原著論文17

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BOMB-CARBON, ^{14}C-DATING AND ^{13}C - MEASUREMENTS AS TRACERS OF ORGANIC MATTER DYNAMICS AS WELL AS OF MORPHOGENETIC AND TURBATION PROCESSES

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SUMMARY

Organic matter dynamics can be traced by the thermonuclear-bomb-test induced rise of natural C-14,the "bomb-C", in the whole photosynthesis - nutrition - organic decomposition chain. Layerwise C-14 dated soil profiles from 1965 -1980 and past 1980 are evaluated for bomb-C depth penetration. The problem of soil rejuvenation or aging by Bomb-C or fossil fuel-C in conjunction with nutrient pool transfer and enhancement of organic matter production is described. C-dynamics is reflected also by D^{14}C and δ^{13}C levels in thin layerwise sampled soil profiles of different climates. These measurements can contribute to clarify the C-dynamics in morphogenetic processes,such as our examples of peloturbation and bioturbation.

INTRODUCTION

Bomb-C influences the natural ^{14}C-concentration in the biosphere and in soils since begin of thermonuclear testing mid of the 50th with a small concentration peak 1958,a maximum one 1962/63 (fig.1).

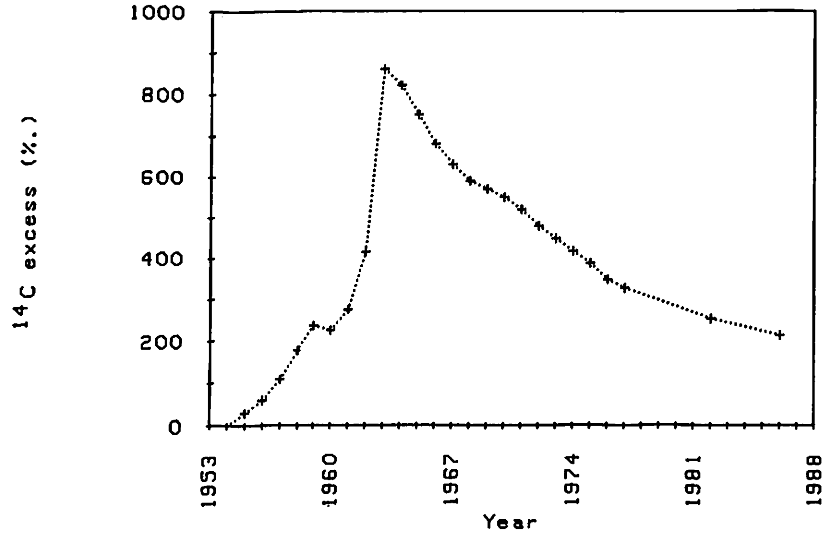


Fig. 1. Atmospheric bomb radiocarbon (Tans,1981,continued by own measurements)

While it is a major obstacle for ^{14}C-dating of the top soil layers,it can serve as a pollution induced tracer for the depth penetration and migration of soil organic matter or in conjunction with natural ^{14}C and δ^{13}C measurement as an instrument for studying the mechanism of morphogenetic,f.ex. turbation processes in soils.

However, the rejuvenating effect of bomb-C,decreasing in concentration since 1962/63 (Fig.1) is counteracted by a large older and dead carbon input due to increasing nutrient - (N,P,K) pool transfer from the atmosphere (ca 150 mil t of N.y^{-1},half from mineral fertilizer,half from diazotrophic systems) as well as from the lithosphere (ca 40 mil t of P and K . y^{-1}) as well as due to the annual release of additional 7 bil t of C (ca 5.5 bil t C from fossil fuel, ca 1.5 bil t of C from slash and burn of 8-15 mil ha of woodland per year), both together leading to a C - enrichment in soils during the past few decenniums at the order of ca 60 gt (gigatons) of C (ref.1) .

It is otherwise obvious, that according to (refs 2-4) and Fig.2 in the recycling system organic matter decomposition has a steep initial spike and a slow steady state phase. Most of the annually recycling C is therefore very young,derived from turnover of fresh vegetable substrate. Thus, from the annual input of young C the major part is quickly volatilized again. Only a small percentage, certainly $<1\%$, in soils of high biological activity <1 %o contributes to the remaining resident,mostly complexed humic carbon.

BOMB CARBON PENETRATION AND ORGANIC MATTER MOVEMENT IN SOILS OVER TIME

Fractions of soil organic matter can migrate in acid and alkaline soils or can be translocated by root growth and animal transport of C, depending on the soil's biological activity, its assortment of bases, its variable charges

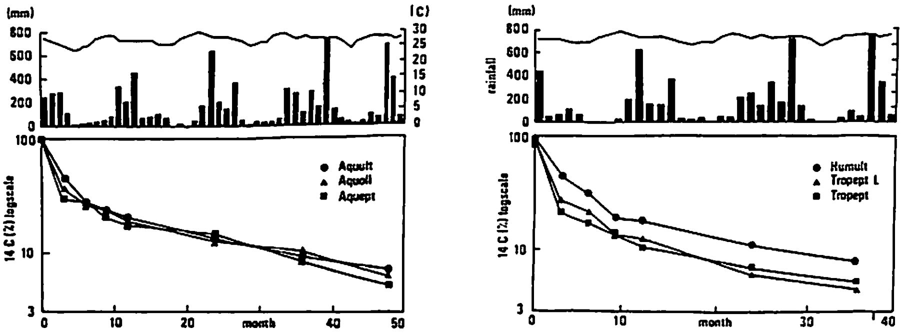


Fig. 2. Decomposition pattern of ^{14}C-labeled rice straw ,left in tropical upland soils,right in flooded tropical lowland soils (ref. 4) .

and its type of oxide and clay matrix (HAC or LAC). In LAC-soils soil organic matter is often at acid soil pH the only compartment,whose low-pH -PZC (point of zero charge) is below the soil-pH,which gives the s.o.m. at soil-pH a negative charge and a CEC (cation exchange capacity).

Short term C-penetration in soils during the last 30 years is traced by the bomb-^{14}C and measurable. Although texture,pH, Eh ,s.o.m.-content and other modifiers,which in effect determine the formation of different Great Soil Groups, contribute, it was felt useful, scrutinizing all layerwise ^{14}C-dated soil profiles from 1965 to 1980 and after since. Our systematic ^{14}C-dating works on soil profiles began in 1965. Restricting ourselves to layerwise sampled soil profiles only (mostly 10 cm or sub-horizon wise) and omiting the available 36 profiles of Histosols, the data collective comprises for the sampling period 1965-1980 129 terrestrial soil profiles, Alfisols, Inceptisols, Mollisols, Spodosols and Vertisols. 105 profiles were sampled 1965 till 1975, 24 profiles 1975 to 1980. ^{14}C-dates of all samples,layerwise differentiated in table 1,all show a trend of increasing age with depth. One path of explanation would be a model of slow build-up of the epipedon,which will be discussed in the last part of the paper.

TABLE 1

Average regression,correlation factor and corresponding AMRT (Apparent Mean Residence Time) for different depth levels of soil profiles from all layerwise dated soil profiles till 1980 (13 Alfisols, 16 Inceptisols (mostly Plaggepts), 47 Mollisols, 9 Spodosols,44 Vertisols). Paleosols were not included; soil profiles are sampled in different W-,E-,S-European countries,in Argentina , Australia, Israel, Sudan and Tunisia.

Soil Order	Ascend of regression line	Corresponding AMRT of regression line (years B.P.)					
	Correlation factor	10 cm	20 cm	50 cm	100 cm	150 cm	200 cm
Alfisols	0.4651 0.739	480	960	2400	4800	7200	9600
Inceptisols (Plaggepts)	0.0225 0.209	870	920	1000	1160	1350	1490
Mollisols	0.4695 0.888	750	1240	2700	5150	8050	10000
Spodosols	0.0747 0.332	1350	1430	1680	2100	2520	2930
Vertisols	0.4014 0.772	0	410	1620	3650	5670	7700
All soils, Alf+Inc+Mol +Spod+Vert	0.4415 0.755	460	920	2300	4600	6900	9200

Another option is the realization that -which Fig.2 would also support- the annual pool of freshly produced organic substance is to its largest extent very quickly decomposed,while the clay organic complexes, once formed,are quite stable, and their is but little partition chromatography-like exchange of the organic ligand at the complexes. Plaggepts to the depth of the plaggen horizon and Vertisols to the depth of cracks show expectedly moderate age increase with depth only, due to the repeated deposition of young plaggen material or the inherent principle of mixing by peloturbation,churning,self mulching respectively. Till 1980 the rejuvenating effect of bomb-C penetration was in the average of all profiles of the different Great Soil Groups insufficient to render the ^{14}C-age modern.

TABLE 2

14 soil profiles, sampled 2 cm wise; maximum percentage of natural ^{14}C and depth threshold without bomb - ^{14}C , i.e. ^{14}C$<$100 % NBS-oxalate standard

Kind of soil	Great Soil Group	Origin Location	Maximum % of nat.^{14}C	Depth threshold w/o bomb-C,$<$100% NBS-St.
Terrestrial	spodic aquic Hapludalf	FRG,Wohldorf	125	10cm,14cm,28cm,45cm
"	spodic aquic Hapludalf	FRG,Ohlendorf	118	38cm
"	Hapludalf (forest)	FRG,Timmendorf	120	10cm
"	Hapludalf (plowed)	FRG,Kleinaltendorf	96	0cm
"	Pelloxerert	Israel,Akko	112	15cm
"	Pelloxerert	Israel,Qedma	110	22cm
"	Rhodustalf	India,Patancheru	115	12cm
Rice	Tropaquept	Thailand,Klong Luang	101	5 to 10cm
paddy	Eutropept	Thailand,Khon Kaen	119	14cm,20cm
rainfed	Tropaquept	Philippines,Pangil	124	20cm
"	Hydraquent	Philippines,Bugallon	116	ca. 5cm
"	Paleudult	Philipp.San Dionisio	121	20cm,32cm
Rice ir-	Haplaquoll	Philippines,Tiaong	122	24cm,70cm,74cm
rigated	Tropaquept	Philipp.,Los Banos	125	62cm,70cm,74cm

Since beginning of 1980 soil profiles were sampled 2cm - thin layer - wise. All post 1980 measurements of D^{14}C and δ^{13}C are quite revealing regarding bomb-C input,smoothness in the trend of age increase with depth and concerning organic matter percolation, which manifests itself by enrichment of the heavy ^{13}C and a decreasing δ^{13}C-value (Fig. 3 - 6). Table 2 , in an overview of 14 terrestrial,hydromorphic and mostly submerged profiles reflects with the added accuracy of thin layer sampling an increasing depth of bomb-C invasion in permanently moderately moist soils of the temperate climate, less penetration in more semiarid (ustic) or mediterranean (xeric) locations, again a trend to deeper penetration in ustic or udic climate soils with higher precipitation, an extremely deep impact of bomb-C on older volcanic ash soils with porous tuffaceous bedrock,and surprisingly minimum 0 to 5 cm immigration only in strongly reduced, almost permanently wet or submerged soils. A short information on climate versus depth penetration of bomb-C, especially of the examples in fig. 3 to 6, is given in table 3.

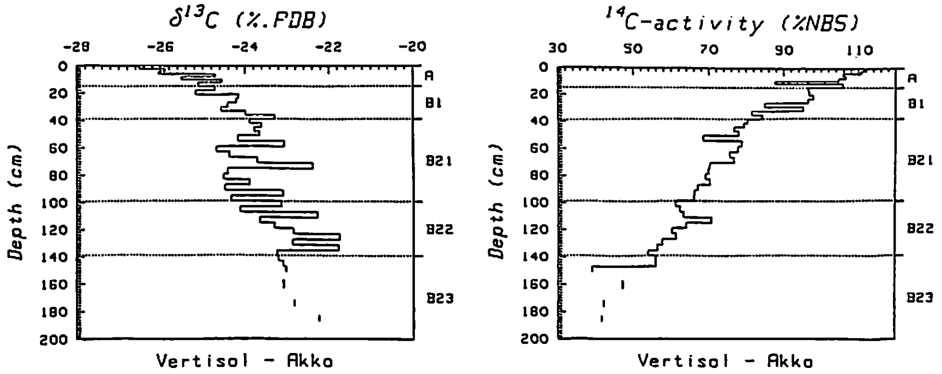


Fig. 3. Thin layer $\delta^{13}C$ and ^{14}C scanning curve of Vertisol profile,Akko,Israel (xeric climate, Peloxerert).

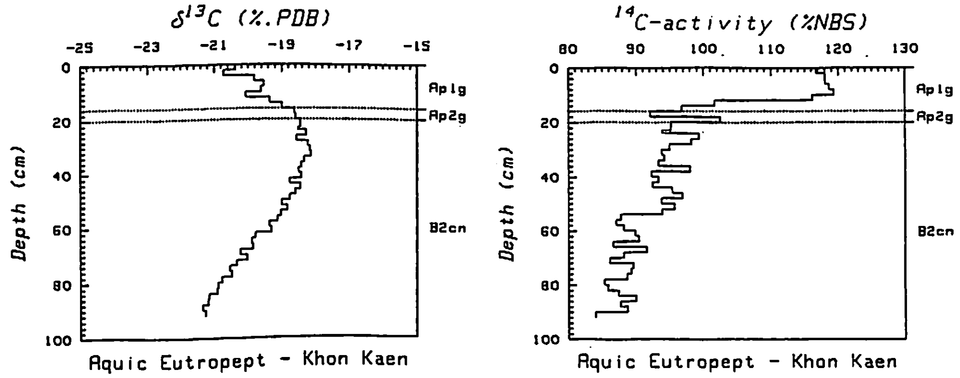
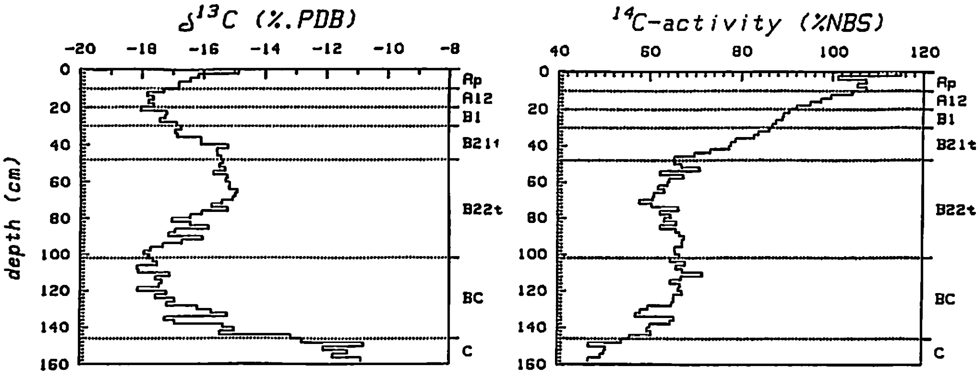


Fig. 4. Thin layer $\delta^{13}C$ and ^{14}C scanning curve of Eutropept profile,Khon Kaen, NE- Thailand (ustic climate).

The thin layer graphs of $\delta^{13}C$ and $D^{14}C$ measurements also allow deduction with regard to organic matter mobility. Xeric Akko (Fig.3) shows bomb-C to a depth of 10 to 15 cm,thereafter down to 75 cm only relatively slow increase of age, expectedly about to the depth of Vertisol cracks, deeper still a trend to ca. 40 % ^{14}C activity, compared with the NBS oxalate standard, equivalent to ca. 7000 years of age. δ^{13}C decreases rather steeply during upper 40 cm, thereafter less rapidly, which points to the humus-C of the lower profile part being influenced by former C-4 or CAM vegetation, the top soil humus-C however with intensified agricultural use more by the C of C-3 crops in direction to their δ^{13}C of -25 ‰.



Udic Rhodustalf - Patancheru

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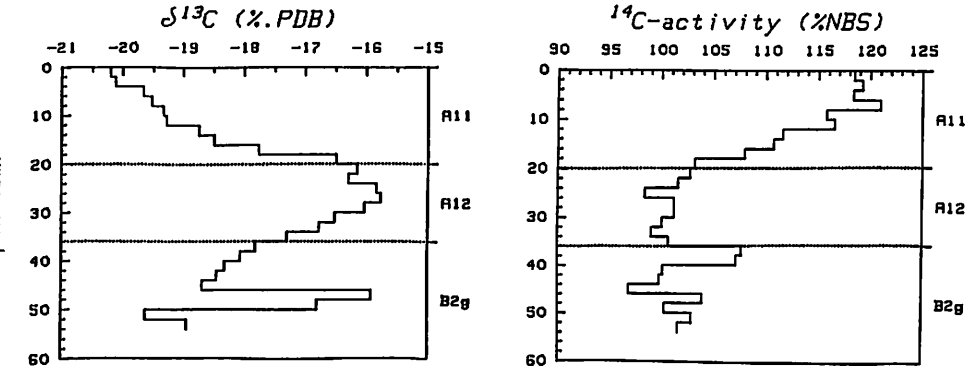
Fig. 5. Thin layer δ^{13}C and ^{14}C scanning curve of Rhodustalf profile, ICRISAT, Patencheru, India (ustic climate, semiarid).



Typic Haplaquoll - Tiaong (H)

Typic Haplaquoll - Tiaong (H)

Fig.6. Thin layer δ^{13}C and ^{14}C scanning curve of Haplaquoll (H) profile, Tiaong, Laguna, Philippines (udic climate).

The semiarid and ustic Patencheru (Fig.5) shows a bulging rise of the ^{13}C-content in the B2 horizon, which could indicate evaporation of C, which seems unlikely, or percolation of organic matter with enrichment of the less reactive heavier isotope during the partition steps, which seems more likely, since the underlying BC horizon shows an inflection of inverse trend within the increase of ^{14}C-age with depth.

TABLE 3

Bomb-C / organic matter migration in soil profiles of different climate regions, based on thin layerwise profile scanning by natural ^{14}C and δ^{13}C measurements.

Location of soil profiles	Climate	Mean temperature	Annual rainfall	Depth penetration of bomb - C
Wohldorf, Ohlendorf,Timmendorf,all FRG	udic (temperate)	8 to 9^{o} Celsius	650 mm	(10) till 45cm (variable)
Akko;(similar but drier) Qedma ,both Israel	xeric	ca 18^{o}	620 mm	10 to 15 cm
ICRISAT,Patencheru,India	ustic (semiarid)	25.8^{o}	760 mm	12 cm
Khon Kaen ,NE Thailand (similar,Pangil,Luzon; San Dionisio, Panay,both Philippines)	ustic	27^{o}	1300 mm	20 cm
Tiaong (similar Los Banos),both Laguna/Philippines in old volcanis ashes on top of tuffaceous bedrock	udic	26^{o}	2150 mm	60 to 80 cm
Bugallon,Pangasinan,Philippines and Klong Luang,Thailand (both almost constantly reduced and wet)	udic	27^{o}	ca 2000 mm	ca 5 cm

Ustic Khon Kaen (Fig.4) in the savannah of NE Thailand shows a similar tendency. Again, δ^{13}C decreases, i.e. the heavier ^{13}C is enriched, beginning with the lower part of the epipedon towards the cambic versus argillic horizon,laying proof of humus-C migration to the subsoil and eventually further on to the phreatic groundwater. Bomb - carbon is traceable down to 20 cm. Thereafter the ^{14}C-age is increasing slowly but steadily with depth.

The udic Tiaong soil (Fig.6) in old volcanic ashes with its deep entrance of bomb - C shows expectedly also organic matter migration, manifested by the considerably rising ^{13}C-concentration in the A12 horizon and the even receeding ^{14}C-age in the underlying B2g horizon.

TRACING MORPHOGENETIC PROCESSES,SUCH AS PELOTURBATION AND BIOTURBATION BY δ^{13}C AND D^{14}C MEASUREMENTS

Soil dynamics,manifesting itself in formation of morphogenetic products ,the Great Soil Groups,involves organic matter transport. Thus, bomb - C , δ^{13}C, D^{14}C and δ^{18}O can often reveal like a tracer or also disprove the existence of major process links,f.ex. in turbation processes,such as cryoturbation in tundra soils, peloturbation in Vertisols, bioturbation in Mollisols.

Peloturbation

Vertisols show at closer look often kind of a stratification in layers or horizons,which they should due to peloturbation,churning action,self mulching sensu strictu not possess,just , as the ^{14}C-dates should down to the maximum depth of cracks increase but moderately and only thereunder in the usual progressive trend.

Fig.7 shows the regression lines "age versus depth" of 378 ^{14}C-dates of Vertisols originating from 10 different countries. The corresponding regression equations are listed in Table 4 , see also (ref. 5) .

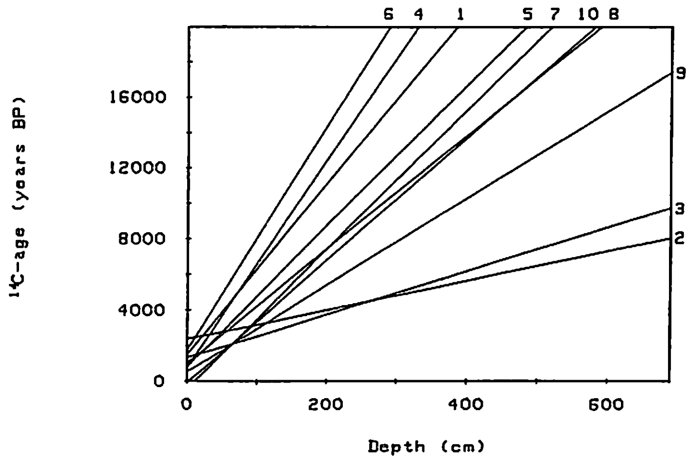


Fig. 7. Regression lines of 378 ^{14}C-dates of Vertisol profiles from 10 different countries of origin (1=Germany, 2=Sudan, 3=Tunisia, 4=Argentina, 5=Israel, 6=Bulgaria, 7=Italy, 8=Spain, 9=Portugal, 10=Australia).

The steepest regression line,here for the Bulgarian Vertisols, stands for the best conservation of old C-species, for fastest decomposition of young organic matter and for poorest peloturbation. The flattest regression line, here for Sudanese Vertisols,indicates the reverse, including strong peloturbation (probably due to the extended dry season). The absolute member of the regression equation (Table 4) , being negative,expresses, that in the average of all soil profiles of the same country of origin,which are represented by the regression,there is bomb-C penetration in the epipedon and vice versa.

A possibility to confirm or disprove the real existence of the peloturbation model is given by layerwise profile sampling and scanning the δ^{13}C profile curve (ref. 6) . In our case (Fig.8) existence of peloturbation is proven by the depth range of C-species´ from C-4 durra plants (staple food crop), sandwiched by pre-

TABLE 4

Regression equations for age versus depth of ^{14}C-dated Vertisol samples from different countries of origin (1=Germany, 2=Sudan, 3=Tunisia, 4=Argentina, 5=Israel, 6=Bulgaria, 7=Italy, 8=Spain, 9=Portugal, 10=Australia).
(*=0.95, **=0.99, ***=0.999 levels of significance).

Number code	Country of Origin	Regression equation and significance of correlation for "Age versus Depth"; n=number of samples		
1	Germany (FRG)	n=18;	$y = 48.07\ X + 1469.6$	$r = 0.71^{***}$
2	Sudan	n=97	$y = 8.22\ X + 2387.3$	$r = 0.47^{***}$
3	Tunisia	n=26	$y = 12.21\ X + 1341.3$	$r = 0.66^{***}$
4	Argentina	n=11	$y = 58.32\ X - 755.4$	$r = 0.67^{*}$
5	Israel	n=31	$y = 39.79\ X + 801.5$	$r = 0.85^{***}$
6	Bulgaria	n=12	$y = 63.01\ X - 1735.5$	$r = 0.89^{***}$
7	Italy	n=65	$y = 39.42\ X - 436.9$	$r = 0.69^{***}$
8	Spain	n=29	$y = 32.23\ X + 1026.9$	$r = 0.79^{***}$
9	Portugal	n=30	$y = 24.53\ X + 542.9$	$r = 0.54^{**}$
10	Australia	n=59	$y = 34.55\ X - 80.3$	$r = 0.76^{***}$

sent day C-3 cotton carbon and the underlying lighter humus-C of the in situ Nile alluvium. A break in the steadiness of the age versus depth ^{14}C - scanning curve at 120 to 140 cm towards steeper age versus depth increase confirms the boundary of cracks at this level and the veritable existence of peloturbation.

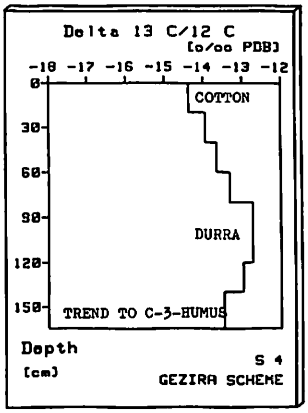


Fig. 8. $\delta^{13}C$ profile curve of a Sudanese Vertisol.

Bioturbation

Bioturbation, especially in mollic epipedons, is often lighthandedly treated as a kind of homogenization of the soil by the action of the living biomass, especially the earthworm population. Two observations speak against such a simplistic model : At once, there is not one Mollisol profile, subjected by us to layerwise ^{14}C-dating (Fig.9), which did not indicate considerable increase of age with depth, thus excluding simple (coprogenic) homogenization (ref. 7) . The regression lines and -equations in Fig. 9 and Table 5 indicate again, that the steepest regression lines stand for conservation of old C-species'and fast turnover of fresh organic substance. All absolute members of the regression equations are positive,showing in the average of the profiles of the same country of origin nowhere an input of bomb-C , intense enough to make D^{14}C >100 % modern NBS-standard,i.e.,suppress the ^{14}C-age below zero.

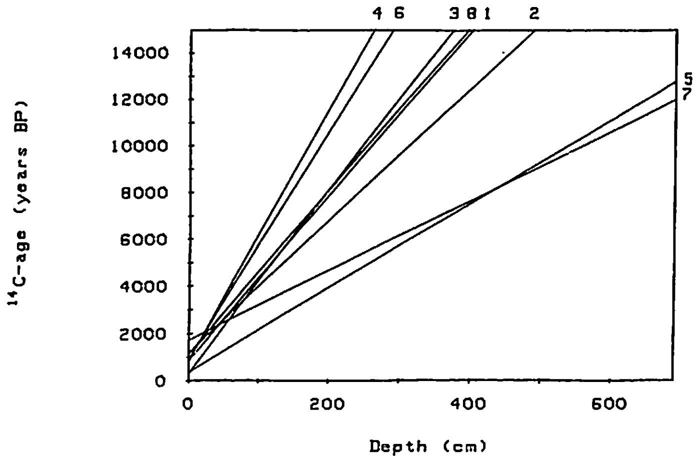


Fig. 9. Regression lines of 291 ^{14}C-dates of Mollisol profiles from 7 different countries of origin (1=Germany, 2=CSSR, 3=USSR, 4=Hungary, 5=Australia, 6=Bulgaria, 7=Tunisia (uncovered), 8=Tunisia (covered by "Historique"=sand layer).

TABLE 5

Regression equations for age versus depth of ^{14}C-dated Mollisol samples from 1=Germany, 2=CSSR, 3=USSR, 4=Hungary, 5=Australia, 6=Bulgaria, 7 and 8=Tunisia. (*=0.95, **=0.99, ***=0.999 levels of significance)

Number code	Country of Origin	Regression equation and significance of correlation for "Age versus Depth"; n=number of samples		
1	Germany (FRG)	n=115	$y = 35.5\ X + 810$	$r = 0.69^{***}$
2	CSSR	n=38	$y = 28.4\ X + 1175$	$r = 0.89^{***}$
3	USSR	n=15	$y = 39.5\ X + 284$	$r = 0.93^{***}$
4	Hungary	n=17	$y = 49.0\ X + 893$	$r = 0.69^{**}$
5	Australia	n=24	$y = 18.0\ X + 364$	$r = 0.56^{**}$
6	Bulgaria	n=10	$y = 54.3\ X + 818$	$r = 0.97^{***}$
7	Tunisia (uncovered)	n=56	$y = 14.9\ X + 1719$	$r = 0.70^{***}$
8	Tunisia (covered)	n=16	$y = 35.3\ X + 1107$	$r = 0.74^{**}$

At second, collecting the earthworm population of individual soil layers in a typic Hapludoll and converting their body-C into benzene for natural ^{14}C-measurement, revealed (Fig.10) that all earthworms out of topsoil as well as of deepest subsoil layers consist of modern (bomb) carbon in an environment, where the humus-C of the soil layers had a ^{14}C-age of several thousand years.

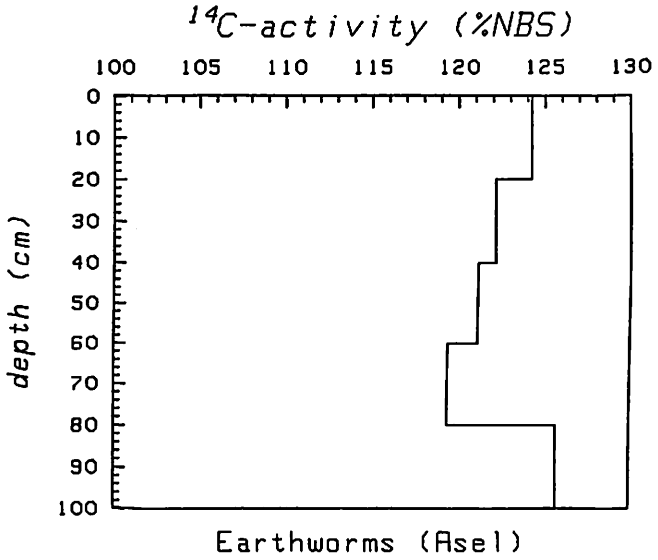


Fig. 10. Natural ^{14}C-activity in body - carbon of earthworms,collected in different depth layers of a typic Hapludoll (Aseler Wald , FRG)

In consequence, one has to conclude , that all earthworms,involved in this study, are preferentially feeding at or near the soil surface on modern plant residues and discharge also their coprogenic products to the surface. A fine stratification of coprogenic products with increasing age towards depth, a builtup of the epipedon,replaces as model the superficial interpretation of bioturbation as merely kind of a homogenization.

Those earthworms of the deepest layer,mostly identical with the dead end of the escape tracks, show even most bomb-C ,therefore feed on recent organic matter only. This is in accord with a trend inversion of age versus depth curves in the deepest profile layer, which was frequently also observed,when dating layerwise soil organic matter carbon in soils of high biological activity. It occurred obviously due to deposition of coprogenic products at the end of the earthworms escape tracks. (The authors are aware,not all earthworm proveniences may behave identically).

REFERENCES

1 H.G. Bertram, Zur Rolle des Bodens im globalen Kohlenstoffzyklus, Dissertation University of Cologne, Veröffentlichungen der Naturforschenden Gesellschaft zu Emden, Band 8, Serie 3-D3 (1986) 1-144.

2 D.R. Sauerbeck and M.A. Gonzalez, Field-Decomposition of C-14 labelled plant residues in different soils of Germany and Costa Rica, Intern.Symp.on Soil Organic Matter Studies, Brunswick,FRG, IAEA-SM-211/18 (1976) 14 pages.

3 D.S. Jenkinson and A. Ayanaba, Decomposition of carbon-14 labelled plant material under tropical conditions, Soil Sci.Soc.Am.J. 41 (1977) 912-915.

4 H.U. Neue and H.W. Scharpenseel, Decomposition pattern of C-14 labelled rice straw in aerobic and submerged rice soils of the Philippines, The Science of the Total Environment, Elsevier,Amsterdam, 62 (1987) 431-434.

5 H.W. Scharpenseel, J. Freytag und P. Becker-Heidmann, C-14 Altersbestimmungen und δC-13 - Messungen an Vertisolen,unter Berücksichtigung der Geziraböden des Sudan, Z.Pflanzenernaehr.Bodenk. 149 (1986) 277-289.

6 J. Freytag, Das C-13/C-12 - Isotopenverhältnis als aussagefähiger Bodenparameter , untersucht an tunesischen Kalkkrusten- und sudanesischen Vertisolprofilen, Hamburger Bodenkundliche Arbeiten, Band 3 (1985) 1-264.

7 H.W. Scharpenseel, K. Tsutsuki, P. Becker-Heidmann und J. Freytag, Untersuchungen zur Kohlenstoffdynamik und Bioturbation von Mollisolen, Z. Pflanzenernaehr.Bodenk. 149 (1986) 582-597.

8 P. Tans, A compilation of bomb C-14 data for use in global carbon model calculations, in B. Bolin, ed. Carbon cycle modelling, SCOPE 16, Wiley, Chichester, (1981) 131-157.