The Response of CO_2 Evolution from Soils to Global Temperature Changes

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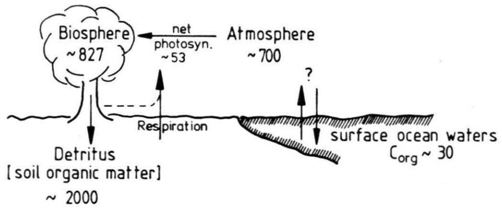
Own experiments and literature data point at a strong correlation between mineralization processes in soils i.e. the corresponding CO_2 release and temperature variations. This seems to be important with regard to the global CO_2 problem, since it implies that due to the global temperature increase over 80 years (1860—1940) large additional amounts of CO_2 were released to the atmosphere. These additional quantities seem to have been at least as important as the anthropogenic release of CO_2 from the burning of fossil fuels.

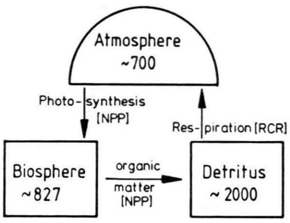
Introduction

Over the past decade numerous publications have dealt with the global carbon cycle [1—6]. It has been stressed that only an accurate understanding of all its aspects will finally provide the knowledge which is necessary, to answer reliably questions about the future consequences inherent in the evolution of CO_2 from fossil fuel burning.

The correct global circulation of carbon is still elusive, due to the paucity and uncertainty of experimental data. As a consequence, interpretations of past interactions as well as predictions of future developments are still questionable. Further experimental data are therefore urgently needed.



a) Natural carbon pools which participate in short term carbon cycling and annual exchange rates. Quantities are in units of 10^9 metric tons.



b) Model for the evaluation of relaxation phenomena from temperature induced excess CO_2 evolution out of soils.

Fig. 1. Simplified representation of the global carbon cycle. Pool sizes are stated according to Woodwell [2].

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The natural carbon pools which exchange their carbon in terms of a few years or decades are atmosphere, biosphere, detritus and ocean surface waters, respectively. Although their sizes are still not accurately known, detritus undoubtedly contains the largest amount of carbon as shown in Figure 1. Most probably it contains two to three times as much as the atmosphere. Consequently small changes therein, which alter the evolution rate of CO_2, may cause significant changes in the CO_2 content of the atmosphere. Global temperature records have revealed an increasing trend during the time period of 1860—1940 [7, 8]. This rise has not been large, nevertheless it seems to have triggered an additional and important source of CO_2.

Temperature Induced CO_2 Evolution from Soils

In general, chemical as well as biochemical reaction rates increase as the temperature is raised. Biologists describe the effect of temperature on a biochemical reaction in terms of the "temperature coefficient" or Q_{10} value, which designates the rate of reaction at one temperature compared with the rate at a temperature 10 °C lower.

$$Q_{10} = k_{T+10}/k_T\,.$$

In this equation k_{T+10} and k_T denote the rate constants at temperatures $T + 10$ and T respectively.

For numerous biological processes Q_{10} ranges from 3 to 4 at room temperature (18—20 °C). With regard to soils, where microbial activity is most

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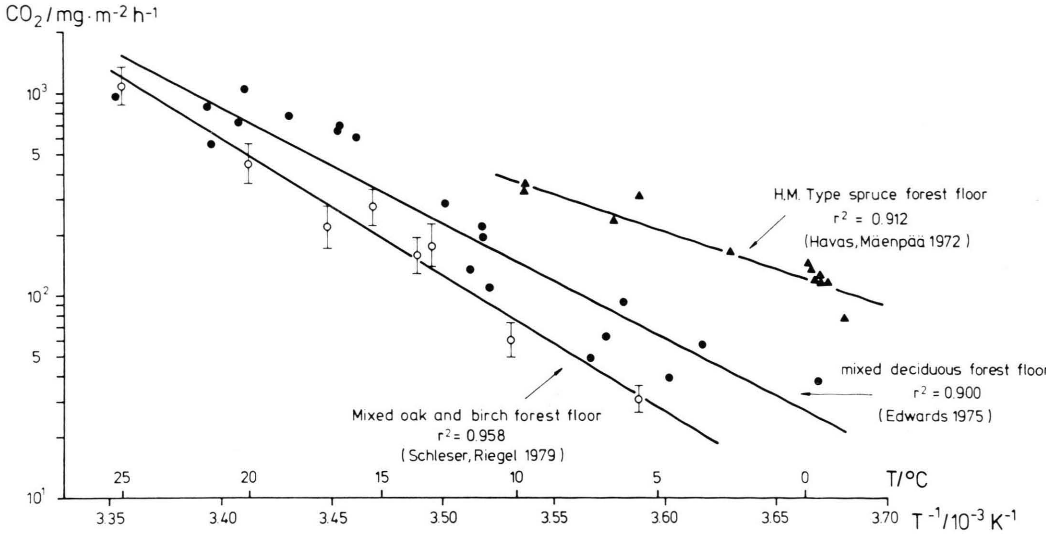

Fig. 2. Arrhenius plot of CO_2 evolution and temperature for different soils.

important for the degradation of organic matter and a strong temperature correlation exists too, temperature coefficients may occasionally be as low as 2 or lower, depending on environmental conditions such as nutrient supply, moisture content a.s.o. [9, 10, 11]. In general, however, our unpublished laboratory experiments with undisturbed soil cores as well as our in situ measurements of various forest soils led to temperature coefficients of up to 6. In context with soils the temperature coefficient will henceforth be designated as Q_{RCR} (RCR = Respiratory CO_2 Release Rate). Figure 2 exhibits three examples of forest floor measurements [12, 13, 14] which indicate the possible range of Q_{RCR} values.

Field and laboratory measurements together with the available data from literature revealed, that temperature coefficients as high as 6 are not impossible, though they are uncommon. A significant outcome is the increasing trend of temperature coefficients with decreasing temperatures according to Figure 3. This enhances the importance of detritus from higher latitudes, where also much stronger layers of soil organic matter prevail. Table 1 shows the detrital accumulation of tropical, temperate and tundra areas.

It is evident from these figures that temperate and tundra zones are more important compared with the tropics. Beyond that, temperature records indicate a larger increase for higher latitudes [7].

In summary, it seems justified to restrict the forthcoming estimate to higher latitudes, because:

— temperature coefficients are higher for lower temperatures,

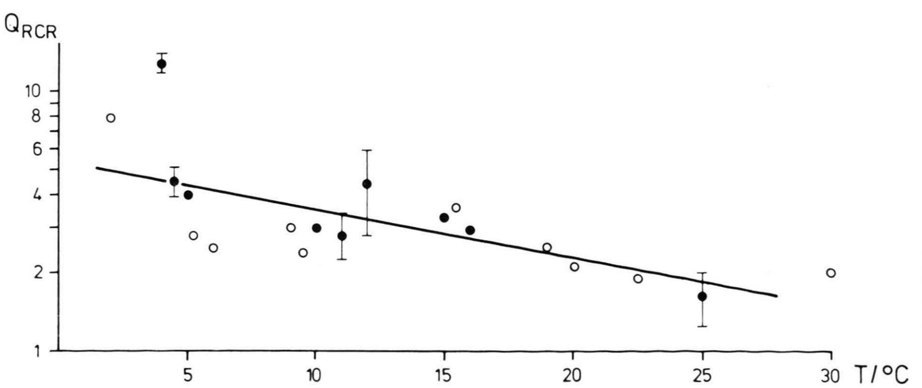

Fig. 3. Q_{RCR}-values from various soils as a function of temperature. Solid circles: averages of up to 18 different soils, open circles: single soils ($r = 0.76$).

Table 1. Distribution of detritus in selected zones.

Ecosystem	Mean organic matter/ $kgCm^{-2}$	Global detritus[a]/ Gt C	Covered area[b]/ $10^{+12}m^2$
Tropical forest	10.4	255	24.5
Tropical savanna	3.7	56	15
Mean & total	7.9	311	39.5
Temperate forest	11.8	142	12
Temperate grassland	19.2	173	9
Boreal forest	14.9	179	12
Tundra & alpine	21.6	173	8
Mean & total	16.2	667	41

[a] Data according to Schlesinger [15].
[b] Areas from Whittaker [16].

— past temperature records exhibit larger effects for northern latitude zones compared to the tropics,
— northern latitude zones hold the largest amount of soil organic matter.

For the present investigation the mean temperature trend between latitude zone 40—70 °N has been chosen. This choice merely reflects the availability of the mean annual temperature trend for this area and is by no means ideal, since for example large areas of North America are excluded. However, the results may give a first impression of the importance of global temperature variations for the CO_2 release of soils.

Global Temperature Increase and CO_2 Evolution

On the basis of a box model (Figure 1 b), the following assumptions have been made, in order to arrive at an estimate for the contribution of CO_2 from soils with temperature:

I. at the beginning of the global temperature increase, a steady state prevailed, i.e. input as net primary productivity (NPP) equalled output of CO_2 from soils (RCR):
$$\mathrm{NPP}_0 = \mathrm{RCR}_0,$$
where the subscript $_0$ refers to the original undisturbed condition;

II. organic matter input into detritus i.e. net primary productivity (NPP) will not be affected by increasing temperatures:
$$\mathrm{NPP}_0 = \mathrm{NPP}(t) = \mathrm{const};$$

III. increasing evolution rates of CO_2 will deplete the detrital content;

IV. a depletion in soil organic matter (SOM) will reduce the corresponding respiratory CO_2 release rate (RCR) by:
$$-\Delta\mathrm{RCR} = \mathrm{RCR}_0(1 - \mathrm{SOM}/\mathrm{SOM}_0);$$

V. the temperature increase from 1860 to 1940 will be approximated by a linear function:
$$\Delta T(t) \sim t,$$
where t represents the time in years*.

The evolution of CO_2 from soils as a function of time may then be expressed as follows:

$$\mathrm{RCR}(t) = \mathrm{RCR}_0[1 + \alpha(T)\,\Delta T(t)]\frac{\mathrm{SOM}}{\mathrm{SOM}_0}, \quad (1)$$

where $\alpha(T)$ is the CO_2 response to temperature per °C at temperature T. The differential equation for the corresponding depletion of soil organic matter (SOM) is given by

$$\frac{\mathrm{dSOM}}{\mathrm{d}t} = \mathrm{NPP}_0 - \mathrm{RCR}_0[1 + \alpha(T)\,\Delta T(t)]\frac{\mathrm{SOM}}{\mathrm{SOM}_0}.$$

Introducing the previously defined temperature coefficient Q_{RCR} and neglecting its temperature dependence due to the small temperature increase of the present problem and furthermore assuming a global temperature increase of 0.01 °C/year which gives an increase of 0.8 °C for the time period of 1860 to 1940 results in:

$$\frac{\mathrm{dSOM}}{\mathrm{d}t} = \mathrm{NPP}_0 - \frac{1}{\tau}\left[1 - \frac{Q_{\mathrm{RCR}} - 1}{10}\,0.01\,t\right]\mathrm{SOM}, \quad (2)$$

where τ represents the mean residence time of detrital carbon and t_0 being zero.

The solution of this equation leads to

$$\mathrm{SOM}(t) = \frac{\mathrm{NPP}_0}{\sqrt{\beta/2\tau}}D(y) + \exp\{1/2\beta\tau\} \cdot \left[\mathrm{SOM}_0 - \frac{\mathrm{NPP}_0}{\sqrt{\beta/2\tau}}D(1/\sqrt{2\beta\tau})\right]\cdot e^{-y^2} \quad (3)$$

with $y = (1 + \beta t)/\sqrt{2\beta\tau}$, $D(y)$ being Dawson's integral [17] and $\beta = (Q_{\mathrm{RCR}} - 1)10^{-3}$.

* A similar model-approach has been presented by Prof. Kohlmaier at a meeting of the contact group "Anthropogenic Climate Perturbations" in Brussels. October 1981.

An estimate of soil organic matter for $t = t_0$ results in 600 Gt C as compared to 667 Gt C stated in Table 1. This figure accounts for the fact that temperate forests and grasslands are not restricted to areas between 40–70 °N.

Primary production data from Box [18] updated according to Lieth and Esser [19] result in an annual growth rate for dry matter of 22.18 Gt (40–70 °N). As dry matter contains about 45% carbon by weight, the corresponding annual fixation rate of carbon amounts to:

$$NPP_0 = 9.98\ \mathrm{Gt\,C}, \quad (40\text{–}70\ ^\circ\mathrm{N}).$$

On the basis of $Q_{RCR} = 4$ Eqs. (1) and (3) lead to evolution rates of CO_2 and the corresponding depletion of soil organic matter, as shown in Figure 4. Table 2 exhibits the cumulative amounts of CO_2 released from soils in comparison to the emission of CO_2 from the combustion of fossil fuels.

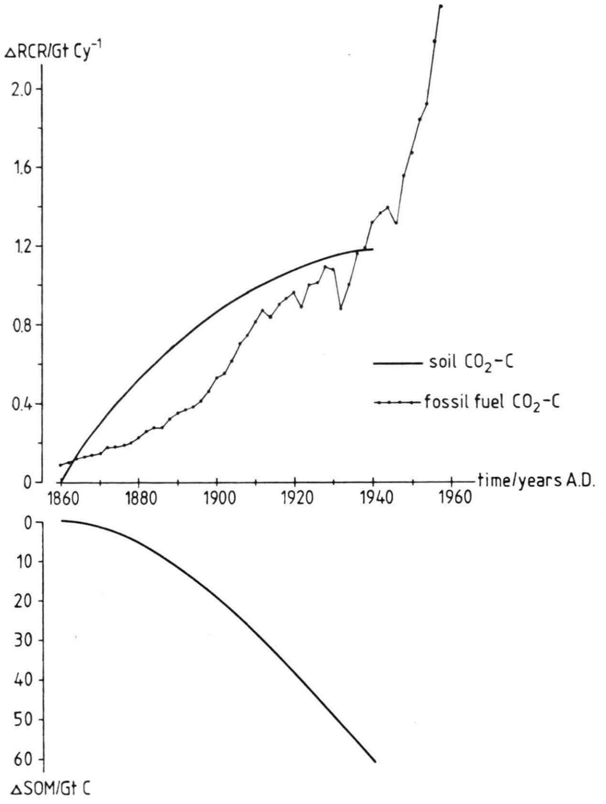

Fig. 4. CO_2 release from fossil fuels in comparison with emission from soils (ΔRCR) due to the global temperature increase from 1860–1940. ΔSOM designates the depletion of soil organic matter as a result of the CO_2 emission out of soils.

Table. 2. Cumulative release of CO_2 from soils due to the global temperature increase as compared to the emission of CO_2 from burning of fossil fuels.

		Release of CO_2/Gt C	
t/year	ΔT/°C	soils	fossil fuels[a]
1860	—	—	0.09
1880	0.2	5.4	3.2
1900	0.4	19.1	10.4
1920	0.6	38.2	26.0
1940	0.8	60.4	47.2

[a] Data after Keeling [20], Rotty [21].

Discussion

A comparison between manmade CO_2 and the release from soils due to the global temperature increase shows the importance of the latter contribution as a net source. It is by no means negligible, but has probably been a substantial additional release from the biota.

Further evidence for this fact seems to stem from ^{13}C-data of tree rings which indicate, that the biota have released about 1.9 Gt C per year at the turn of the century and about 3.9 Gt C per year around 1935 [22]. For the same periods, fossil fuels have only been released at rates of 0.5 and 1.1 Gt C per year, respectively. The corresponding cumulative values exhibit similar proportions: Wagener [22] arrives at a biospheric contribution of roughly 150 Gt C for the time period from 1850–1935, while Stuiver's estimate leads to 120 Gt C for the period from 1850–1950 [23]. These figures have to be compared with 41 Gt C and 60 Gt C, respectively, from fossil fuel burning during the corresponding time periods.

The fact that soils represent a net source with increasing temperatures and a net sink with decreasing temperatures implies that biota may have recently acted as a sink because a strong decreasing temperature trend has been noticed since 1940.

The temperature increase resulted in a considerable depletion of soil organic matter (Figure 4). More than 10% of the original amount has been released to the atmosphere as CO_2. With 60.4 Gt C (Table 2) released from 1860–1940, the total loss per m^2 within the latitude zone 40–70 °N amounts to 1.7 kg C/m^2 heeding the area figures of Table 1. This value lies well within the range of data given by Bolin [1] for the loss due to deforestation and cultivation. This indicates that even a small global temperature increase may result in changes of the CO_2 release from detritus which are comparable to the manmade CO_2 emission.

The limitations of data on which the assumptions are based must be kept in mind when judging the presented results. The uncertainties are still so great that the matter warrants further investigation.

In a number of cases the moisture content of soils counteracts temperature effects. Although this is occasionally true [15], for some locations, it has been found that, in the majority of cases, temperature is by far more important than moisture content [f.e. 14, 24] and has, therefore, been omitted for this study.

Furthermore, temperature effects have only been considered in relation to respiration. However, net assimilation over a fairly broad temperature range around the optimum temperature shows less than 10% variation [25, 26]. Even for larger temperature ranges, temperature coefficients hardly exceed values of 1.8 and in many investigations far lower values have been reported [27—29]. Therefore, it seemed justified to neglect the response of photosynthesis to temperature. If it is true that temperature does not decisively increase assimilation, increased CO_2 contents might yet enhance photosynthesis. However, if nutrients other than CO_2 are growth limiting, increased assimilation would be unlikely.

A far more serious problem seems to be the assumption of a uniform temperature trend for a large area such as the latitude zone 40—70 °N. It is well known that rather large differences have been reported within this zone. However, due to the limited informations presently at hand there was no better approach to the problem.

A more detailed investigation is presently under way in co-operation with Prof. Kohlmaier, University Frankfurt. The corresponding paper is in preparation.

Acknowledgement

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[1] B. Bolin, Science **196**, 613 (1977).
[2] G. M. Woodwell, Sci. Amer. **238**, 34 (1978).
[3] W. S. Broecker, T. Takahashi, H. J. Simpson, and T. H. Peng, Science **206**, 409 (1979).
[4] G. G. Killough and W. R. Emanuel, Tellus **33**, 274 (1981).
[5] B. G. Hunt, Tellus **33**, 78 (1981).
[6] G. H. Kohlmaier, Rad. Environm. Biophys. **19**, 67 (1981).
[7] J. M. Mitchell Jr., Ann. New York Acad. Sci. **95**, 235 (1961).
[8] G. S. Callendar, Quat. J. Roy. Met. Soc. **87**, 1 (1961).
[9] K. H. Domsch, Zbl. Bakt. Abt. II **116**, 33 (1961).
[10] J. L. Ingraham, The Bacteria. I. C. Gunsalus, and R. Y. Stanier (eds.) Vol 4, Academic Press, New York 1962.
[11] G. H. Schleser, Rad. Environm. Biophys. **17**, 85 (1979).
[12] G. H. Schleser and U. Riegel, Unpublished data (1979).
[13] N. T. Edwards, Soil. Sci. Soc. Amer. Proc. **39**, 361 (1975).
[14] P. Havas and E. Mäenpää, Aquilo Ser. Bot. **11**, 4 (1972).
[15] W. H. Schlesinger, Ann. Rev. Ecol. Syst. **8**, 51 (1977).
[16] R. H. Whittaker, Mac Millan 2nd ed. New York 1975 p. 387.
[17] M. Abramowitz (ed.), Dover Publ. Inc., New York 1970 p. 319.
[18] E. Box, Rad. Environm. Biophys. **15**, 305 (1978).
[19] H. Lieth and G. Esser, II. Arbeitstagung Umweltbiophysik der DDR, in press (1981).
[20] C. D. Keeling, Tellus **25**, 174 (1973).
[21] R. Rotty, in: Andersen and Malahoff (eds.), Plenum Press, New York 1977, p. 167.
[22] K. Wagener, Rad. Environm. Biophys. **15**, 101 (1978).
[23] M. Stuiver, Science **199**, 253 (1978).
[24] J. J. Reinke, D. C. Adriano, and K. W. McLeod, Soil Sci. Soc. Amer. J. **45**, 620 (1981).
[25] J. W. Wilson, Ann. Bot. **30**, 753 (1966).
[26] D. M. Gates, Biophysical Ecology, Springer-Verlag, New York 1980, p. 530.
[27] H. A. Mooney and W. D. Billings, Ecol. Monogr. **31**, 1 (1961).
[28] D. Müller, Planta **6**, 22 (1928).
[29] H. G. Wager, New Phyt. **40**, 1 (1941).