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ORIGINAL PAPER

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Temperature dependence of organic matter decomposition: a critical review using literature data analyzed with different models

Abstract The literature was reviewed regarding laboratory incubation studies where C mineralization was measured. Experiments were selected in which the same substrate was incubated at least at two different temperatures and where time-series were available with at least four measurements for each substrate and temperature. A first-order one-component model and a parallel first-order two-component model were fitted to the CO_2–C evolution data in each experiment using a least-squares procedure. After normalising for a reference temperature, the temperature coefficient (Q_{10}) function and three other temperature response functions were fitted to the estimated rate constants. The two-component model could describe the dynamics of the 25 experiments much more adequately than the one-component model (higher R^2, adjusted for the number of parameters), even when the rate constants for both were assumed to be equally affected by temperature. The goodness-of-fit did not differ between the temperature response models, but was affected by the choice of the reference temperature. For the whole data set, a Q_{10} of 2 was found to be adequate for describing the temperature dependence of decomposition in the intermediate temperature range (about 5–35 °C). However, for individual experiments, Q_{10} values deviated greatly from 2. At least at temperatures below 5 °C, functions not based on Q_{10} are probably more adequate. However, due to the paucity of data from low-temperature incubations, this conclusion is only tentative, and more experimental work is called for.

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Introduction

It has been hypothesized that the positive response to increases in temperature is higher for decomposition than for primary productivity (Woodwell 1978; Jenkinson et al. 1991; Schimel et al. 1994; Kirschbaum 1995). Temperature increases are expected due to the emission of greenhouse gases (e.g. Houghton et al. 1990) and may provide a positive feed-back in the global C cycle due to decreases in soil C stocks.

The basic theory of decomposition kinetics has been well described by several authors (Bunnell and Tait 1974; Swift et al. 1979). The strong correlation between soil respiration and temperature was noted by Lundegårdh (1927) and has been quantified for many soils under different conditions (for reviews see: Singh and Gupta 1977; Raich and Schlesinger 1992; Lloyd and Taylor 1994; Kirschbaum 1995). However, there is no consensus on the form of the relationship between decomposition and temperature. In many decomposition studies, the temperature coefficient Q_{10} relationship (van't Hoff 1898) is used to describe the dependence of decomposition on temperature. Kirschbaum (1995) reviewed 20 different data sources and compiled reported Q_{10} values regarding C mineralization. Fitting the Q_{10} function to this data set resulted in high Q_{10} values at low temperatures, decreasing from about 8 at 0 °C to about 2.5 at 20 °C.

Besides the Q_{10} relationship, several other functions have been used to describe temperature responses: linear functions (e.g. Witkamp 1966; Froment 1972; Gupta and Singh 1981), power functions (e.g. Kucera and Kirkham 1971), Arrhenius-type functions (e.g. Howard and Howard 1979; Lloyd and Taylor 1994), S-shaped functions (e.g. De Neve 1996) and the heat sum concept (e.g. Andrén and Paustian 1987; Honeycutt et al. 1988)

which corresponds to Q_{10} values exponentially decreasing with temperature. These functions can easily be converted into each other by changing parameters into temperature-dependent variables. Thus, a comparison between studies where different approaches were used is possible. However, problems arise when making a comparison, since experimental procedures and their analyses vary. The fact that sometimes accumulated values were used and sometimes rates were used in the studies is probably a minor problem. However, initial rates (Winkler et al. 1996), rates observed during different time periods at different incubation temperatures (Ross and Cairns 1978), or rate constants as estimated by different models and using different algorithms to fit the data (e.g. Blet-Charaudeau et al. 1990; Updegraff et al. 1995; Thierron and Laudelout 1996; Lomander et al. 1998) have been used to estimate temperature responses.

The objective of the work presented here was to estimate the functional relationship between decomposition rates and temperature. The literature was reviewed and a data set was compiled from data given in figures and tables. This data set was analyzed using dynamic one-component and two-component models.

Materials and methods

Data sources

The literature was reviewed regarding laboratory incubation studies where C mineralization was measured. The selection criteria were:

1. The same substrate was incubated at least at two different temperatures.

2. Time-series were available and comprised at least four measurements for each substrate and temperature.

From the resulting data set, several experiments were excluded:

1. Azmal et al. (1996a) presented results for eight different substrates. To avoid depending too heavily on a single study, we included only three substrates (low, medium and high decomposition rates).

2. Since only monotonously increasing response functions were considered, two substrates were excluded from one reference (E and B horizon; Winkler 1996) where decomposition rates decreased with temperature, and one substrate was excluded from Pöhhacker and Zech (1995), where temperature did not affect C mineralization (in a humic mineral horizon). The highest temperature (32 °C) was also excluded for another substrate (beach litter) presented by Pöhhacker and Zech (1995), since CO_2 evolution was higher at 22 °C than at 32 °C.

Data from experiments where incubation temperatures exceeded 40 °C were also excluded (Roper 1985).

One reference was excluded, where temperatures (10–60 °C) had almost no affect on C mineralization in a Mediterranean soil (Varnero et al. 1987). An overview of the resulting data set is given in Table 1.

Data analysis

The data were scaled to a common unit. A first-order one-component model and a parallel first-order two-component model were used for the analysis of CO_2-C evolution rates (C_{flux}; mg g^{-1} substrate day^{-1}) or cumulative CO_2-C evolution (C_{cum}; mg g^{-1} substrate):

Table 1 Short description of the experiments included in the data set and rate constants (k) as estimated by fitting a one-component (k) and a two-component (α, k_1 and k_2) decomposition model to C evolution *rates* or cumulative C evolution (*cum.*) from the experiment with the highest incubation temperature. The corresponding goodness of fit, R^2_{1adj} and R^2_{2adj}, were determined by linear regression (modelled vs. measured values). Parameter values determining the four temperature response functions (Eqs. 3–6) refer to the two-component model and were determined by non-linear regression. When the C concentration ($C\%$) was given in the references, the dimension of the rate constants was relative to substrate mass (mg C g^{-1} substrate); otherwise ($C\% = 100$) the rates were relative to the C mass (mg C g^{-1} substrate C)

ID	Data source	Vegetation and soil	Substrate	Incubation temperatures (°C)	Days	Data type	C%	k (×10⁻⁴)	R^2_{1adj}	α (×10⁻³)	k_1 (×10⁻²)	k_2 (×10⁻⁴)	R^2_{2adj}	E	T_0	Q_{10}	T_{min}
1	Winkler et al. (1996)	Mixed forest, Ultisol	A-horizon	4, 15, 22, 38	120	rates	1.0	11.1	0.54	13.7	15.3	6.49	0.92	48.7	231	1.92	−5.55
2	Honeycutt et al. (1988)	Agriculture	Soil and sludge	5, 10, 15, 20, 25, 30	77	cum.	34.6	4.12	0.03	19.1	13.7	0.342	0.92	55.6	232	2.15	−4.65
3	Ross and Cairns (1978)	Tussok grassland, silt loam	Topsoil	5, 10, 15, 20, 24	45	rates	4.6	7.70	0.80	2.07	189	7.32	0.97	59.5	230	2.33	−6.39
4	Ross and Cairns (1978)	Tussok grassland, loamy sand	Topsoil	5, 10, 15, 20, 24	45	rates	2.5	23.2	0.49	35.2	8.10	13.1	0.95	59.9	230	2.34	−6.59
5	Waksman and Gerretsen (1931)	Straw, dry, nonutrients	Oat straw	7, 27, 37	273	cum.	100	46.5	0.93	620	1.33	0.00	0.98	29.4	211	1.48	−22.7
6	Waksman and Gerretsen (1931)	Straw, dry, nutrients added	Oat straw	7, 27, 37	273	cum.	100	106	0.82	497	7.18	19.4	0.97	40.5	225	1.72	−9.93
7	Waksman and Gerretsen (1931)	Straw, moist, nutrients added	Oat straw	7, 27, 37	273	cum.	100	163	0.88	609	6.04	18.6	0.99	43.9	227	1.80	−7.47
8	Reichstein (unpublished)	Heath, podzol	Organic layer	5, 15, 25	104	cum.	43.5	1.84	0.99	1.67	11.0	1.61	1.00	64.6	233	2.50	−5.16
9	Reichstein (unpublished)	Subalpine herbs and grass, podzol	A-horizon	5, 15, 25	104	cum.	6.13	3.12	0.97	9.01	4.98	1.94	1.00	71.5	236	2.75	−2.90
10	Pöhhacker and Zech (1995)	Deciduous, forest, brown earth	L-layer	5, 12, 22, 32	50	rates	100	11.4	0.86	370	0.62	2.40	0.93	60.6	229	2.40	−8.28
11	Blet-Charaudeau et al. (1990)	Wheat field, Rendoll	Topsoil	2, 10, 19, 28	56	cum.	1.8	0.94	0.95	3.72	15.9	1.43	0.99	69.6	237	2.64	−1.39
12	Blet-Charaudeau et al. (1990)	Native grassland, Rendoll	Topsoil	2, 10, 19, 28	56	cum.	7.4	0.94	0.98	0.82	28.4	0.69	0.99	27.7	204	1.47	−30.9
13	Roper (1985)	Wheat field, clay	Topsoil+straw	10, 19, 28	105	rates	50	6.93	0.67	21.6	37.7	12.5	0.94	60.8	243	2.19	+6.28
14	Roper (1985)	Wheat field, loamy sand	Soil+straw	15, 20, 25, 30, 35, 40	300	rates	50	53.4	0.29	26.0	54.7	16.9	0.82	63.9	244	2.28	+6.21
15	Azmal et al. (1996b)	Upland field, clay loam	Topsoil	25, 35	56	cum.	2.2	6.76	0.98	7.88	11.4	4.83	0.99	42.9	229	1.75	−5.81
16	Azmal et al. (1996b)	Upland field, clay loam	Topsoil+rice straw	25, 35	11	cum.	2.4	15.9	0.96	30.3	19.9	8.14	0.99	23.0	202	1.35	−36.6
17	Azmal et al. (1996b)	Upland field, clay loam	Topsoil+Azolla	25, 35	9	cum.	2.4	20.7	0.90	48.9	21.5	7.90	0.99	48.5	233	1.89	−1.77
18	De Neve (1996)	Chicory field, loamy sand	Topsoil+cauliflower	5.5, 10, 16	300	cum.	100	255	0.81	523	11.9	25.3	0.99	50.1	220	2.10	−15.9
19	Azmal et al. (1996a)	Upland field, clay loam	Topsoil	15, 25, 35	56	cum.	2.2	7.83	0.98	2.20	98.7	7.27	0.99	57.8	237	2.16	+0.17
20	Azmal et al. (1996a)	Upland field, clay loam	Topsoil+rice straw	15, 25, 35	56	cum.	2.4	17.9	0.91	25.3	62.5	11.3	0.99	69.2	233	2.51	+5.19
21	Azmal et al. (1996a)	Upland field, clay loam	Topsoil+Sesbania	15, 25, 35	56	cum.	2.4	22.6	0.85	42.5	35.2	11.3	0.98	50.7	233	1.96	−2.36
22	Jansson (1958)	Agriculture	Topsoil	25, 35	720	cum.	2.56	5.33	0.91	13.3	15.9	2.80	1.00	46.8	226	1.91	−9.11
23	Jansson (1958)	Agriculture	Topsoil+straw	25, 35	720	cum.	2.97	17.6	0.85	85.7	49.0	2.80	0.98	44.4	226	1.84	−10.8
24	Lomander et al. (1998)	Arable field, heavy clay	Topsoil	0.3, 5, 15, 25	300	rates	2.37	16.3	0.87	51.8	2.30	11.6	0.95	74.1	236	2.88	−2.48
25	Lomander et al. (1998)	Arable field, heavy clay	Subsoil	15, 25	300	rates	1.3	4.70	0.73	17.7	1.40	3.68	0.75	60.3	233	2.33	−4.05

$$C_{flux} = \alpha C_0 k_1 e^{-k_1 t} + (1-\alpha) C_0 k_2 e^{-k_2 t}; \qquad 0 \leq \alpha \leq 1 \qquad (1a)$$

$$C_{cum} = \alpha C_0 (1 - e^{-k_1 t}) + (1-\alpha) C_0 (1 - e^{-k_2 t}); \; 0 \leq \alpha \leq 1 \qquad (1b)$$

where C_0 is the initial amount of total C in the substrate and αC_0 and $(1-\alpha)C_0$ are the initial amounts of C in the two respective pools in the two-component model, and k_1 and k_2 are the corresponding rate constants. In the one-component model, $\alpha = 1$, and thus only one pool remains. If both C_{flux} and C_{cum} were available, we analyzed the rates to avoid statistical problems concerning autocorrelated residuals (Hess and Schmidt 1995).

The models were fitted to the time-series for the highest incubation temperature (T_{max}) in each experiment by optimising values for α, k_1 and k_2 simultaneously, by using an algorithm for non-linear least squares (Ralston and Jennrich 1979). Thereafter, the model was fitted to the time-series for the remaining incubation temperatures of the corresponding experiment. For all temperatures below T_{max}, the value for α was the same as that estimated for T_{max} and the ratio between k_1 and k_2 (as estimated for T_{max}) was also fixed, i.e. temperature was assumed to affect k_1 and k_2 equally:

$$k_1 = r k_{1max} \qquad (2a)$$

$$k_2 = r k_{2max} \qquad (2a)$$

where r is the temperature response factor and k_{1max} and k_{2max} are the rate constants at T_{max}.

The next step was to describe the dependence of these response factors on temperature for each experiment (cf. Andrén and Paustian 1987). We tested four $r(T)$ functions, all with one free parameter apart from the reference temperature (T_{ref}), i.e. the temperature at which r equals unity:

1. An Arrhenius-type function

$$r(T) = e^{\left[\frac{E}{R} \left(\frac{1}{T_{ref}+273.15} - \frac{1}{T+273.15} \right) \right]} \qquad (3)$$

where R is the universal gas constant (8.314 J mol^{-1} K^{-1}) and E is the activation energy (J mol^{-1}).

2. A two-parameter function proposed by Lloyd and Taylor (1994)

$$r(T) = e^{E_0 \left(\frac{1}{T_{ref}+273.15-T_0} - \frac{1}{T+273.15-T_0} \right)} \qquad (4)$$

where E_o and T_o are parameters used to fit the data (Lloyd and Taylor 1994). Here, we used the value for E_o ($=35.41\,°C$) proposed by Lloyd and Taylor (1994).

3. The exponential Q_{10} function

$$r(T) = Q_{10}^{\frac{T-T_{ref}}{10}} \qquad (5)$$

4. A function proposed by Ratkowsky et al. (1982)

$$r(T) = \frac{(T - T_{min})^2}{(T_{ref} - T_{min})^2} \qquad (6)$$

where T_{min} is a hypothetical value at which C_{flux} equals zero.

By fitting these functions to the r factors for each experiment ($T_{ref} = T_{max}$), we obtained a set of 25 parameter values normalized for T_{max}. Since T_{max} differed (ranging from 16 to 40 °C) between the experiments, we had to normalize these functions for a common T_{ref} to estimate a common parameter value for each response function (Eqs. 3–6) representing all experiments. Thus, we recalculated the r factors as estimated for each experiment and function and fitted the corresponding four functions to these normalized r factors (as estimated using the same functions) for the whole data set. R^2_{adj}, the coefficient of determination, adjusted for the number of parameters, as calculated by linear regression, was used as a measure for goodness-of-fit between C_{cum} measurements and model output; R^2 as calculated by non-linear regression was used as a measure of goodness-of-fit between $r(T)$ and r factors.

Results and discussion

The two-component model could describe the dynamics of the 25 experiments much more adequately than the one-component model. The agreement between all modelled and measured values (all temperatures) of each experiment resulted in much higher R^2_{adj} values for the two-component model than for the one-component model (Table 1).

All three, simultaneously estimated, parameters (α, k_1 and k_2) were highly correlated. This implies that changes in one are compensated by changes in the other two parameters, without greatly affecting the fit of the model. For example, reducing α by 50% of the optimized value affected the resulting r factors, on average by less than 5%. The strong correlation between the parameters hardly makes it possible to interpret each of them separately as Updegraff et al. (1995) did.

All four tested temperature response functions fitted well to the response factors of each experiment (R^2_{adj} values were generally high; not shown). However, the estimated parameter values varied greatly between experiments. For example, the estimated Q_{10} values varied between 1.35 and 2.88 in the 25 experiments (Table 1).

The choice of T_{ref} when rescaling the r factors from T_{max} to the common T_{ref}, influenced the resulting total response function (Table 2). The R^2 value was highest ($=0.96$) for all four tested response functions when 30 °C was chosen as T_{ref} (Table 2). For example, for

Table 2 Parameter values for E (Eq. 3), T_0 (Eq. 4), Q_{10} (Eq. 5), T_{min} (Eq. 6), as estimated for the whole data set at different reference (T_{ref}) and maximum (T_{max}) temperatures. R^2 indicates goodness-of-fit between the two-component model and temperature response factors according to non-linear regression

T_{ref}	T_{max}	E	R^2	T_0	R^2	Q_{10}	R^2	T_{min}	R^2
10	40	54.1	0.74	237	0.57	2.04	0.75	+3.54	0.36
20	40	53.6	0.89	236	0.85	2.02	0.89	+0.50	0.82
30	40	54.2	0.96	233	0.96	2.06	0.96	−3.78	0.96
40	40	52.7	0.91	231	0.92	2.05	0.90	−5.17	0.93
10	30	54.8	0.79	235	0.59	2.10	0.78	+2.07	0.28
20	30	53.6	0.95	233	0.92	2.07	0.95	−2.81	0.89
30	30	54.8	0.93	231	0.93	2.13	0.93	−5.25	0.92

$T_{ref} = 10\,°C$, the R^2 values were as low as 0.36 for the "Ratkowsky model" (Table 2). We also tested the sensitivity of the response functions when excluding high incubation temperatures uncommon under field conditions (Table 2). When excluding temperatures above $30\,°C$ from the data set, the R^2 values decreased when T_{ref} was equal to $30\,°C$.

The fit of the response functions to r factors deriving from the one-component model was much poorer (Table 1) and the response was generally less concave than that of the two-compartment model, i.e. r factors increased less with temperature than they did for the two-component model. For the one-component model, the values for E, E_o, Q_{10} and T_{min}, were 32.5, 213, 1.56 and –21.8, respectively, and the corresponding R^2 values were 0.80, 0.87, 0.79 and 0.87 (with $T_{ref} = 30\,°C$ and $T_{max} = 40\,°C$) i.e. lower than for the two-component model (Table 2).

The assumption made in the two-compartment model that k_1 and k_2 are equally affected by temperature was tested. These two parameters were estimated independently for each incubation temperature and experiment, whereupon the response functions (Eqs. 3–6) were fitted to the r factors according to the procedure described above, but for k_1 and k_2 separately. For ten experiments the optimized values for k_2 became negative for one or several temperatures. In these cases k_2 was set to "missing" for the whole experiment. The resulting response functions as estimated for k_1 and k_2 were similar to each other and to those for their combined response (i.e. when k_1 and k_2 were equally affected by temperature). For k_1, the estimated parameters E (R^2), E_o (R^2), Q_{10} (R^2) T_{min} (R^2) were 47.3 (0.89), 228 (0.89), 1.89 (0.89) and –7.99 (0.87), respectively. Corresponding values for k_2 (R^2) were 44.5 (0.60), 226 (0.85), 1.85 (0.59) and –4.80 (0.86). Consequently, the assumption that k_1 and k_2 were equally affected by temperature seems to be reasonable.

The goodness-of-fit did not differ between the temperature response models in the intermediate temperature range (about 5–35 °C). A Q_{10} value of 2 as used in many model applications is probably an adequate value when modelling the effect of temperatures between about 5 °C and 35 °C on decomposition, at least when simulating ecosystem responses at larger scales. However, for individual substrates, Q_{10} values may deviate greatly from 2. Possibly, this variation in Q_{10} values is due to temperature optima which can differ in time and space between organism communities. For example, lignin decomposers may have another temperature dependence than other functional groups of decomposers. It is also possible that soil organism communities in cold climates are adapted to these, and thus will show comparatively high activities at low temperatures (e.g. Kirschbaum 1995). Hidden interactions of temperature response with other factors (e.g. soil moisture, salt concentration or O_2 oxygen partial pressure) during the incubations may also have caused variation in Q_{10} values.
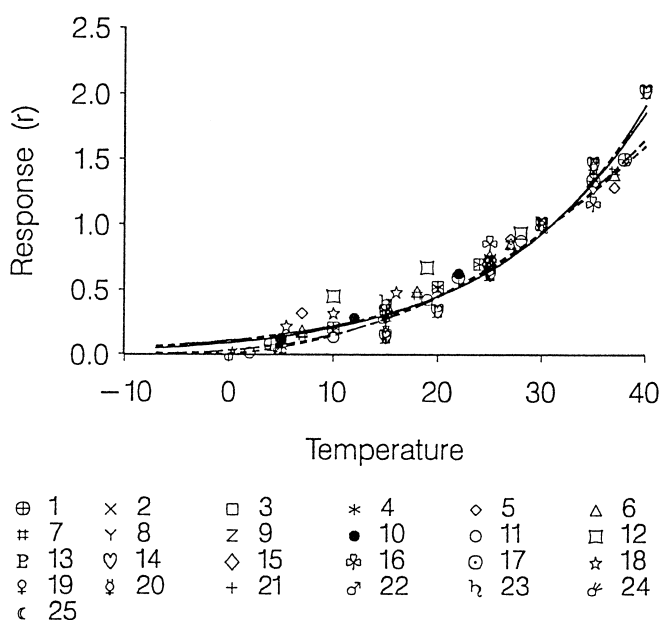
Fig. 1 The dependence of the first-order decomposition rates k_1 and k_2 on temperature. *Lines* denote four tested temperature response (r) models with parameter values given in Table 2: Eq. 3 —— Eq. 4 — — —, Eq. 5 – – –, Eq. 6 – – –. The reference temperature is 30 °C. Symbols are r-factors (see text) as normalized for the reference temperature using Eq. 6. *Numbers* in the legend correspond to those given under "ID" in Table 1

In the data set analyzed here, only two or three experiments included temperatures above 35 °C or below 5 °C. Although R^2_{adj} values for the four temperature response models were similar, the models diverged considerably above and below these temperatures (Fig. 1). Probably, the models proposed by Ratkowsky et al. (1982) and Lloyd and Taylor (1994) are more adequate for the lower temperature range and possibly for the whole temperature range examined here. To model temperature responses above 35 °C, bell-shaped functions – which consider that responses decrease above an optimum temperature – should be used (cf. Kirschbaum 1995). Constant values for E and Q_{10} at lower temperature intervals are also theoretically unreasonable since both E and Q_{10} approach infinity when $r(T)$ approaches zero. Thus, under natural conditions where temperatures are close to 0 °C during longer time periods, e.g. at high elevation or latitude, functions not based on Q_{10} are probably more adequate. However, due to the paucity of data from low-temperature incubations, this conclusion is only tentative, and more experimental work is called for.

References

Andrén O, Paustian K (1987) Barley straw decomposition in the field: a comparison of models. Ecology 68:1190–1200

Azmal AKM, Marumoto T, Shindo H, Nishiyama M (1996a) Mineralization and microbial biomass formation in upland soil amended with some tropical plant residues at different temperatures. Soil Sci Plant Nutr 42:463–473

Azmal AKM, Marumoto T, Shindo H, Nishiyama M (1996b) Mineralization and changes in microbial biomass in water-saturated soil amended with some tropical plant residues. Soil Sci Plant Nutr 42:483–492

Blet-Charaudeau C, Muller J, Laudelout H (1990) Kinetics of carbon dioxide evolution in relation to microbial biomass and temperature. Soil Sci Soc Am J 54:1324–1328

Bunnell FL, Tait DEN (1974) Mathematical simulation models of decomposition processes. In: Holding AJ, Heal OW, MacLean SF Jr, Flananagan PW (eds) Soil organisms and decomposition in tundra. Tundra Biome Steering Committee, Stockholm, Sweden, pp 207–225

De Neve S, Pannier J, Hofman G (1996) Temperature effects on C- and N-mineralization from vegetable crop resitues. Plant Soil 181:25–30

Froment A (1972) Soil respiration in a mixed oak forest. Oikos 23:273–277

Gupta SR, Singh JS (1981) Soil respiration in a tropical grassland. Soil Biol Biochem 13:261–268

Hess TF, Schmidt SK (1995) Improved procedure for obtaining statistically valid parameter estimates from soil respiration data. Soil Biol Biochem 27:1–7

Hoff van't, JH (1898) Lectures on theoretical and physical chemistry. Part 1. Chemical dynamics. Edward Arnold, London, pp 224–229

Honeycutt CW, Zibilske LM, Clapham WM (1988) Heat units for describing carbon mineralization and predicting net nitrogen mineralization. Soil Sci Soc Am J 52:1346–1350

Houghton JT, Jenkins CJ, Ephraums JJ (eds) (1990) Climate change, the IPCC scientific assessment. Cambridge University Press, Cambridge

Howard JA, Howard DM (1979) Respiration of decomposing litter in relation to temperature and moisture. Oikos 33:457–465

Jansson SL (1958) Tracer studies on nitrogen transformations in soil with special attention to mineralisation-immobilization relationships. K Landbrukshögsk Ann 24:105–361

Jenkinson DS, Adams DE, Wild A (1991) Model estimates of CO_2 emissions from soil in response to global warming. Nature 351:304–306

Kirschbaum MUF (1995) The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. Soil Biol Biochem 27:753–760

Kucera C, Kirkham D (1971) Soil respiration studies in tallgrass prairie in Missouri. Ecology 52:912–915

Lloyd J, Taylor JA (1994) On the temperature dependence of soil respiration. Funct Ecol 8:315–323

Lomander A, Kätterer T, Andrén O (1998) Modelling the effects of temperature and moisture on CO_2 evolution from top- and subsoil using a multi-compartment approach. Soil Biol Biochem (in press)

Lundegårdh H (1927) Carbon dioxide evolution of soil and crop growth. Soil Sci 23:417–453

Pöhhacker R, Zech W (1995) Influence of temperature on CO_2 evolution, microbial biomass C and metabolic quotient during the decomposition of two humic forest horizons. Biol Fertil Soils 19:239–245

Raich JW, Schlesinger WH (1992) The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus 44:81–99

Ralston ML, Jennrich RI (1979) DUD, a derivative-free algorithm for non-linear least squares. Technometrics 1:7–14

Ratkowsky DA, Olley J, McMeekin, TA, Ball A (1982) Relationship between temperature and growth rate of bacterial cultures. J Bacteriol 149:1–5

Roper MM (1985) Straw decomposition and nitrogenase activity (C_2H_2 reduction): effects of soil moisture and temperature. Soil Biol Biochem 17:65–71

Ross DJ, Cairns A (1978) Influence of temperature on biochemical processes in some soils from tussock grasslands. N Zealand J Sci 21:581–589

Schimel DS, Braswell BH, Holland EA, McKeown R, Ojima DS, Painter TH, Parton WJ, Townsend AR (1994) Climatic, edaphic, and biotic controls over storage and turnover of carbon in soils. Global Biogeochem Cycles 8:279–293

Singh JS, Gupta SR (1977) Plant decomposition and soil respiration in terrestrial ecosystems. Bot Rev 43:449–528

Swift MJ, Heal OW, Anderson JM (1979) Decomposition in terrestrial ecosystems. Blackwell, Oxford

Thierron V, Laudelout (1996) Contribution of root respiration to total CO_2 efflux from the soil of a deciduous forest. Can J For Res 26:1142–1148

Updegraff K, Pastor J, Bridgham SD, Johnston CA (1995) Environmental and substrate controls over carbon and nitrogen mineralization in northern wetlands. Ecol Appl 5:151–163

Varnero MMT, Santibáñez QF, Espinosa TM (1987) Effect of soil moisture levels and temperature on organic matter decompostion, under laboratory conditions. Agric Tec (Chile) 47:97–100

Waksman SA, Gerretsen FC (1931) Influence of temperature and moisture upon the nature and extent of decomposition of plant residues by microorganisms. Ecology 12:33–60

Winkler JP, Cherry RS, Schlesinger WH (1996) The Q_{10} relationship of microbial respiration in a temperate forest soil. Soil Biol Biochem 28:1067–1072

Witkamp M (1966) Decomposition of leaf litter in relation to environment, microflora and microbial respiration. Ecology 47:194–201

Woodwell GM (1978) The carbon dioxide question. Sci Am 238:34–43