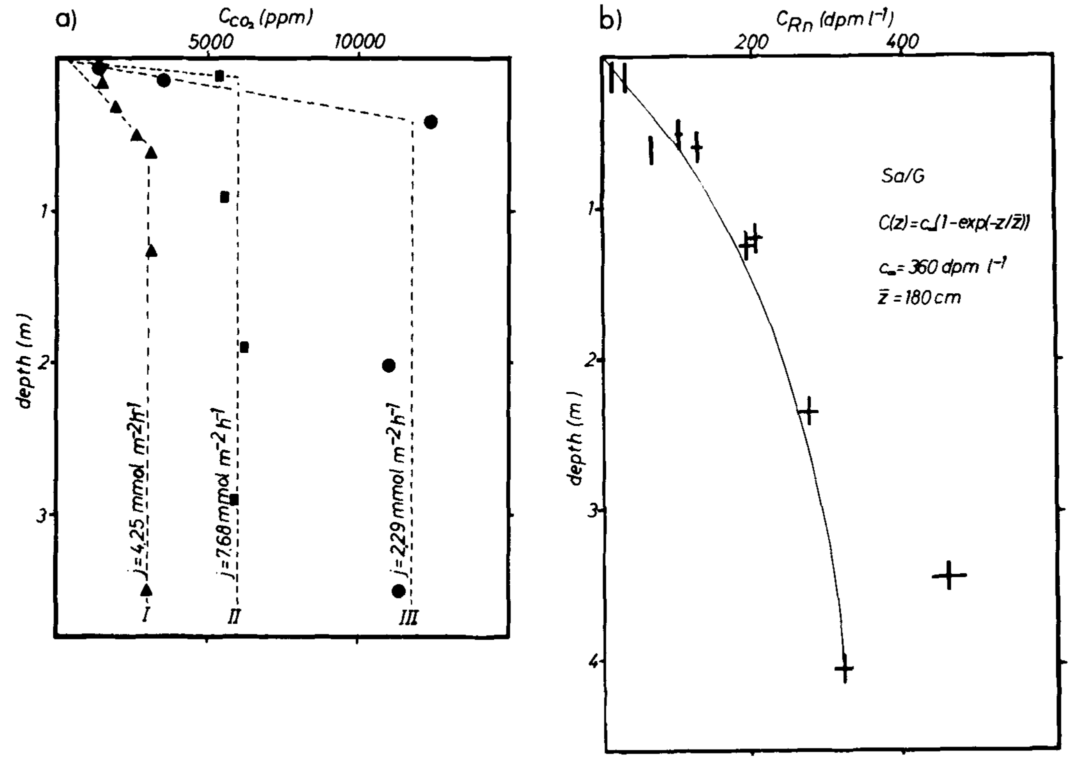

Fig. 1. (a) Soil CO_2 profiles in different soils with different vegetation. The CO_2 flux at the soil surface is noted for each profile. (b) ^{222}Rn depth profile taken parallel to CO_2 profile no 1. Soil gas concentration depends both on production rate and on gas transport.

by sampling. This indirect method of CO_2 flux determination has been checked with direct CO_2 flux measurements on bare soils (Dörr, 1984).

3.2. The effect of temperature and soil moisture on CO_2 production

Fig. 2 shows monthly values of soil respiration and temperature between 1979 and 1984 on a loamy, grass-covered soil (NU). The CO_2 production is strongly correlated with soil temperature. The parameters of a linear regression analysis of monthly means for the years 1979 to 1984 are given in Table 1:

Fig. 3 shows the relation between monthly means of soil respiration and soil temperature at location NU for 1979. Although most of the biological and biochemical processes follow an exponential temperature dependence, the data imply a linear relationship. This may probably be due to the fact that CO_2 production in the soil is a combined plant physiological (root respiration) and microbiological process. Microbial decomposition of soil organic matter itself includes the action of many species of microorganisms. The observed linear temperature relation could thus originate from a superposition of different temperature relationships in the quoted temperature interval. The mean slope of the regression line or the more commonly used mean Q_{10} value for the years 1979 to 1984 of $Q_{10} = 2.4$ is in good agreement with data from Schleser (1982). In the present paper, the slope of the regression line is used as a parameter for the temperature dependence of soil respiration, rather than Q_{10} values which by definition are temperature-dependent themselves. The Q_{10} values reported in Table 1 are calculated for a temperature interval between 5 and 15°C.

Fig. 4 shows soil respiration and temperature on a sandy soil in a beech-spruce forest (SA).

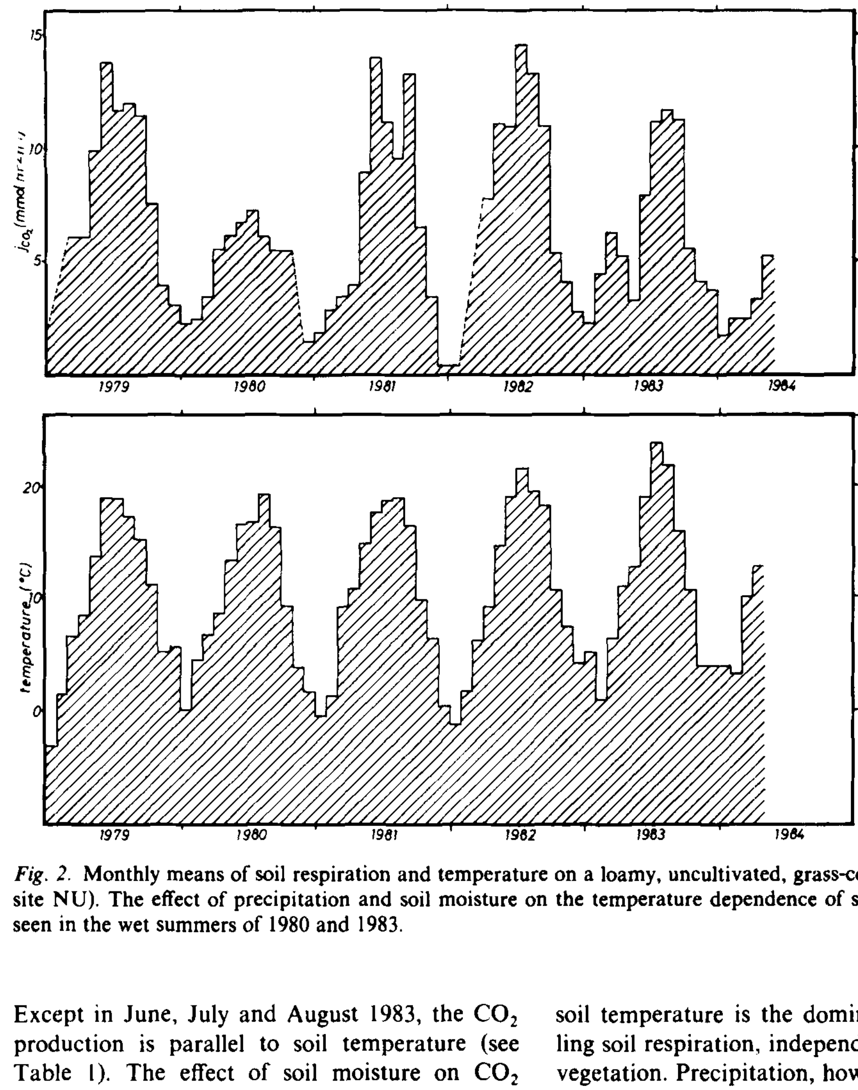

Fig. 2. Monthly means of soil respiration and temperature on a loamy, uncultivated, grass-covered area (sampling site NU). The effect of precipitation and soil moisture on the temperature dependence of soil respiration can be seen in the wet summers of 1980 and 1983.

Except in June, July and August 1983, the CO_2 production is parallel to soil temperature (see Table 1). The effect of soil moisture on CO_2 production can be seen in the rainy year 1980, the rainy spring 1983 and the hot and dry summer 1983. At site NU (Fig. 2), high summer precipitation in 1980 and 1983 leads to a reduction of soil respiration to 66% and 89% of the 1979 to 1984 mean value, respectively. In April and May 1983, precipitation was about 3 times higher than the long-term mean value and CO_2 production is reduced to winter respiration rates. At site SA (Fig. 4), soil respiration is hardly influenced by high precipitation, but is strongly decreased in the hot and dry months June, July and August 1983.

From Fig. 2 and Fig. 4, it is evident that top-soil temperature is the dominant factor controlling soil respiration, independent of soil type and vegetation. Precipitation, however, is linked with soil moisture via the hydraulic conductivity of the soil (Eagleson, 1978), and thus the influence of precipitation on soil respiration changes with soil type. In a sandy soil with high hydraulic conductivity, soil moisture is only slightly influenced during periods with high precipitation, while on a loamy or clay soil, high soil water content is induced for a longer period. At our specific sampling sites, this effect is increased by the type of vegetation. In the forested, sandy soil with high hydraulic conductivity, soil water consumption by the trees is high and soil moisture content is more easily reduced in hot and dry periods than increased during precipitation. In the loamy, Table. 1. *Results of the analysis of soil respiration data for sampling site NU and SA*

	T_0	m	R^2	Nd	Q_{10}	T	j_0
NU 1979	−0.7	0.66	0.95	70%	2.7	15.4	10.8
NU 1980	−7.3	0.27	0.83	122%	1.8	15.0	6.2
NU 1981	−1.0	0.59	0.81	89%	2.7	16.0	10.1
NU 1982	−1.9	0.59	0.93	79%	2.4	16.8	11.4
NU 1983	−7.1	0.38	0.78	161%	1.8	17.1	8.4
NU 1984	−1.8	0.35	0.96	119%	2.5	15.5	5.5
SA 1983	−27	0.15	0.46	161%	1.4	17.1	5.7
SA 1984	+0.2	0.56	0.81	119%	3.1	15.5	5.8
SA 1985	−6.3	0.30	0.60	102%	1.9	16.5	7.1

T_0 is the temperature in °C at which CO_2 production is zero.
m is the slope of the regression line (mmol m^{-2} h^{-1} $°C^{-1}$).
R is the correlation coefficient (Bevington, 1969).
Nd is the summer precipitation (April to September) in % of the long-term mean value.
Q_{10} is the change in CO_2 production for a temperature change of 10°C.
T is the summer mean temperature in °C.
j_0 is the summer mean CO_2 production (mmol m^{-2} h^{-1}).

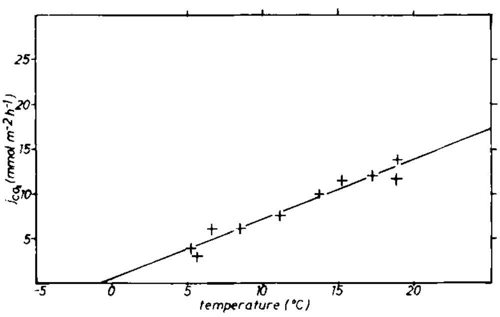

Fig. 3. Linear correlation of the monthly means of soil respiration and soil temperature at location NU in 1979. The parameters of the linear regression of the data are given in Table 1.

grass-covered soil with low hydraulic conductivity, evapotranspiration is less and soil moisture is not so strongly influenced in hot and dry periods, but is increased during times of high precipitation.

In Fig. 5, the slope of the soil respiration–temperature regression m for the years 1979 to 1984 is plotted versus the summer precipitation, expressed as the deviation from a long-term mean value. Q_{10} values are noted in parentheses; the circles represent measurements from NU, the squares from SA.

The data show that the influence of temperature on the annual cycle of soil respiration is masked by the effect of precipitation or soil moisture. In years with more rain compared to the long-time mean value, soil CO_2 production is reduced and Q_{10} values decrease to nearly half of the "mean condition"-value. Comparison of mean summer temperature and Q_{10} value (see Table 1) shows that during rainy periods, soil respiration is less reduced at higher and more reduced at lower summer mean temperatures. Both effects are presumably due to an evolutional adaptation of soil micro-organism and vegetation to long-time mean climatic conditions. A change in environmental parameters always leads to worse living conditions and thus to a reduction of productivity of soil flora and fauna.

Up to now, the summer climate in the sampling region did not allow one to study the effect of low summer precipitation on annual soil respiration, but monthly data from site SA (see Fig. 4) suggest that Q_{10} values are also decreased, if summer precipitation is less than the long-time mean value.

3.3. *Regional mean annual cycle of soil respiration*

To evaluate a regional mean annual cycle of soil respiration, 125 direct CO_2 flux data from the years 1979 to 1984 on 35 locations with different soils and different vegetation in an area of about 50 km radius around Heidelberg are plotted in Fig. 6, upper curve. The summer mean value is $j_{summer} = 9$ mmol m^{-2} h^{-1}; the annual mean value is $j_{annual} = 6$ mmol m-2 h-1.

The large scatter in the data is due to local differences in CO_2 production *and* differences in the transport parameters, in the unsaturated soil zone. As discussed above, the influence of gas transport on soil respiration is traced by parallel measurement of ^{222}Rn concentration and flux. In Fig. 6, lower curve, the annual cycle of the CO_2/Rn flux ratio, calculated from eq. (2), is plotted for those locations, where in addition to the CO_2 fluxes from Fig. 6 upper curve, parallel CO_2 and ^{222}Rn data exist. The regional mean annual cycle of soil respiration, calibrated for soil gas transport, is obtained by multiplication with the mean regional ^{222}Rn flux of $j_{Rn} = 2500$ dpm

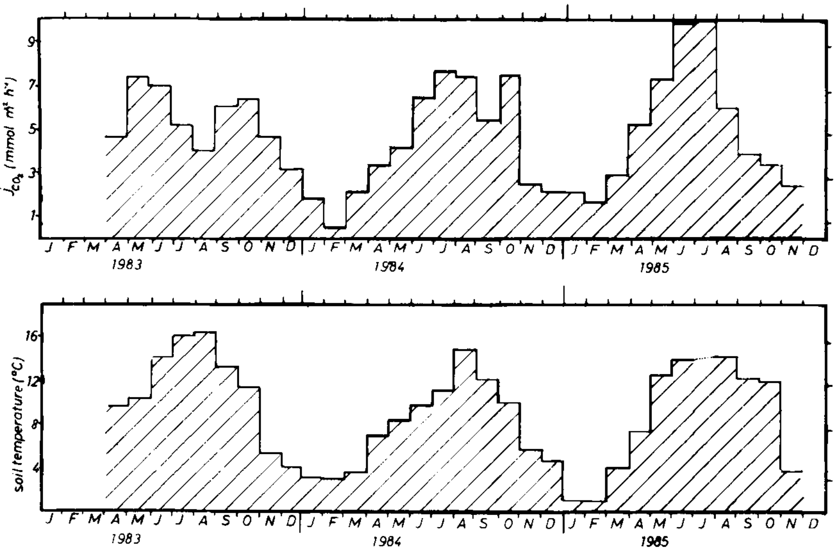

Fig. 4. Monthly means of soil respiration and temperature on a sandy soil in a forested area (sampling site SA). The effect of low-summer precipitation and dry soil can be seen in the summer 1983.

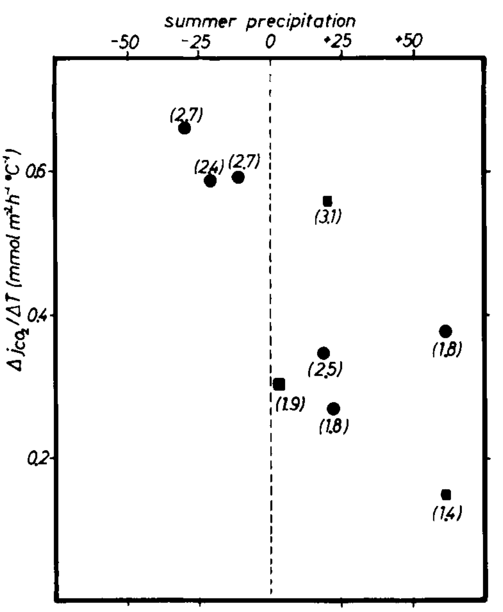

Fig. 5. Slope of the soil respiration — temperature regression in mmol m^{-2} h^{-1} $°C^{-1}$ versus the summer precipitation (April to September) as % of the long-term mean value. Circles indicate measurements from NU, squares from SA. Q_{10} values are given in parentheses. The effect of temperature on soil respiration is masked by the effect of precipitation and soil moisture resp.

m^{-2} h^{-1}. Minimum CO_2 production of about $j_{min} = 2$ mmol m^{-2} h^{-1} occurs in February; the maximum of about $j_{max} = 15$ mmol m^{-2} h^{-1} is in June.

The annual cycle of CO_2 production in the soil and the influence of climate variables include both microbial decomposition and root respiration. Concentration profiles and soil respiration in general yield information on both processes. If, however, in a soil profile, organic material and plant roots are separated spatially, root respiration and microbial decomposition can be distinguished from the change of the concentration gradient in the different soil layers (Dörr and Münnich, 1985).

As the turn-over of soil organic matter is of the order of several years, and root respiration CO_2 is released within 1 year after assimilation from the atmosphere, root respiration CO_2 can be identified measuring the ^{14}C content of respiration CO_2, soil organic matter and atmospheric CO_2 using a two-component mixing model. The component with the contemporary atmospheric ^{14}C content, however, includes not only root respiration but also fast (1 year) microbially decomposed CO_2 (Dörr and Münnich, 1985). ^{14}C measurements of soil CO_2 at locations SA and NU show

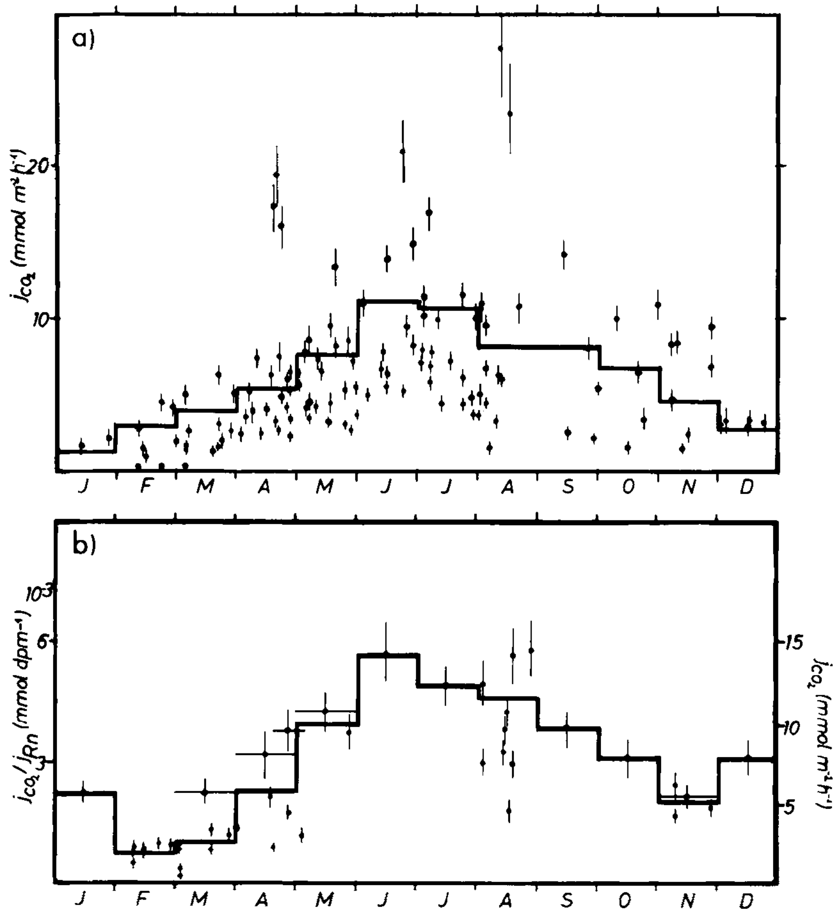

Fig. 6. (a) Regional mean annual cycle of soil respiration (125 direct flux measurements). (b) Regional mean annual cycle of the CO_2/Rn flux ratio. CO_2 flux data (right-hand ordinate) are obtained by multiplication with the regional mean ^{222}Rn flux of $j_{Rn} = 2500$ dpm m^{-2} h^{-1}. Horizontal bars indicate that a location is sampled more than once a month. Monthly means of all locations are given as a histogram.

that fast decomposition and root respiration dominates in May and June, whereas during fall and winter, the slow microbial decomposition is the dominant source of soil CO_2. In a forest area, fast decomposition and root respiration contributes about 40% and in an uncultivated area with grass cover about 10% to the total yearly CO_2 production in the soil.

4. Conclusions

Parallel measurements of CO_2 and ^{222}Rn in soil air provide reliable data on the CO_2 production in the unsaturated soil zone.

The CO_2 release to the atmosphere not only depends on temperature, but is also controlled by summer precipitation. The results presented are obtained from measurements on two soils and vegetations of different type, which cover the range of CO_2 productivity, hydraulic conductivity, and soil gas permeability of most of the soils and vegetation in the southwest of Germany. Thus, the results should be representative for the whole region and for areas with comparable soils and climatic conditions.

The regional mean annual CO_2 release to the atmosphere of 6 mmol m^{-2} h^{-1} = 630 g C m^{-2} a^{-1} has to be corrected for the contribution of root respiration, to be comparable with data of net primary production (NPP) for this region.

From the distribution of forest, cultivated and uncultivated areas in the studied region and from analysis of ^{14}C measurements in soil respiration, the fraction of root respiration can be estimated to be about 40 to 50% of the total soil CO_2 production. The obtained annual CO_2 production from decomposition of soil organic matter of 315 to 380 g C m^{-2} a^{-1} which in a steady state is equivalent to NPP, is in agreement with NPP data used by Fung et al. (1983) and from Lieth (1975), for this latitude.

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