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SHIFTS IN ^{14}C PATTERNS OF SOIL PROFILES DUE TO BOMB CARBON, INCLUDING EFFECTS OF MORPHOGENETIC AND TURBATION PROCESSES

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ABSTRACT. Principles contributing to changes and the final balance of rejuvenation in ^{14}C dates of soil profiles are identified. The annual addition to the atmosphere of ca $5.5 \cdot 10^{12}$kg of dead carbon from fossil carbon sources and $1.5 \cdot 10^{12}$kg of older carbon from forest clearing make soil appear older. Bomb carbon and annual recycling of most of the $115 \cdot 10^{12}$kg of terrestrial organic carbon, equivalent to the annual photosynthetic turnover of carbon, rejuvenates soil dates. This also applies to root growth, animal transport, and in acid or alkaline soils, to humus percolation. All available ^{14}C dates of soil profiles were evaluated for the impact of bomb carbon. We also studied the effects of morphogenetic soil-forming processes, such as turbations, on soil rejuvenation. Bioturbation, as a general principle of soil dynamics, requires more differential treatment due to modern and bomb carbon that constitutes body carbon of earthworms as well as steadily increasing ^{14}C age with depth in all Mollisols.

INTRODUCTION

Figure 1 shows the difference between true ^{14}C age (TA) and apparent mean residence time (AMRT) of soil samples or soil profiles. It stands under a rising AMRT due to annual turnover of ca $5.5 \cdot 10^{12}$kg of dead carbon from fossil fuel sources (Suess effect) and at a more moderate rate due to liberation of carbon from wood clearing at 8–15,000,000 ha/yr, releasing some $1.5 \cdot 10^{12}$kg of mostly 100–1000 yr-old carbon. This represents, with $7 \cdot 10^{12}$kg of C/yr, ca 1% of the total CO_2 pool of the atmosphere. The reverse trend of reducing the AMRT compared to the TA originates from bomb carbon rises of natural ^{14}C (Fig 2) and from annual turnover of ca $115 \cdot 10^{12}$kg of terrestrial organic carbon, equivalent to the annual photosynthetic gain. Since organic matter decomposition for terrestrial and for submerged soils shows an initial steep trend and even spike (Fig 3) followed by a much slower steady-state phase of decomposition, much of the recycled carbon is young (Jenkinson & Ayanaba, 1977; Neue & Scharpenseel, 1987). A moderate increment of this rejuvenation effect, being difficult to assess quantitatively, has to be tacitly implied due to enhancement of current modern organic matter production by annual pool transfer of ca $150 \cdot 10^9$kg of N ($75 \cdot 10^9$kg as mineral N fertilizer, $75 \cdot 10^9$kg as diazotrophic, collected N by Rhizobium and blue/green algae) from the atmosphere into the pedosphere and annual pool transfer of ca $40 \cdot 10^9$kg of P and K from the lithosphere into the pedosphere.

Besides these biogeochemical effects, agronomic processes contribute to rejuvenation by percolation of humic substances in acid or alkaline soils, root growth and animal transport of carbon, depending on the biological activity. However, the clay/oxide matrix and mainly their variable charge is

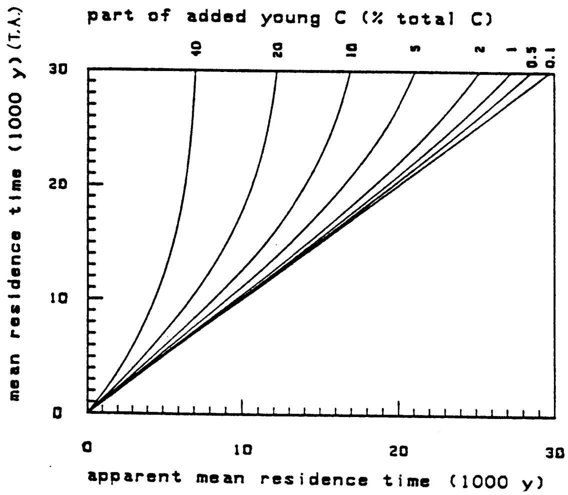

Fig 1. Effect of admixture of modern carbon on ^{14}C age

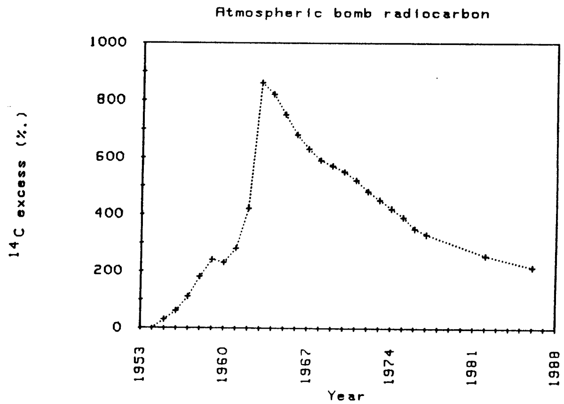

Fig 2. Atmospheric bomb C level (after Tans, 1981; continued by our measurements)

decisive for the degree of organic matter fixation or decomposition. The feeding habits of earthworms also contribute. Soil organic matter dynamics are integrated in morphogenetic and turbation processes typical of the Great Soil Groups.

BOMB CARBON SHIFTS IN ^{14}C PROFILES OF SOILS

Only a few soil profiles have been ^{14}C dated during the first decade since the beginning of thermonuclear testing. Our systematic investigations on soils began in 1965, and for the period until 1980, 129 soil profiles of different terrestrial Great Soil Groups (Alfisols, Inceptisols, Mollisols,

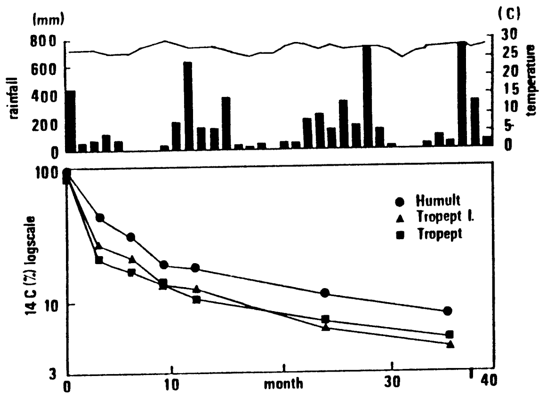

Fig 3A. Decomposition of organic matter in terrestrial soils of the Philippines

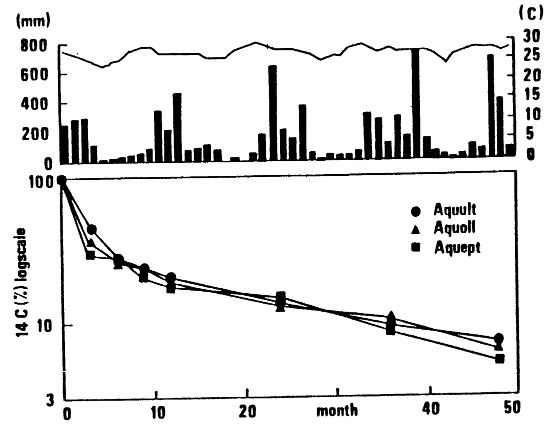

Fig 3B. Decomposition of organic matter in submerged soils of the Philippines

Spodosols and Vertisols), 105 until 1975, 24 to 1980, and 36 profiles of Histosols and sybhydric soils were subjected to layerwise, soil profile dating. Table 1 lists mean AMRT levels at different soil depths. The typical trend of increasing age with depth can be interpreted in two ways – 1) the humus-horizon/epipedon is slowly built up with time, which, according to Figure 4 seems to be the case at least in mollic horizons, or 2) due to high biological activity, recent, modern plant residues are quickly decomposed in the top soil, and the clay organic complexes in the deeper soil are quite stable and do not exchange the organic ligand. Plaggepts and Vertisols down the maximum depth of cracks show little age increase with depth due to anthropogenic deposition of plaggen or due to the inherent principle of peloturbation. Table 1 shows the rejuvenating effect of bomb carbon is still moderate and, until 1980, scarcely penetrates into deeper soil layers or horizons.

TABLE 1

Average regression, correlation factor and corresponding AMRT levels for different depths of soil profiles from all layer-dated soil profiles till 1980 (13 Alfisols, 16 Inceptisols (most Plaggepts), 47 Mollisols, 9 Spodosols, 44 Vertisols). Paleosols were not included; soil profiles were sampled in Europe, Australia, Israel, Tunisia, Sudan and Argentina.

Soil order	Ascent of regression line Correlation factor	Corresponding AMRT of regression line (B C) 10cm	20cm	50cm	100cm	150cm	200cm
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	10,000
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

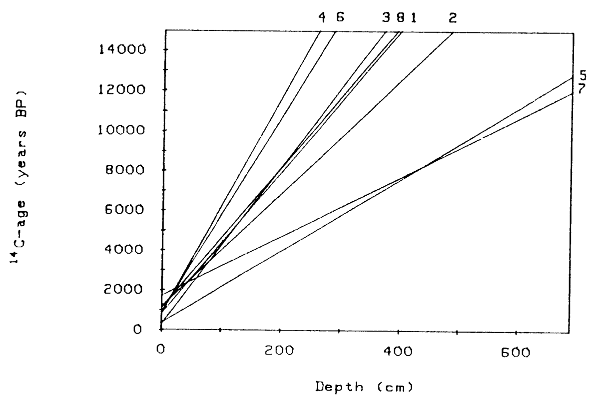

Fig 4. Mollisol dates; regression lines represent countries of origin (1 FRG, 2 CSSR, 3 USSR, 4 Hungary, 5 Australia, 6 Bulgaria, 7 Tunisia – surface, 8 Tunisia – covered)

The effect of bomb carbon on rejuvenation of soil profiles after 1980 is more pronounced and differs in terrestrial and temporarily submerged, hydromorphic soils. For example, the semiarid terrestrial Rhodustalf profile at Patancheru (see Becker-Heidmann & Scharpenseel, 1989) reveals bomb carbon only until 12cm depth; the hydromorphic Spodic Aquic Hapludalf at Wohldorf Forest near Hamburg (see Becker-Heidmann & Scharpenseel,

1986) shows bomb carbon intermittently down to 50cm, where the additional moisture at horizon boundaries, due to impeded permeability at the interfaces, causes fine racination and, thus, spikes of modern carbon. The rainfed riceland at Pangil, Philippines (Fig 5), shows bomb carbon down to 18cm depth of puddling, and finally, the normally year-round irrigated soil at Los Baños (Becker-Heidmann & Scharpenseel, 1989) shows bomb carbon again with spikes at the horizon layer transitions down to 70cm, indicating the possible effect of rather deep homogenization of the soil by a motor drawn puddler.

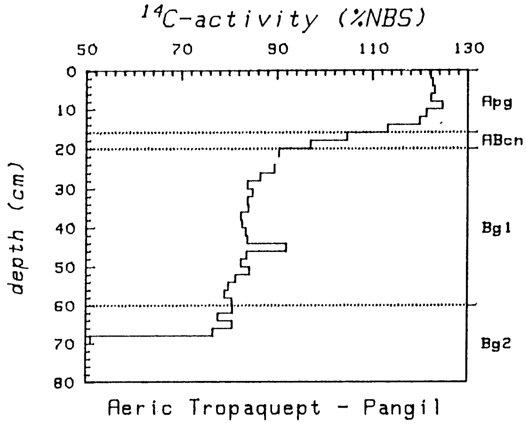

Fig 5. ^{14}C activity depth distribution of the Pangil profile

The highest bomb carbon levels of 1962/63 did not manifest themselves strongly in the natural ^{14}C level of the soil profiles at that time. It was by repetitive input rates of bomb carbon over some 20–25 years that its influence became increasingly apparent particularly in the organic raw humus layer of Spodosols and the humic substances of the topsoil epipedon. Table 2 summarizes the results of 14 soil profiles thin-layerwise ^{14}C dated after 1980, which are divided into terrestrial upland, temporarily submerged and mostly submerged lowland categories. We sampled in 2cm thin layers except for the lower part of the deep Vertisol profiles, Akko and Qedma, with 5cm thin layers. The maximum observed bomb carbon level at any depth of the profiles above the indicated boundary of <100% NBS standard is 125 pM. The terrestrial soils are modern in approximately the upper 6–22cm, with some possible modern spikes at a deeper level, which only the thorough 2cm thin layer sampling reveals, in the case of the hydromorphic soil with perched water table. The alternately submerged and dry soils of the monsoon climate are not very different, whereas the long-term submerged, irrigated soils, homogenized as deeply as possible during the puddling process, show greater bomb carbon influence by decomposition of modern plant residues, including straw, in the full depth of the puddling operation. Possibly the underlying, percolation promoting, tuffaceous layer enhances the process.

TABLE 2

14 soil profiles, sampled at 2cm layers; maximum percentage of natural ^{14}C and depth ranges w/o bomb C ranges <100% NBS oxalate standard

Soil type	Great Soil Group	Country, location	Max % NBS standard	Depth range w/o bomb C
Terrestrial	Spodic aquic Hapludalf	W Germany Wohldorf	125	10–12, 14–23, 28–36, 44–48, 50+
	Spodic aquic Hapludalf	W Germany Ohlendorf	118	6–38, 40+
	Hapludalf	W Germany Timmendorf	120	10+
	Hapludalf	W Germany Klein Altendorf	96	0+
	Pelloxerert	Israel Akko	112	15+
	Chromoxerert	Israel Qedma	110	22+
	Rhodustalf	India Patancheru	115	12+
Rice paddy, rainfed	Tropaquept	Thailand Klong Luang	101	12+
	Eutropept	Thailand Khon Kaen	119	14–18, 20+
	Tropaquept	Philippines Pangil	124	20+
	Hydraquent	Philippines Bugallon	116	16+
	Paleudult	Philippines San Dionisio	121	20–30, 32+
Rice paddy	Haplaquoll	Philippines Tiaong	122	24–26, 32–34, 42–46, 54+
	Tropaquept	Philippines Los Baños	125	62–64, 70–72, 74–76

REJUVENATION DUE TO MORPHOGENETIC PROCESSES, SUCH AS PELOTURBATION AND BIOTURBATION

Soil dynamics account for considerable transport processes, eg, so-called turbations such as cryoturbation in tundra soils, peloturbation in Vertisols and bioturbation in Mollisols.

Vertisols with Peloturbation

Vertisols (Soil Taxonomy, 1975) with >30% of mostly swelling and shrinking smectite clays and, during the drier part of the year, deep cracks of >1cm width at 50cm depth, support a self-mulching system (peloturbation) of material, dropping from the surface into the cracks. This creates a lack of space; the cracks close during the rainy season, causing lateral

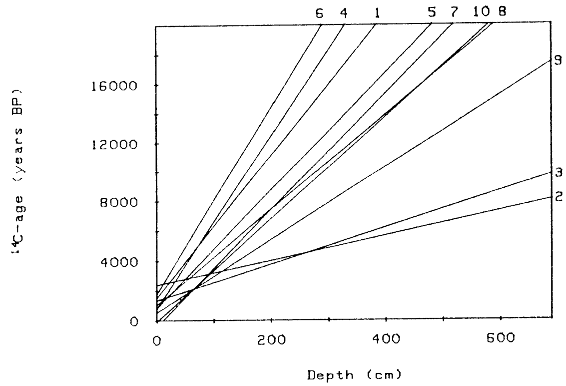

Fig 6. Vertisol dates; regression lines represent countries of origin (1 FRG, 2 Sudan, 3 Tunisia, 4 Argentina, 5 Israel, 6 Bulgaria, 7 Italy, 8 Spain, 9 Portugal, 10 Australia)

TABLE 3

Regression equations for age *vs* depth as well as age/profile maximum age *vs* depth of Vertisol samples from different countries

No.	Country	Regression equation and significance of correlation for "age *vs* depth"	Regression equation and significance of correlation for "age/profile maximum age *vs* depth"
1	Federal Republic of Germany	n = 18 r = 0.71† y = 48.07 X + 1469.6	n = 18 r = 0.46* y = 0.00305 X + 0.43
2	Sudan	n = 97 r = 0.47† y = 8.22 X + 2387.3	n = 97 r = 0.32** y = 0.00088 X + 0.48
3	Tunisia	n = 26 r = 0.66† y = 12.21 X + 1341.3	n = 26 r = 0.35* y = 0.00061 X + 0.38
4	Argentina	n = 11 r = 0.67* y = 58.32 X − 755.4	n = 11 r = 0.91† y = 0.00863 X −0.24
5	Israel	n = 31 r = 0.85† y = 39.79 X + 801.5	n = 31 r = 0.44* y = 0.00091 X + 0.60
6	Bulgaria	n = 12 r = 0.89† y = 63.01 X − 1735.5	n = 12 r = 0.79** y = 0.00465 X − 0.04
7	Italy	n = 65 r = 0.69† y = 39.42 X − 436.9	n = 65 r = 0.57† y = 0.00326 X + 0.260
8	Spain	n = 29 r = 0.79† y = 32.23 X + 1026.9	n = 29 r = 0.73† y = 0.00416 X + 0.29
9	Portugal	n = 30 r = 0.54** y = 24.53 X + 542.9	n = 30 r = 0.58† y = 0.00538 X + 0.29
10	Australia	n = 59 r = 0.76† y = 34.55 X − 80.3	n = 59 r = 0.81† y = 0.00459 X + 0.07

Significance levels:
* 0.95
** 0.99
† 0.999

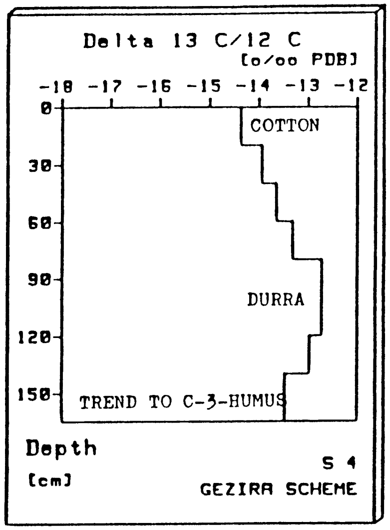

Fig 7. $\delta^{13}C$ profile curve of a Sudanese Vertisol

pressure to set up a churning process of homogenization. In a true Vertisol, the ^{14}C age should increase only slightly with depth until the maximum depth of the cracks, below them in the usual progression. Figure 6 shows the regression lines of all measured Vertisol profiles from 10 countries. Table 3 lists the regression equations (see also Scharpenseel, Freytag & Becker-Heidmann, 1986). The steepest regression line belongs to the Bulgarian Vertisols and shows the strongest conservation of old carbon, the fastest decomposition of recent C species and poorest peloturbation. The flattest curve is that of the Sudanese Vertisols, which points to the reversal of the above trends. A $\delta^{13}C$ profile curve (Fig 7; *cf* Freytag, 1985) confirms the peloturbation by the depth of C species from C4 durra plants, framed due to the ^{13}C shift by present day C3 cotton C and the deeper lighter humus C of the Nile alluvium before soil utilization by man.

The effect of bomb carbon exists (Fig 6) only in some Vertisol profiles. Since the regression lines comprise dates of different soil profiles, the individual soil profiles with bomb carbon cannot be identified, only the trend in the sum of profiles from individual countries is clearly distinguishable.

Mollisols with Bioturbation

Mollisols (Soil Taxonomy, 1975) are soils with, among other criteria, a mollic epipedon >25cm thick. Due to their prevalent micaceous clays, they do not or, only weakly, swell and shrink (crack). Bioturbation is responsible for C transport in the profile by the soil biomass, especially the earthworm population. Corresponding rejuvenation strongly depends, besides root growth, on the pattern of feeding and disposal of coprogenic products of earthworms. Thus, earthworms were collected carefully from different depth layers of the mollic horizon. They were converted to benzene and ^{14}C dated (*cf* Scharpenseel *et al*, 1986). Figure 8 shows that all earthworm

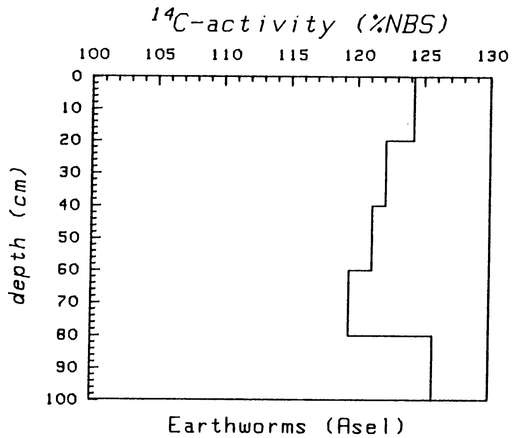

Fig 8. ^{14}C activity of earthworms at different depths of the Asel profile

TABLE 4

Regression equations for age *vs* depth as well as for age/profile maximum age *vs* depth of all Mollisol profile samples

No. Country	Regression equation and significance of correlation for "age *vs* depth"	Regression equation and significance of correlation for "age/profile maximum age *vs* depth"
1 Federal Republic of Germany	n = 115 r = 0.69† y = 35.5 X + 810	n = 115 r = 0.73† y = 0.00712 X + 0.25
2 CSSR	n = 38 r = 0.89† y = 28.4 X + 1175	n = 28 r = 0.79† y = 0.00911 X + 0.29
3 USSR	n = 15 r = 0.93† y = 39.5 X + 284	n = 15 r = 0.74** y = 0.00366 X + 0.20
4 Hungary	n = 17 r = 0.69** y = 49.0 + 893	n = 17 r = 0.79† y = 0.00885 X + 0.15
5 Australia	n = 24 r = 0.56** y = 18.0 X + 364	n = 24 r = 0.54** y = 0.00463 X + 0.27
6 Bulgaria	n = 10 r = 0.97† y = 54.3 X + 818	n = 10 r = 0.92† y = 0.00535 X + 0.02
7 Tunisia (surface)	n = 56 r = 0.70† y = 14.9 X + 1719	n = 56 r = 0.53† y = 0.00108 X + 0.52
8 Tunisia (covered)	n = 16 r = 0.74** y = 35.3 X + 1107	n = 16 r = 0.54* y = 0.00246 X + 0.23
All dates of Mollisols	n = 291 r = 0.71 y = 20.1 X + 1513	n = 281 r = 0.45† y = 0.00161 X + 0.48

Significance levels:
- * 0.95
- ** 0.99
- † 0.999

samples consist of modern (bomb) C, although the humus C of the soil layer from which the earthworms were collected, has a ^{14}C age of several thousand years. This indicates that the earthworms of all depth layers feed on modern plant residues at or near the soil surface, where their coprogenic products collect. Earthworms of the deepest layer, which mostly coincides with the dead end of earthworms escape tracks, show even more bomb C than those of the next higher layer, due to the deposit of waste products. The same trend of age curves inversion in the deepest layer was also frequently found with layerwise dating of the humus matter of soil profiles with high biological activity.

Figure 4 shows age *vs* depth curves as regression lines of dated Mollisol profiles from seven countries. The profiles from Tunisia are partly at the soil surface (I), and partly covered by a thin sediment blanket (II). The corresponding regression equations and the slope of the regression lines (Table 4) indicate, by means of the Hungarian and the Bulgarian Mollisols, the best conservation of old C species as well as the most durable clay organic matter complexes. Yet in the same soils, the recent organic matter has strongly decomposed and the homogenizing effect of bioturbation is manifested in its mildest form. The reverse holds true for the Tunisian surface profiles and the Australian Krasnozem-like Mollisols. Again, the bomb C influence in individual soil profiles is integrated in regression lines representing the country of origin. These reveal that the effect of homogenization by bioturbation is more moderate than in most descriptions of Mollisol dynamics. German Mollisols, eg, are definitely of Holocene origin with a main phase of early soil formation in Boreal and Atlantic periods. We can safely deduce from Figure 1 that a soil sample with an AMRT of close to 6000 BP *vs* a TA of ca 8000 BP represents an admixture of ca 20% of modern carbon species.

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