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Influences of organic fertilization and solarization in a greenhouse on particle-size fractions of a Mediterranean sandy soil

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Abstract The effects of a composted organic amendment and solarization on the organic matter (OM) of a sandy soil were determined by means of particle-size fractionation and analysis of carbon and nitrogen contents. After 2 years, total soil carbon increased under organic fertilization but did not significantly change with solarization. As a consequence of the climatic conditions in the greenhouse, the carbon concentrations (g kg^{-1} fraction) of the particle-size fractions were lower than those found for temperate soils and closer to those for tropical soils. The carbon amounts (g kg^{-1} soil) and carbon:nitrogen ratios, which were highest in fractions >200 μm, reflected the short-term influence of the industrially processed organic amendment, rich in composted coarse plant debris. In contrast, the characteristics of the OM associated with each fraction were not significantly affected by solarization. In comparison with other coarse-textured temperate or tropical soils, carbon concentrations in fine silt (2–20 μm) and clay (0–2 μm) fractions were very low. This suggests a "greenhouse effect", together with a high rate of carbon mineralization affecting fine silt and clay fractions.

Keywords Soil organic matter · Particle-size fractions · Organic fertilization · Solarization · Mediterranean sandy soil

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Introduction

Intensive market gardening in greenhouses is often associated with high applications of fertilizers and pesticides which can damage the environment, and with persistent soil-borne pathogens. Greenhouse cultivation, by enhancing the temperature and using intense irrigation, induces high mineralization of the soil organic matter (SOM). It can even decrease the SOM content due to insufficient OM inputs, affecting in turn the physical, chemical and biological properties of the soil.

Different strategies are sometimes used to overcome these problems. For example, (1) chemical fertilizers can be associated with or replaced by organic fertilizers, mostly organic amendments like composts, and (2) the use of pesticides can be replaced by the ecological practice of soil solarization (Katan 1981, 1996). On the one hand, we have observed that the use of organic fertilization can maintain or improve several of the most important soil properties through an increase in the total soil carbon concentration and Stock (Thuriès et al. 1998, 2000). On the other hand, although solarization has a marked positive influence on market-gardening yields through a drastic reduction of soil-borne pathogens (Chen et al. 1991; Chellemi et al. 1997; Thuriès et al. 2000), this treatment does not have a significant effect on the total soil carbon concentration.

Particle-size fractionation (PSF) can be valuably used in studies about SOM dynamics (Christensen 1992, 1996; Feller 1993) and the effect of soil management on SOM forms. Considering that: (1) organic fertilization increases SOM contents, and (2) solarization probably leads to a decrease in SOM by enhanced mineralization, our main objective was thus to investigate in more detail, by means of PSF, which forms of SOM were involved in related variations of total SOM contents.

Materials and methods

Experimental design

The experiment was initiated in 1994 in Théza (Réart Plain, Perpignan, France), and was previously described in Thuriès et al. (2000). Four plastic greenhouses (tunnels) were chosen (T1–T4, 400 m^2 each), each divided into two 200-m^2 plots (Table 1) according to their orientation, i.e. north and south. Two types of treatments were applied:

1. T1 and T2 received mineral fertilization ($N/P_2O_5/K_2O$ ~240/315/685 kg $ha^{-1}year^{-1}$ by means of ammonium nitrate, super phosphate 45, and potash sulphate) plus 4.2 t OM ha^{-1} in 1994, and 1.2 t OM ha^{-1} in 1996 (MINo treatment).
2. Between 1994 and 1996, T3 and T4 received 19–23 t OM ha^{-1} in the 0- to 20-cm layer in two applications per year of: (1) Vegethumus™ (carbon:nitrogen ~13) an industrially processed, pelleted compost made from sheep manure and coffeecake after a 12-week composting period, and (2) a guano-based organic fertilizer, Guanor™ (carbon:nitrogen ~3) (ORG treatment).

During summer, the northern plots of T1 and T2 (1N, 2N) were left uncropped (bare soil), and the northern plots of T3 and T4 (3N, 4N) were cropped for sorghum, a green manure, whereas all the southern plots (1S–4S) were solarized according to the technique described in Katan (1981, 1996). Solarization involves the use of heat as a lethal agent for soil-borne pathogen control through the use of transparent polyethylene soil mulches for capturing solar energy (Katan 1981). This technique is used during the summer, the period of highest temperatures and intense solar irradiation, on freshly tilled and irrigated soils to improve heat conduction in the soil depths.

Sampling

The soils were collected in the summer of 1996 in the 0–10, 10–20 and 20–40 cm depths of the experimental design described above. Six samples (each composite of ten random subsamples per 18-m^2 subplot) were collected in each tunnel and the soil bulked by layer.

Soils

The sandy soil (~65% sand, ~25% silt, ~10% clay) was previously described by Servat and Callot (1966). It was classified as a fluvisol (FAO-UNESCO-ISRIC 1988) or Udifluvent (Soil Survey Staff 1975). Bulk density was determined on cores taken with sharp-edged cylinders (500-cm^3). Samples were partially air dried at room temperature (20 °C) until they could be crushed and passed through a 2-mm sieve, then air dried to a constant weight. The mean values for the different samples were $pH_{(H20)}$ 6.6, bulk density 1.5 Mg m^{-3}, cation-exchange capacity ~56 mmol c^+ kg^{-1}, and water-holding capacity ~220 g kg^{-1}. Texture was determined by physical fractionation (particle-size analysis, PSA) using the international pipette method, after destruction of OM with hydrogen peroxide and dispersion with sodium hexametaphosphate according to the French norm AFNOR X31.107 (AFNOR 1983).

Table 1 General description of the field experimental design; division according to fertilization type, and summer soil treatments. For more details see Thuriès et al. (2000). *MINo* Mineral with low organic matter (OM) inputs, *ORG* exclusively (high) OM inputs, *BS* bare soil, *GM* green manure, *SOLAR* solarization

Orientation	Treatment	Greenhouses			
		T1	T2	T3	T4
North (N)	Fertilization type	MINo[a]	MINo[a]	ORG[b]	ORG[c]
	Summer soil treatment	BS	BS	GM	GM
South (S)	Fertilization type	MINo[a]	MINo[a]	ORG[b]	ORG[d]
	Summer soil treatment	SOLAR	SOLAR	SOLAR	SOLAR

[a] 5.46 t OM ha^{-1} between 1994 and 1996, when soils were sampled
[b] 19.05 t OM ha^{-1} between 1994 and 1996
[c] 23.38 t OM ha^{-1} between 1994 and 1996
[d] 21.30 t OM ha^{-1} between 1994 and 1996

Data analysis and comparison of the different treatments

Since SOM content is generally related to soil texture (Feller and Beare 1997), it was necessary to take this into account and compare samples with the slightest textural differences. There were no significant differences between coarse sand plus fine sand, coarse silt plus fine silt, or clay plus fine silt contents between the southern parts of the plots from MINo and ORG treatment soils, at 0–10 and 10–20 cm depths. However, some textural differences existed (coarse sand plus fine sand) when considering the entire plots i.e. between T1 and T3, T1 and T4, T2 and T3, and T2 and T4.

Thus, the general characterization of the soil organic status was done on the whole set of soil samples, whereas the effects of organic fertilization were investigated by comparing the southern plots of the MINo treatments with the southern plots of the ORG treatments, and the effects of solarization by comparing the northern plots of the MINo treatments with the southern plots. Taking into account the cropping history of the experimental design and the textural similarity (Thuriès et al. 2000), the effect of organic fertilization was studied by strictly comparing plots 2S and 3S, and the effects of the solarization by comparing plots 2N and 2S.

Particle-size fractionation

The 40-g soil subsamples were separated into particle-size fractions according to Gavinelli et al. (1995). Briefly, soils were suspended in 200 ml distilled water with 0.5 g sodium hexametaphosphate in a 250-ml centrifuge tube, then shaken for 2 h with five agate balls (diameter 1 cm) in a rotary shaker at a frequency of 50 revolutions per minute. The coarse (200–2000 μm) and fine (50–200 μm) sand fractions were recovered by sieving. Dispersion was completed by ultrasonication of the 0- to 50-μm soil suspension during 10 min. This was preferred to sonication of the whole soil (0–2 mm) in order to avoid the artificial degradation of coarse sand-sized plant debris (>200 μm) and their transfer (up to 50%) to size fractions <50 μm (Balesdent et al. 1991). Coarse silt fractions (20–50 μm) were obtained by sieving. Fine silt (2–20 μm) and clay (0–2 μm) were obtained by four sedimentation/decantation cycles and centrifugation. All the fractions were dried (40 °C), weighed and finely ground. The OM solubilized by water during the fractionation procedure was called the "water-soluble fraction". Fractionations were made in triplicate for the 0- to 10-cm samples, and duplicate for the 10- to 20-cm samples. In order to make comparisons and for simplification, some results were expressed for the total (coarse plus fine, 50–2000 μm) sand fraction and the total (coarse plus fine, 2–50 μm) silt fraction.

The major methodological objective of PSF is to achieve maximum dispersion of the soil with minimum SOM alteration (Gavinelli et al. 1995; Feller and Beare 1997). The efficiency of the dispersion method can be evaluated by comparing PSA and PSF results (Tables 2, 3). Dispersion of clay was quite good, as the highest discrepancies between PSA and PSF (<2% in absolute values) were smaller than the ordinary experimental error (~5%). The mass recovery of soil separates by PSF was satisfac-

Table 2 Particle-size fractionation (*PSF*) of mineral-fertilized (solarized vs. unsolarized) soils compared to standard particle-size analysis (*PSA*)[a]. Distribution of carbon and carbon:nitrogen within the particle-size fractions (±SDs). *SOM* Soil organic matter

Soil	Fraction (μm)	Mass (g kg^{-1} soil)		C			Carbon: nitrogen	Soil	Mass (g kg^{-1} soil)		C			Carbon: nitrogen
		PSA	PSF	(g kg^{-1} fraction)	(g kg^{-1} soil)	(g 100 g^{-1} soil carbon)			PSA	PSF	(g kg^{-1} fraction)	(g kg^{-1} soil)	(g 100 g^{-1} soil carbon)	
1N (0–10 cm)	200–2000	420	451±29	2.65±0.0	1.20±0.08	22.6	12.2±0.8	1N (10–20)	514	400±9	3.48±1.7	1.39±0.66	23.8	15.9±6.2
	50–200	225	210±20	4.79±0.8	1.01±0.2	19.0	11.7±1.6		192	243±2	4.17	1.01	17.3	11.9-
	20–50	69	86±6	4.48±1.3	0.38±0.12	7.3	9.5±1.3		65	94±5	7.29	0.69	11.8	10.8-
	2–20	129	138±1	6.12±0.4	0.85±0.06	16.0	5.9±0.1		117	141±1	7.71±1.5	1.09±0.21	18.6	7.0±0.6
	0–2	113	105±4	14.42±0.0	1.52±0.06	28.7	7.0±0.2		110	111±1	14.43±0.0	1.61±0.01	27.5	7.1±0.1
	Soluble		0.3±0		0.30	5.7				0.4±0		0.35	6.0	
	SOM	9							10					
	Recovery[b]	956	991±1		5.3	99.2			998	990±0.9		6.1	105.0	
	Bulk soil	1000	1000		5.29	100	8.9		1000	1000		5.85	100	9.5
1S (0–10 cm)	200–2000	554	483±14	2.88±0.2	1.39±0.12	26.7	14.7±0.4	1S (10–20)	557	467±3	2.73±0.2	1.27±0.11	21.9	13.1±1.0
	50–200	175	201±9	4.55±0.4	0.92±0.09	17.6	12.6±1.4		173	213±2	4.55±1.2	0.97±0.25	16.7	12.6±0.7
	20–50	53	80±4	3.89±0.8	0.31±0.06	6.0	9.2±1.7		62	86±0	4.45±0.2	0.38±0.01	6.6	9.9±0.3
	2–20	111	129±2	7.30±0.8	0.94±0.10	18.2	6.7±0.4		102	128±2	5.95±0.2	0.76±0.02	13.1	6.2±0.0
	0–2	116	97±1	14.65±0.2	1.43±0.03	27.4	8.3±0.1		101	100±1	14.94±0.1	1.50±0.02	25.7	7.6±0.1
	Soluble		0.3±0		0.35	6.7				0.4±0		0.37	6.3	
	SOM	9							10					
	Recovery[b]	1009	991±1		5.3	102.7			995	994±2.4		5.3	90.3	
	Bulk soil	1000	1000		5.20	100	9.2		1000	1000		5.81	100	10.8
2N (0–10 cm)	200–2000	391	378±5	3.98±0.4	1.50±0.16	23.2	15.5±1.0	2N (10–20)	408	358±1	3.05±0.4	1.09±0.15	21.1	12.7±1.0
	50–200	270	250±4	4.94±0.1	1.24±0.04	19.1	13.2±0.5		239	263±4	4.81±1.0	1.26±0.27	24.5	12.2±1.2
	20–50	83	104±1	6.25±2.7	0.65±0.28	10.0	11.0±1.7		84	109±4	4.39±0.2	0.48±0.03	9.2	10.0±0.1
	2–20	129	150±1	6.12±2.3	0.92±0.35	14.2	6.2±0.5		129	150±2	5.70±0.1	0.85±0.01	16.5	6.2±0.2
	0–2	113	109±0	15.25±0.1	1.66±0.01	25.6	7.0±0.0		125	111±1	15.06±0.1	1.68±0.02	32.5	7.1±0.0
	Soluble		0.4±0		0.39	6.0				0.3±0		0.33	6.4	
	SOM	11							9					
	Recovery[b]	986	990±0		6.3	98.0			985	991±3.3		5.7	110.1	
	Bulk soil	1000	1000		6.48	100	10.2		1000	1000		5.17	100	8.1
2S (0–10 cm)	200–2000	448	385±10	4.20±0.6	1.62±0.24	25.8	17.4±1.4	2S (10–20)	463	380±6	3.36±0.3	1.28±0.11	20.5	14.8±1.4
	50–200	209	234±5	5.48±0.2	1.28±0.06	20.4	13.6±0.2		199	236±4	6.09±0.9	1.43±0.21	23.1	14.7±0.1
	20–50	88	99±8	4.60±0.1	0.45±0.04	7.2	9.7±0.2		80	105±3	4.66±0.2	0.49±0.03	7.9	11.1±0.9
	2–20	132	163±2	5.82±0.0	0.95±0.01	15.1	6.7±0.1		132	157±1	6.27±0.1	0.98±0.02	15.8	6.8±0.2
	0–2	110	110±2	16.16±0.0	1.78±0.03	28.4	7.3±0.0		104	112±2	15.90±0.0	1.78±0.03	28.7	7.5±0.1
	Soluble		0.4±0		0.37	6.0				0.3±0		0.33	5.4	
	SOM	11							11					
	Recovery[b]	987	991±2.5		6.5	102.8			978	991±2.3		6.3	101.3	
	Bulk soil	1000	1000		6.28	100	10.2		1000	1000		6.22	100	10.1

[a] Results of the particle-size analysis after hydrogen peroxide treatment (destruction of SOM) and dispersion with sodium hexametaphosphate
[b] Sum of fractions

Table 3 PSF of organic fertilized (solarized vs. unsolarized) soils compared to standard PSA[a]. Distribution of carbon and carbon:nitrogen within the particle-size fractions (±SDs). For abbreviations, see Table 2

Soil	Fraction (μm)	Mass (g kg^{-1} soil)		C			Carbon:nitrogen	Soil	Mass (g kg^{-1} soil)		C			Carbon:nitrogen
		PSA	PSF	(g kg^{-1} fraction)	(g kg^{-1} soil)	(g 100 g^{-1} soil carbon)			PSA	PSF	(g kg^{-1} fraction)	(g kg^{-1} soil)	(g 100 g^{-1} soil carbon)	
3N (0–10 cm)	200–2000	312	280±19	6.62±0.6	1.86±0.22	21.8	15.4±1.4	3N (10–20)	333	299±4	5.87±0.9	1.75±0.26	21.7	15.8±3.2
	50–200	296	298±13	5.07±0.4	1.51±0.14	17.7	11.7±0.7		302	284±2	4.71±1.5	1.34±0.42	16.6	11.4±0.1
	20–50	96	126±4	5.35	0.68	7.9	9.3		80	122±3	4.96±0.4	0.60±0.05	7.5	9.6±1.5
	2–20	153	171±1	7.76	1.33	15.6	6.3		138	171±1	6.23±0.5	1.07±0.08	13.2	6.2±0.1
	0–2	125	113±3	18.74±0.6	2.12±0.1	24.9	7.4±0.2		116	116±0	17.49±0.2	2.03±0.02	25.1	7.2±0.1
	Soluble		0.5±0.1		0.52	6.1				0.4±0		0.36	4.4	
	SOM	15							14					
	Recovery[b]	982	989±2		8.0	94.0			969	992±0.1		7.1	88.6	
	Bulk soil	1000	1000		8.52	100	10.0		1000	1000		8.06	100	11.2
3S (0–10 cm)	200–2000	315	282±7	7.13±0.3	2.01±0.11	25.0	17.8±0.8	3S (10–20)	311	277±6	7.23±0.3	2.00±0.09	23.8	16.7±1.6
	50–200	251	268±7	5.69±1	1.52±0.27	18.9	12.7±1		279	267±4	6.35±0.6	1.70±0.17	20.2	13.4±0.6
	20–50	121	134±12	4.20±0	0.56±0.05	7.0	9.7±0.6		118	135±3	4.63±0.3	0.62±0.04	7.4	9.3±0.1
	2–20	150	179±6	5.30±0.1	0.95±0.04	11.8	6.2±0.3		174	187±1	5.43±0	1.02±0.01	12.1	6.4±0.1
	0–2	119	126±6	16.84±0.1	2.13±0.11	26.5	7.4±0.1		122	125±2	16.50±0.6	2.06±0.09	24.5	7.3±0.1
	Soluble		0.4±0		0.40	4.9				0.4±0		0.39	4.6	
	SOM	14							14					
	Recovery[b]	956	989±2		7.6	94.1			1004	991±1.3		7.8	92.7	
	Bulk soil	1000	1000		8.04	100	9.7		1000	1000		8.40	100	9.5
4N (0–10 cm)	200–2000	268	219±3	11.29±1.1	2.47±0.25	25.5	18.4±0.5	4N (10–20)	267	224±4	11.47±2.4	2.57±0.54	27.4	20.7±2.8
	50–200	309	321±0	5.97±0.8	1.92±0.26	19.8	12.3±1		287	313±3	7.06±0.2	2.21±0.07	23.5	13.5±0.9
	20–50	131	151±13	4.26±0.5	0.64±0.10	6.7	9.0±0.7		130	148±6	4.34±0.0	0.64±0.03	6.8	9.4±0.1
	2–20	162	180±6	5.61±0.3	1.01±0.07	10.4	6.2±0.1		168	186±4	6.02±0.2	1.12±0.05	11.9	6.3±0.4
	0–2	116	122±5	18.84±0.2	2.30±0.10	23.8	7.6±0.1		110	118±0	18.86±0.1	2.23±0.02	23.7	7.5±0.1
	Soluble		0.4±0		0.44	4.6				0.4±0		0.39	4.1	
	SOM	17							16					
	Recovery[b]	986	994±1.2		8.8	90.7			962	989±0.2		9.2	97.6	
	Bulk soil	1000	1000		9.69	100	10.1		1000	1000		9.38	100	9.6
4S (0–10 cm)	200–2000	252	191±9	11.44±1.6	2.19±0.33	24.2	18.7±0.1	4S (10–20)	224	200±6	12.35±0.5	2.47±0.12	30.9	20.3±2.3
	50–200	361	304±6	6.29±0.3	1.91±0.10	21.1	13.1±0.3		278	294±5	6.63±0.2	1.95±0.07	24.4	13.3±1.1
	20–50	137	166±8	4.31±0.5	0.72±0.10	7.9	9.0±0.9		150	169±2	4.22±0.4	0.71±0.07	8.9	9.1±0.7
	2–20	126	204±8	7.55±0.5	1.54±0.12	17.0	6.6±0.1		183	196±3	5.47±0.6	1.07±0.13	13.4	6.1±0.1
	0–2	113	122±0	18.20±0	2.22±0.00	24.5	7.4±0.1		125	130±4	17.81±0.1	2.32±0.07	29.0	7.6±0.1
	Soluble		0.5±0		0.55	6.0				0.4±0		0.41	5.1	
	SOM	16				1			14					
	Recovery[b]	989	988±2.7		9.1	100.7			960	989±1.3		8.9	111.8	
	Bulk soil	1000	1000		9.06	100	10.0		1000	1000		7.99	100	9.9

[a] Results of the particle-size analysis after hydrogen peroxide treatment (destruction of SOM) and dispersion with sodium hexametaphosphate
[b] Sum of fractions

Table 4 PSF of four representative samples of pelleted organic amendments used for fertilizing the ORG treatment plots and to a lesser extent the MINo treatment plots. Distribution of carbon and carbon:nitrogen ratios within the particle-size fractions. For abbreviations, see Table 1

Fraction (μm)	Mass (g kg^{-1})	C			Carbon:nitrogen
		(g kg^{-1} fraction)	(g kg^{-1} compost)	(g 100 g^{-1} compost C)	
>2000	11	439 ± 11	4.7	1.2	19.5 ± 1.9
1000–2000	108	397 ± 8.3	43.2	11.0	19.1 ± 0.5
500–1000	200	432 ± 2.8	86.9	22.0	21.3 ± 0.1
200–500	250	421 ± 5.0	106.5	27.0	18.0 ± 0.4
50–200	172	390 ± 9.8	67.1	17.0	14.8 ± 0.8
20–50	97	355 ± 6.5	33.6	8.5	13.9 ± 0.4
0–20	50	331 ± 1.8	16.4	4.2	12.3 ± 0.3
Soluble			35.0	8.9	
Recovery	836		393.4	99.8	
Bulk compost	1000		394.31	100	15.7 ± 2.4
200–2000[a]	558	422 ± 31	236.6	60.0	19.1 ± 3.2
50–2000[a]	730	415 ± 30	303.7	77.0	17.9 ± 4.5

[a] By calculation

tory (mean value of 991 ± 1.75 g kg^{-1} soil) whatever the considered treatment or soil layer.

Four representative samples of the pelleted organic amendment, Vegethumus™, used in the experimental design described above were fractionated by wet sieving at 2000 μm, 1000 μm, 500 μm, 200 μm, 50 μm and 20 μm. The different fractions were then dried (40 °C), weighed and finely ground. The OM solubilized by water during fractionation constituted the "water-soluble fraction".

The PSF of the composted organic amendment was not satisfactory, as the mass recovery only reached 84% (Table 4). This may be accounted for by the inorganic material (not determined) solubilized during fractionation. Likewise, the particulate OM of this product tended to remain attached to the sieve screen; repeated and careful inspections of the sieves were thus necessary to recover the maximum amount of OM, but not all of it.

Chemical analyses

Total carbon and nitrogen were determined by dry combustion on an autoanalyzer (Carlo Erba NA 2000). All chemical analyses were done in triplicate. Carbon solubilized during the fractionation procedure was determined on aliquots of the fractionation waters filtered at 0.2 μm. The water-soluble organic carbon was measured by an autoanalyzer Shimadzu TOC 5000. Repeatability was assessed on carbon contents (g carbon kg^{-1} soil) by means of SDs calculated for each fraction. Whatever the layer considered, the best repeatability was found for the carbon contents of the clay fractions, and the worst (but still very low, i.e. <1 g carbon kg^{-1} soil) for those of the sand fractions. The coefficients of variation were 2.9% and 1.8% for the clay fractions and 10.7% and 14.8% for the coarse-sand fractions in the 0- to 10-cm and 10- to 20-cm layers, respectively.

Results and discussion

Climatic conditions in greenhouse trials differ from those in field trials of the Mediterranean area. Under the former, with a high temperature and level of irrigation, the mineralization of OM can be considered as intermediate between that under temperate and tropical conditions. Thus, in this study, despite some methodological differences, the characteristics of the soils and their fractions are discussed with reference to works done on well-drained and coarse-textured soils cultivated under temperate, Mediterranean and tropical climates (Fig. 1a–d).

Total carbon in whole soils

The total carbon contents of the soils from the MINo treatments ranged from 5 g kg^{-1} soil to about 6.5 g kg^{-1} soil (Table 2), whereas those from the ORG treatments ranged from 8 g kg^{-1} soil to about 10 g kg^{-1} soil (Table 3). These carbon contents were low, which is typical for non-calcareous sandy soils of the Mediterranean region studied (Fig. 1b). Our data, indeed, were in agreement with those (3.8–14.8 g carbon kg^{-1} soil, mean value 8.5) of Arrouays et al.'s data bank (1999) for soils sampled at 36 Mediterranean locations (>60% sand, <20% clay). Moreover, these values were close to those reported by different authors (Balesdent et al. 1987; Leinweber and Reuter 1992; Chellemi et al. 1997; Hassink et al. 1997) for temperate and well-drained coarse-textured soils under continuous cultivation, and even closer to those observed for tropical and cultivated sandy soils (Fig. 1a,b) from African sites (Djegui et al. 1992; Feller 1995).

The effects of organic vs. mineral fertilization, and solarization vs. no solarization are presented in Fig. 2. On a short-term scale (3 years, six applications), the organic amendment was able to increase the total soil carbon content (by about +2 g carbon kg^{-1} soil, i.e. +20 ~ 30%). This is in accordance with the results of our previous study (Thuriès et al. 1998; Thuriès et al. 2000) and the observations of other authors (Angers and N'Dayegamiye 1991; Leinweber and Reuter 1992; Hassink et al. 1997) who reported an increase in total soil carbon content with application of farmyard manure or compost. In contrast, during the same time, solarization did not affect the total carbon content signifi-

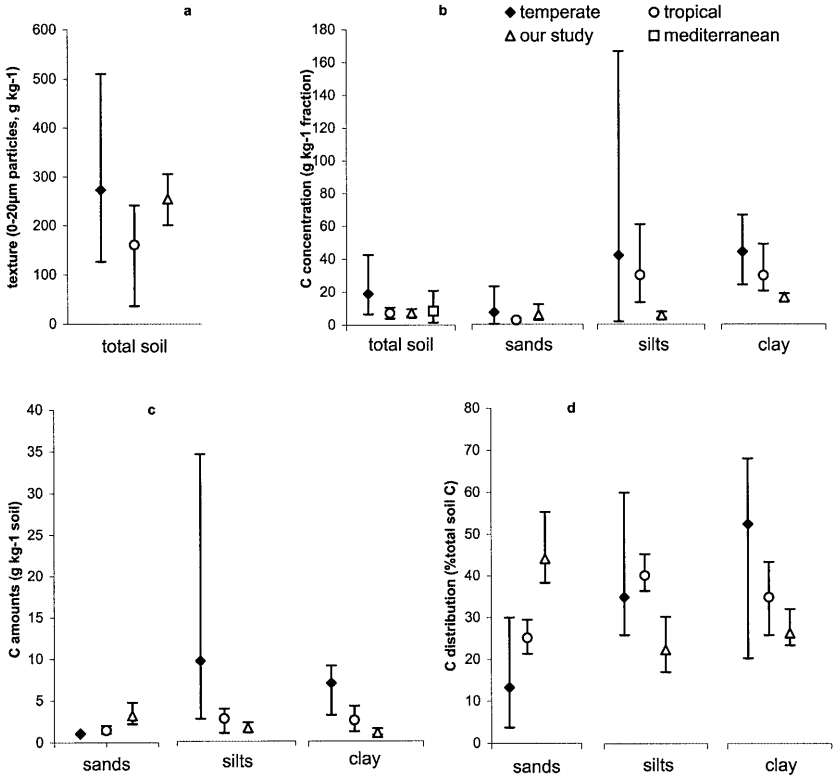

Fig. 1a–d Mean soil characteristics for sandy, cultivated, well-drained temperate and tropical soils. **a** Texture (0–20 μm mass), **b** carbon concentrations (g carbon kg^{-1} fraction), **c** carbon amounts (g carbon kg^{-1} soil), **d** carbon distribution (% of total carbon). *Vertical bars* show the ranges. Temperate soil calculations were made from Dalal and Mayer (1986); Balesdent et al. (1987); Christensen (1987, 1988); Angers and N'Dayegamiye (1991); Christensen (1992); Leinweber and Reuter (1992); Schulten et al. (1993); Hassink et al. (1997); Parfitt et al. (1997). Tropical soil calculations were made from two sites in Djegui et al. (1992), and six sites in Feller (1995). Mediterranean soil characteristics from Arrouays et al. (1999) (36 sites) are discussed in the text

cantly. It is difficult to interpret this result, since no data on solarized soils were available in the literature.

General characteristics of the size fractions

The total amount of carbon recovered in the size fractions was satisfactory, with a mean value of 98.7 ± 6.85 g carbon 100 g^{-1} total carbon (Tables 3, 4). When compared to the other fractions, the clay-size fractions were about 3 times richer in carbon (about 16 g carbon kg^{-1} fraction; Fig. 3a). The mean carbon concentrations of these fine fractions were smaller than those generally measured in temperate soils, and close to the weakest values reported for tropical soils (Fig. 1b). This could be due to the particular microclimate in the greenhouses and/or to differences in clay mineralogy. The lowest mean carbon concentrations were found for the silt fractions; they were close to the smaller values reported for some temperate soils (e.g. Hassink et al. 1997; Fig. 1b), but very different to those (much higher) commonly reported for tropical soils in the literature. The mean carbon concentrations of the sand fractions were comparable to those from temperate and tropical soils. Carbon concentrations thus tended to decrease with increasing particle size, as already widely reported for temperate (Chichester 1969; Adams 1982; Dalal and Mayer 1986; Christensen 1988; Angers and N'Dayegamiye 1991; Leinweber and Reuter 1992) and tropical coarse-textured soils (Djegui et al. 1992; Feller 1995; Fig. 1b).

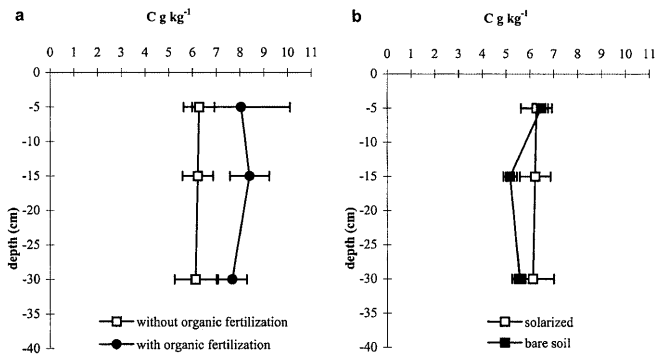

Fig. 2 Carbon contents in g kg^{-1} of soils a with (*3S*) or without (*2S*) organic fertilization; **b** solarized (*2S*) or unsolarized (*2N*)

The mean carbon:nitrogen ratios declined with decreasing particle-size from 12–20 in the coarse-sand fractions (mean value 16.3) to 6–7 in the fine-silt ones (mean value 6.4). This is in accordance with other findings (e.g. Feller et al. 1983; Tiessen and Stewart 1983). Mean carbon:nitrogen ratios of the whole soils and their separates were not affected by depth (Fig. 3b).

The clay- and coarse-sand-size fractions presented the largest mean carbon contents (~1.8 g carbon kg^{-1} soil; Fig. 3c), followed by the fine-sand, fine-silt, and coarse-silt separates (~0.5 g carbon kg^{-1} soil). The carbon amounts of the fractions < 50 μm were lower than those generally reported for temperate sandy soils, but close to those determined for tropical soils (Figs. 1c, 3c).

The largest proportion of total carbon was found in the clay-size fractions (~26%) in accordance with the

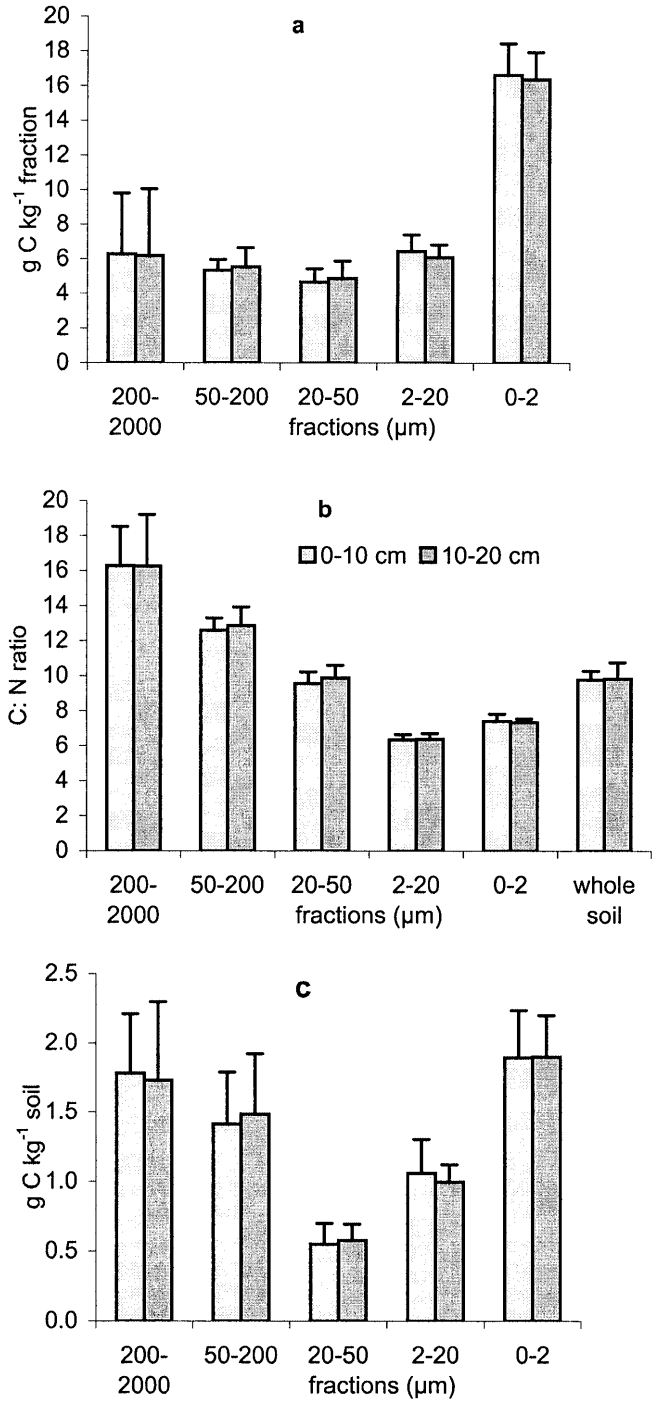

Fig. 3a,b Mean characteristics of the fractionated soils (0- to 10-cm, 10- to 20-cm layers). **a** Mean carbon concentrations (g carbon kg^{-1} fraction), **b** mean carbon:nitrogen ratios, **c** mean carbon contents (g carbon kg^{-1} soil). *Vertical bars* show SDs

observations of Dalal and Mayer (1986) and Christensen (1987). However, when the fine- and coarse-sand fractions were combined in one 50- to 2000-µm fraction, it was found that this total sand-size fraction retained the highest percentage (~44%) of the whole soil carbon, whatever the fertilization or the treatment during the summer. This value was far greater than that reported by Christensen (1988) for temperate soils even richer in sand; indeed, in these latter soils, the 20- to 2000-µm fraction contained only 9–10% of the total carbon. Actually, the carbon distribution in the soils of our study (Fig. 1d) approximated to those encountered in tropical sandy soils (Feller 1995), where more than one third of total soil carbon was associated with particles of 20–2000 µm.

Effect of management on the quality and amounts of carbon in the particle-size fractions

Influence of organic fertilization

In the plot 2S (MINo treatment), the carbon:nitrogen ratios decreased from 17.4 in the sand fraction to 7.3 in the clay fraction from the 0- to 10-cm layer. Lower carbon:nitrogen ratios were found in the 10- to 20-cm layer and ranged from 14.8 in the sand fraction to 7.5 in the clay one (Table 2). In the same manner, the carbon:nitrogen ratios in the plot 3S (ORG treatment) decreased from 17.8 in the sand fraction to 7.5 in the clay fraction for the 0- to 10-cm layer, and from 16.7 to 7.3 in the 10- to 20-cm layer (Table 3). With regard to SDs, the carbon:nitrogen ratios considered as quality criteria were not strongly affected by short-term (3 years) applications of organic amendment. However, the sand fractions, especially the coarse ones, could be considered as good indicators for the impact of organic fertilization on SOM (Tables 2, 3). Indeed, as far as quality was concerned, the carbon:nitrogen ratios of these fractions in the amended soil of plot 3S were higher, albeit slightly, than in the control soil 2S, at 0–10 cm and 10–20 cm depths, despite the high variability amongst the carbon:nitrogen ratios of all the coarse-sand fractions. A similar slight effect was observed in amended soil under tropical conditions (Feller et al. 1983). This is also in accordance with the findings of Leinweber and Reuter (1992) who reported even higher increases in the carbon:nitrogen ratios of sand fractions following applications of compost. In our case, the increases could be explained by the plant debris of sizes 200–2000 µm constituting a large part of the compost (~56%, Table 4). This debris not only represented 60% of the compost carbon, but also had a carbon:nitrogen ratio (mean value 19.1, Table 4) slightly higher than that of the coarse-sand fraction of corresponding size (mean value ~16.1 at 0–20 cm depth) in the control soil 2S. The carbon:nitrogen ratios decreased from the coarse fractions (18–21 in particles 200 to >2000 µm) to the finer ones (about 12–14 in particles 0–50 µm). This is in accordance with the decomposition of the plant debris during the composting process. As for the small difference between the carbon:nitrogen ratios of the 200- to 2000-µm separates in the control soil 2S and amended soil 3S, this can be explained by: (1) the carbon:nitrogen ratio of the plant debris of the compost, rather low for such material, (2) the rapid

turnover of the 200- to 2000-μm soil fraction (Christensen 1987; Balesdent et al. 1988; Feller and Beare 1997; Hassink et al. 1997). Plant debris of the compost and that associated with sand are intensely mineralized. As a consequence, the sand-size soil compartment needs to be constantly rebuilt with organic inputs in greenhouse trials under a Mediterranean climate.

In both the 0- to 10-cm and 10- to 20-cm layers, the positive and significant differences in carbon amounts between plots 2S and 3S (Fig. 4) were more striking for the coarse-sand fractions (0.39 ± 0.19 to 0.73 ± 0.25 g carbon kg^{-1} soil), than for the clay fractions (0.27 ± 0.03 to 0.35 ± 0.05 g carbon kg^{-1} soil). Lower and non-significant differences were shown for the silt and the water-soluble fractions. The carbon amounts of the coarse-sand fractions were on average twofold higher in the amended soil 3S compared to the control one, 2S, despite the variability (~ 0.2 g carbon kg^{-1} soil). Angers and N'Dayegamiye (1991) observed similar increases, although less high (+24%) which affected all the fractions they studied. The importance of these increases may depend upon the nature of the inputs. Whereas farmyard manure generally contains a high proportion of carbon which is more or less soluble and can be easily fixed on fine particles, the organic amendment we studied presented most of its carbon (60%, Table 4) in the form of coarse-sized composted plant debris. Only 12% and 9% of the total carbon was found in the fine-sized particles (0–50 μm) and the water-soluble fraction, respectively (Table 4). This also has been shown by Feller (1985), who found that for a sandy soil depleted in OM, the addition of compost increased mostly the carbon contents in the particles >50 μm.

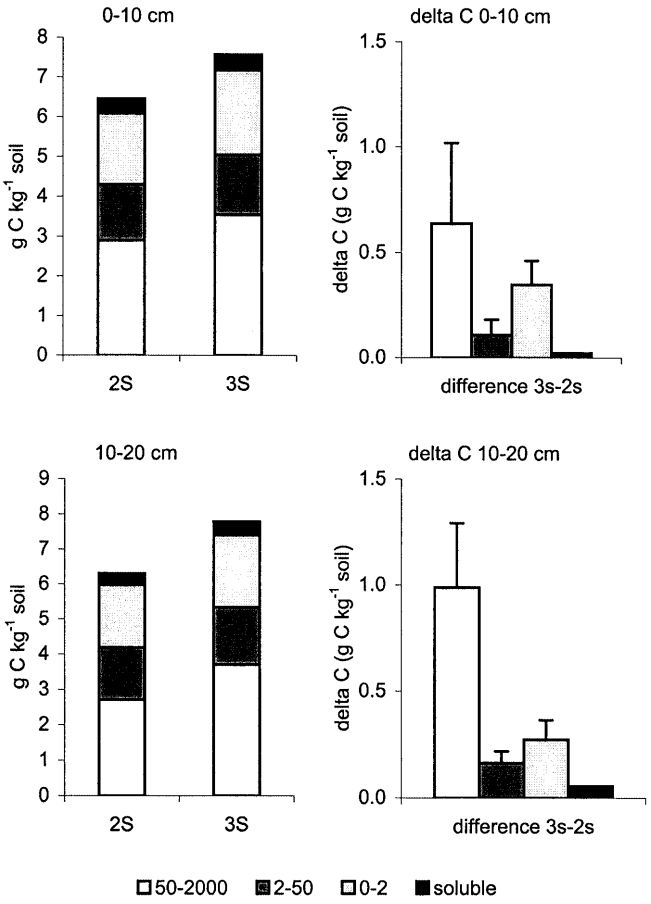

Fig. 4 Comparison of the carbon contents (g carbon kg^{-1} soil) and differences in carbon contents (δ carbon in g carbon kg^{-1} soil) from mineral-fertilized (2S) versus organic-fertilized (3S) soils in the 0- to 10-cm and 10- to 20-cm layers. *Vertical bars* show SDs

Influence of solarization

There was no significant difference between the carbon:nitrogen ratios of the fractions from solarized and unsolarized samples, with the exception of the fine-sand fractions which differed slightly (Table 2). Moreover, the data in Table 2 and Fig. 5 showed that there were no significant differences in carbon amounts in the different fractions isolated from solarized or unsolarized bare soils, whatever the soil layer considered. We expected solarization to diminish the soil carbon contents because of the increased temperature in the surface layers of the soil. Yet, solarization did not strongly affect soil carbon contents or characteristics of the soil particle-size fractions. Indeed, its effects might have been masked because of some solarization-like effect occurring naturally inside the plastic greenhouse throughout the year. A field trial conducted together with the present greenhouse trial would have indicated more precisely the effect of solarization.

In conclusion, while it remains unclear how solarization influenced SOM, our results confirmed the generally reported effects of organic inputs on SOM characteristics. The increase in the overall soil carbon con-

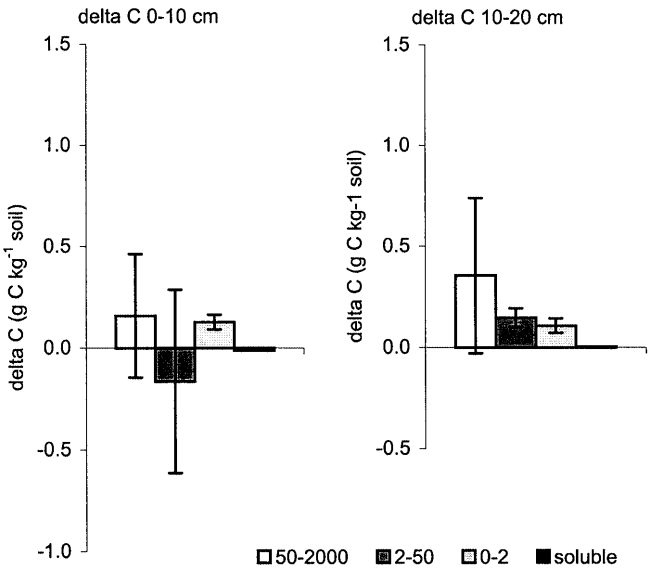

Fig. 5 Differences in carbon contents (δ carbon in g carbon kg^{-1} soil) from bare (2N) versus solarized (2S) soils in the 0- to 10-cm and 10- to 20-cm layers. *Vertical bars* show SDs

tents after repeated compost applications was especially noticeable in the soil particle-size fractions of 200–2000 μm. The comparison of our data with those provided by the literature permitted us to identify similarities with results obtained in studies carried out under tropical conditions; this can probably be accounted for by the particular climatic conditions encountered in greenhouse experiments conducted in Mediterranean zones.

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