Soil Surface Structure Stabilization by Municipal Waste Compost Application

L. M. Bresson,* C. Koch, Y. Le Bissonnais, E. Barriuso and V. Lecomte

ABSTRACT

Loess-derived soils of the northern Paris basin are prone to surface structure degradation leading to erosion, flooding, and pollution. Concomitantly, recycling of municipal solid waste (MSW) has been recognized as an important environmental issue. The aim of this study was to test the impact of compost application on soil surface structure degradation and on the resulting runoff and erosion processes. Aggregates (0–30 mm) from a silty loam Typic Hapludalf were mixed with a MSW compost at a rate of 15 g kg^{-1} (dry matter). Repacked seedbeds were exposed to a 19 mm h^{-1} simulated rainfall for 60 min. Morphological evolution of the soil surface was monitored using sequential photographs. Crust and seedbed microstructures were studied after 4, 15, and 60 min of rainfall, using thin sections from resin-impregnated replicates. Runoff was measured every five minutes, and aliquots were sampled for sediment concentration. In control seedbeds, surface crusts quickly developed and the whole seedbed slumped because of aggregate coalescence through deformation in a viscous state. Compost application delayed crust formation and prevented seedbed slumping. This, in turn, delayed runoff from 2.5 to 9.2 mm of cumulative rainfall. Sediment concentration in the incipient runoff was decreased from 36.4 to 11 g L^{-1}. This could be ascribed to the stabilization of the aggregate framework, which allowed the particles detached from the top of surface aggregates to illuviate a few millimeters deeper. In a highly unstable soil, MSW compost application was efficient in combating soil surface structure degradation and its consequences on runoff and erosion.

Soil surface structure degradation (e.g., crusting and slumping) can have severe consequences, both agriculturally (preventing seedlings to emerge, limiting soil water storage, and inducing soil loss) and environmentally (inducing floodings and increasing surface water pollution).

Northern Paris basin is especially affected by these problems. Most of the landscape is covered by a loess deposit where soils are prone to stucture degradation because of their low clay and organic matter content (<15 and <1.5%, respectively) (Eimberck, 1990). Development, over the last decades, of farming systems where spring crops cover a significant part of the land, lead to increasing structure degradation. As a result, flooding and pollution events began to be clearly identified by farmers and by communities, as a main environmental issue (Papy and Boiffin, 1988; Martin et al., 1997).

Concomitantly, more emphasis has been placed on the recycling of MSWs through their agricultural use as fertilizers or organic amendments. Since organic amendments improve aggregate stability (e.g., Tisdall and Oades, 1982), MSW might be a good substitute for traditional farmyard manure which is no longer available in intensive cropping areas.

Beneficial effects of sewage sludge application have been widely acknowledged, even though Metzger and Yaron (1987) pointed out that controversial results could be found in the literature. Literature is scarce on the effects of compost on soil structure. In their review on the changes in soil physical properties because of organic waste applications, Khaleel et al. (1981) presented 17 papers, only two dealing with MSW composts (Mays et al., 1973; Epstein et al., 1976). They did not find a significant difference between the various types of wastes. Regardless of waste type, both long-term and short-term studies indicated a significant linear relationship between reduction in bulk density and increase in soil organic C. The decrease in bulk density has been ascribed to the dilution effect resulting from the mixing of the soil with less dense organic material added (Khaleel et al., 1981; Tester, 1990). Structural changes resulting from interactions between added organic matter and soil material were seldom suggested, but a close examination of the data published in the literature supports this hypothesis. Changes in soil structure (Guisquiani et al., 1995), as well as, changes in macro and mesoporosity (Pagliai et al., 1981; Guisquiani et al., 1995) have been observed in thin sections and cannot be explained by a mixing effect. This was corroborated by the increase in aggregate stability because of organic waste application (Pagliai et al., 1981; Gerzabeck et al., 1995) or application of humic acid extracts (Canarutto et al., 1996) even though such a stabilizing effect might not be observed in rather stable soils (Guidi et al., 1988).

Based on the studies reported above, we hypothesized that MSW composts may have beneficial effects on soil structure. Also, there is little information available which deals with effects on hydraulic conductivity (Felton, 1995), crust formation, runoff, or erosion, even though the main assessments reported above (i.e., bulk density decrease and aggregate stability increase) lead to the conclusion that compost application might enhance water infiltration, slow down crust formation, delay runoff, and reduce erosion. This might not apply to the highly unstable soils of the European loess belt where seedbeds often slump because of aggregate coalescence (Bresson and Boiffin, 1990; Kwaad and Mücher, 1994; Bresson and Moran, 1995), which is an important process of structure degradation together with aggregate slaking or microcracking (Le Bissonnais et al., 1989).

The aim of the study was to determine if MSW compost application decreases surface structure degradation, i.e., crusting and slumping, on a highly unstable silt loam soil, and to test its possible consequences on runoff and erosion. The experiment involved repacked seedbeds and simulated rainfall. The focus was on (i) the

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Abbreviations: 2D, two dimensions; MSW, municipal solid waste.

description of structural changes both at the soil surface and within the seedbed using macroscopic and microscopic observation methods (Bresson and Boiffin, 1990), (ii) the impact of applied compost on processes of structure degradation, and (iii) the related changes in runoff and sediment production at local scale. The initial stages of degradation were emphasized, because the purpose of compost application is to slow down soil surface degradation until seedlings emerge and crop cover establishes, to prevent further degradation, to delay runoff, and to reduce erosion.

MATERIALS AND METHODS

Soil and Compost

The soil studied was a cultivated, silt loam soil (mixed, mesic typic Hapludalf) developed on loess in the northern Paris basin. The Ap horizon was sampled in winter in a recently tilled field located in an experimental catchment set up in this area for runoff and erosion studies (Le Bissonnais et al., 1998). The 0- to 30-mm aggregates were maintained at the field moisture content (170 g kg^{-1}) in plastic bags stored in a cold room at +4 °C. Main physicochemical data are given in Table 1.

The compost came from an Office Technique de Valorisation des Déchets (OTVD) commercial plant (Orléans, France). Unseparated household waste was first passed through a riddle to remove large pieces of paper and cardboard, then glass, metals, and plastic were separated using densimetric techniques. The resulting material was crushed and submitted to fast aerobic fermentation. After maturation, the compost was stacked. This compost was rich in organic matter and moderately matured (Table 1). Its main physicochemical properties are in accord with data provided by Corti et al. (1998) for MSWs.

Compost was carefully hand mixed with the soil material at a rate of 15 g kg^{-1} (dry matter), which increased the organic C content by 3.6 g kg^{-1}. This rate is similar to a 50 Mg ha^{-1} application rate mixed within the 0- to 25-cm ploughed layer. The amended soil and a control soil (no MSW added) were left for 1 wk in a cool chamber at 4°C.

Surface Morphological Evaluation and Runoff Monitoring

Runoff trays 50 by 50 by 15 cm with buffer zone 15-cm wide (Bradford et al., 1987; Le Bissonnais and Singer, 1992; Fox and Le Bissonnais, 1998) were filled with control soil and amended soil. The repacked seedbeds were slightly compacted up to a bulk density in the 1.10 to 1.20 Mg m^{-3} range to get a structure similar to the structure of seedbeds observed in the field. This was achieved by lifting the side of the tray by about 5 cm up and letting it to fall back, and repeating this operation twice for each side. The seedbed was carefully raked to a depth of 3 cm to homogenize the distribution of the largest clods on the surface. Three replicates were made for the control soil and for the amended soil.

Rainfall simulation with deionized water was performed using a 361 needles, 1 by 1 m simulator, located 6 m high. A 5-mm mesh grid was placed 1.5 m below the simulator to gain a better homogeneity of the rain. Rainfall characteristics included a mean drop diameter of 2.5 mm and 80% of terminal velocity (Le Bissonnais et al., 1995). Rainfall intensity was measured before and after every run, and its variation was <5% so that no statistical design was used. Runoff trays were set at a 5% slope and subjected to a 19 mm h^{-1} simulated rainfall for 60 min. In the Paris basin, such an event has a 3 yr return period and events of 20 mm h^{-1} during 15 min occur every year.

The morphological evolution of the soil surface was monitored using photographs and descriptions according to the method suggested by Boiffin (1986) and Bresson and Boiffin (1990).

Runoff was collected continuously during the rainfall simulation and aliquots were sampled under continuous agitation for sediment concentration. For statistical analysis, variances of both treatments were compared using a *F*-test, then the probability of significance was computed using a two-tailed unpaired Student's *t*-test.

Soil Structure Monitoring

Microstructure boxes, 10 by 30 by10 cm, with free drainage and runoff were used for microstructure studies. These boxes can be directly impregnated after the experiment, avoiding disturbance resulting from handling during sampling. Boxes were filled using the same procedure as for runoff trays, and two replicates were used. Microstructure boxes were then set with the same slope angle and subjected to the same simulated rainfall for 60 min. The 0- to 75-mm upslope part of the boxes was covered as to protect it from rainfall and maintain the soil surface at the initial state. The following 75 to 150 mm and 150 to 225 mm were covered after 4 min and 15 min of rainfall simulation, respectively. The remaining 225 to 300 mm were left exposed up to the end of the simulation, i.e., 60 min. This timing resulted from the previous monitoring of the soil surface macroscopic morphology described above. This procedure aimed to obtain the initial state, two development stages of the structural crust and the first stage of the depositional crust, all within the same box. The procedure did not account for lateral translocation of detached particles because of the small size of the box used. It is relevant here, however, because the first stages of surface degradation mainly depend on aggregate breakdown and slumping processes, rather than on long-range translocation. Microstructure boxes were air dried and impregnated with a polyester resin. Four thin sections, 60 by 130 mm, were prepared for each replicate and observed using a polarizing microscope with 8 to 300 times magnification. Crusts were characterized using the diagnostic features suggested by Valentin and Bresson (1992, 1998).

RESULTS AND DISCUSSION

Soil Surface Morphology

In the control runoff trays, soil surface morphology exhibited strong alterations from the first minutes of rain-

Table 1. Physicochemical data for the soil material, municipal solid waste (MSW) and amended soil.

	Water content	Particle size distribution <2 μm	2–20 μm	20–50 μm	50–200 μm	200–2000 μm	$CaCO_3$	Organic C	Organic N	pH
	g kg^{-1}									
Soil	170	132	140	466	256	6	<1	7.3	0.9	6.7
MSW							57	275	11.6	
Soil + MSW	200	136	144	459	246	15	<1	10.9	1.3	8.6

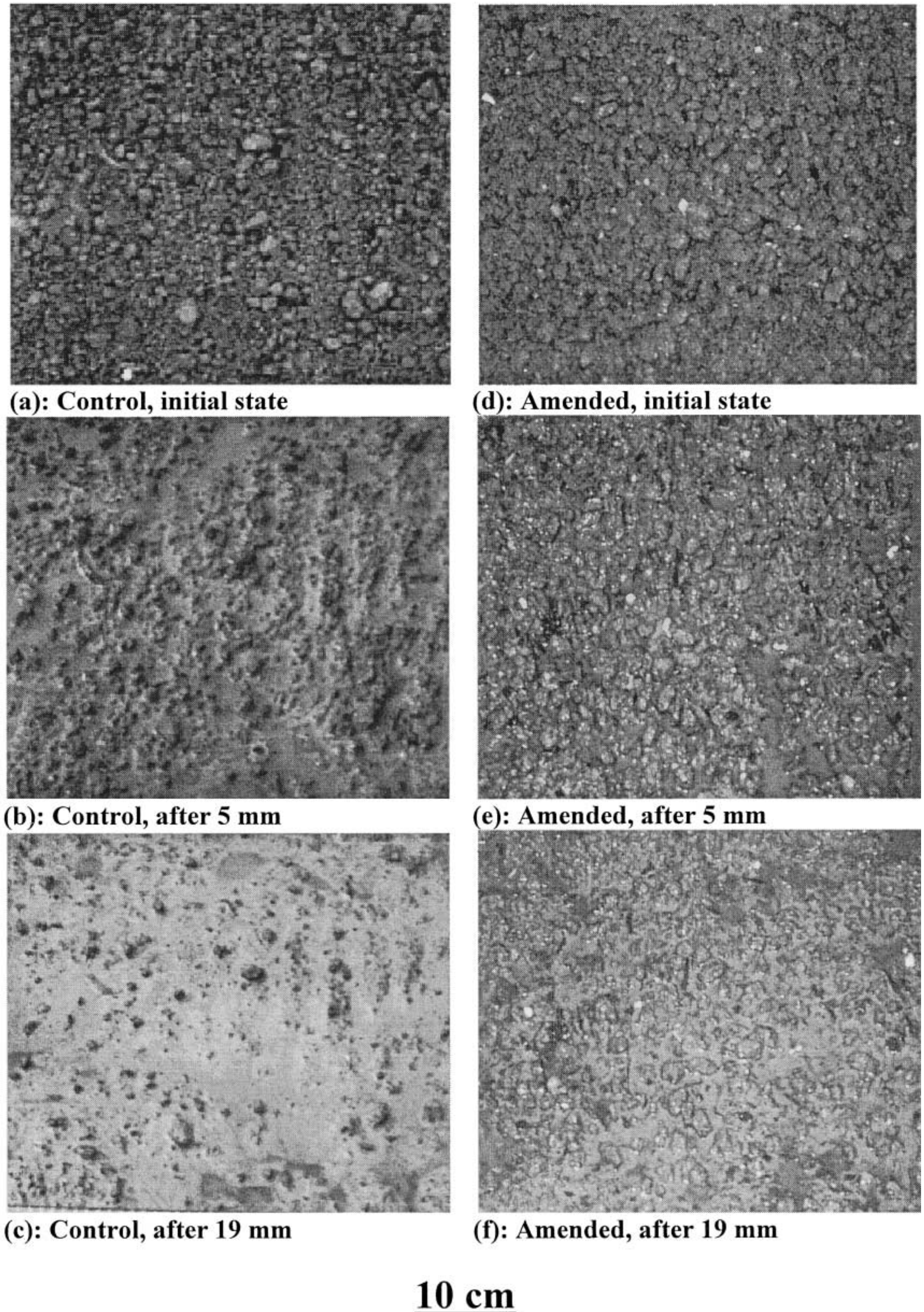

Fig. 1. Macromorphological evolution of the soil surface in the (a, b, c) control and (d, e, f) amended soil after 5 mm and 19 mm of cumulative rainfall (bar length 10 cm).

fall simulation (Fig. 1a, b, and c). After 1 mm of cumulative rainfall, finer aggregates (<2 mm) were fused together and larger aggregates (<10 mm) began to be eroded; the largest clods (>10 mm) remained distinct and some macropores were still visible. After 1.5 mm, a structural crust developed and micropuddles appeared between clods. This soil has a greater sensitivity to crusting than other silty loam soils developed on loess material in western Europe (Le Bissonnais et al., 1989; Bresson and Cadot, 1992; Le Bissonnais et al., 1995) but is common in the northern Paris basin (Eimberck, 1990) as well as in the Netherlands (Kwaad and Mücher, 1994). After 5 mm of cumulative rainfall (Fig. 1b), aggregates <10 mm had disappeared and puddles were interconnected, which induced runoff at the tray scale. Surface roughness decreased continuously as a depositional crust expanded over most of the tray area. After 19 mm of cumulative rainfall (Fig. 1c), few clods remained. The surface level had lowered by about 20 mm, indicating both suface crusting and seedbed slumping.

In the amended runoff trays, the surface morphology changed much more slowly (Fig. 1d, e, and f). Development of a structural crust and related occurrence of micropuddles initiated after 3 mm of cumulative rainfall. After 5 mm of cumulative rainfall (Fig. 1e), puddles were still not interconnected. At the end of the simulation (19 mm of cumulative rainfall), the depositional crust barely covered half of the surface which remained rather rough (Fig. 1f), while the surface level decreased by <0.5 cm. This shows that compost application significantly reduced aggregate breakdown and slumping. This is consistent with increased aggregate stability related to increased organic C (Pagliai et al., 1981; Gerzabeck et al., 1995). For a similar input of organic C, Bresson et al. (1997) showed that the application of an unlimed solid sewage sludge on a similar soil had a small impact on soil surface morphological evolution.

Soil Microstructure

The initial structure of the control microstructure boxes consisted of loosely packed aggregates, which resulted in a high interaggregate porosity (Fig. 2a). Intraaggregate porosity was rather high and consisted of 30-μm wide polyconcave voids. At the primary particle level, the microstructure was quite unusual (Fig. 3a). The fine particles (<20 μm, i.e., fine silt and clay fraction) were not sufficient to form a continuous phase where coarse grains (mostly ranging between 50 and 150 μm) could be embedded. The fine particles were distributed either as coatings around the grains or as 50- to 100-μm microaggregates. The solid phase was not continuous in two dimensions (2D), and the three-dimensional continuity might not involve fine particles at all, but coarse grains instead. The consequences of such a microstructure on aggregate stability are expected to be: (i) a high continuity within pore space, which should reduce air entrapment and therefore aggregate slaking (Le Bissonnais et al., 1989; Bresson and Valentin, 1994; Le Bissonnais, 1996), and (ii) a low cohesion when wet, which should enhance aggregate coalescence (Bresson and Boiffin, 1990; Kwaad and Mücher, 1994; Bresson and Moran, 1995). After 1.3 mm of cumulative rainfall, meniscus-like bridges formed between aggregates a few millimeters below the surface (Fig. 2b). These features indicate that at this incipient stage, the structural crust formed because of an illuvial process which is common in soils wet before rainfall (Boiffin and Bresson, 1987; Le Bissonnais et al., 1989; Bresson and Cadot, 1992). After 4.8 mm of cumulative rainfall, the stuctural crust was well developed (Fig. 2c). Aggregate coalescence was involved rather than illuviation, as evidenced by the typical convex–concave to vesicular shape of the voids (Fig. 3b) (Bresson and Boiffin, 1990; Bresson and Valentin, 1994). This means that, in such an unstable soil, rapid structural collapse prevented further illuviation (Bresson and Cadot, 1992). The coalescence process affected the whole seedbed (Fig. 2c) and the aggregate framework was 2D continuous. Packing voids were polyconcave at the bottom and convexities developed towards the transition with the structural crust. A thin depositional crust overlaid the structural crust in microdepressions between surface aggregates. The deposited material was poorly sorted and microbedded, which is typical of the first stage of depositional crusts (Bresson and Valentin, 1994). After 19 mm of cumulative rainfall, overall macroporosity was very low and consisted of convex–concave to vesicular voids, which shows that coalescence developed throughout the seedbed (Fig. 2d). The depositional crust had spread over 30% of the surface. The deposited material was clearly microbedded, which could be related to variations in the hydrologic behavior of the soil surface (Mücher and De Ploey, 1977; Mücher et al., 1981; Boiffin and Bresson, 1987; Bresson and Boiffin, 1990). Since characteristics of the simulated rainfall remained constant, these variations might be ascribed to variations of surface morphology such as connection between puddles or silting up of puddles.

The surface morphological evolution was similar to the one observed on the runoff trays and the crust microstructure was similar to the one observed in the field, indicating that, despite their small size, microstructure boxes are relevant for the study of the first stages of surface structure degradation.

The initial packing of amended microstructure boxes was slightly looser, and aggregates were slightly better sorted. Compost fragments appeared mainly as fibrous particles and organic microaggregates interspersed between soil aggregates (Fig. 3c). Almost no change in structure was observed after 1.3 mm of cumulative rainfall (Fig. 2e). After 4.8 mm of cumulative rainfall, the structural crust was very thin, about 1 mm thick (Fig. 2f), and consisted of typical bridges composed of bare silt particles (Fig. 3d). No depositional crust could be observed. Crusting developed much slower than in the control soil, and the process was typically an illuviation process instead of a coalescence process. The underlying material did not slump. This suggests that compost application lead to a greater cohesion of the wet soil material, which in turn, maintained the aggregate framework and allowed the illuviation process to develop. Such an impact of organic matter on soil rheological properties has been already suggested (Bresson and Boiffin, 1990). After 19 mm of cumulative rainfall, the structural crust was slightly thicker (about 2.5 mm), and exhibited some coalescing features at the bottom (Fig. 2g). The underlying seedbed remained clearly aggregated, even though less loosely packed, and displayed a sharp transition with the crust. A depositional crust developed in the microde-

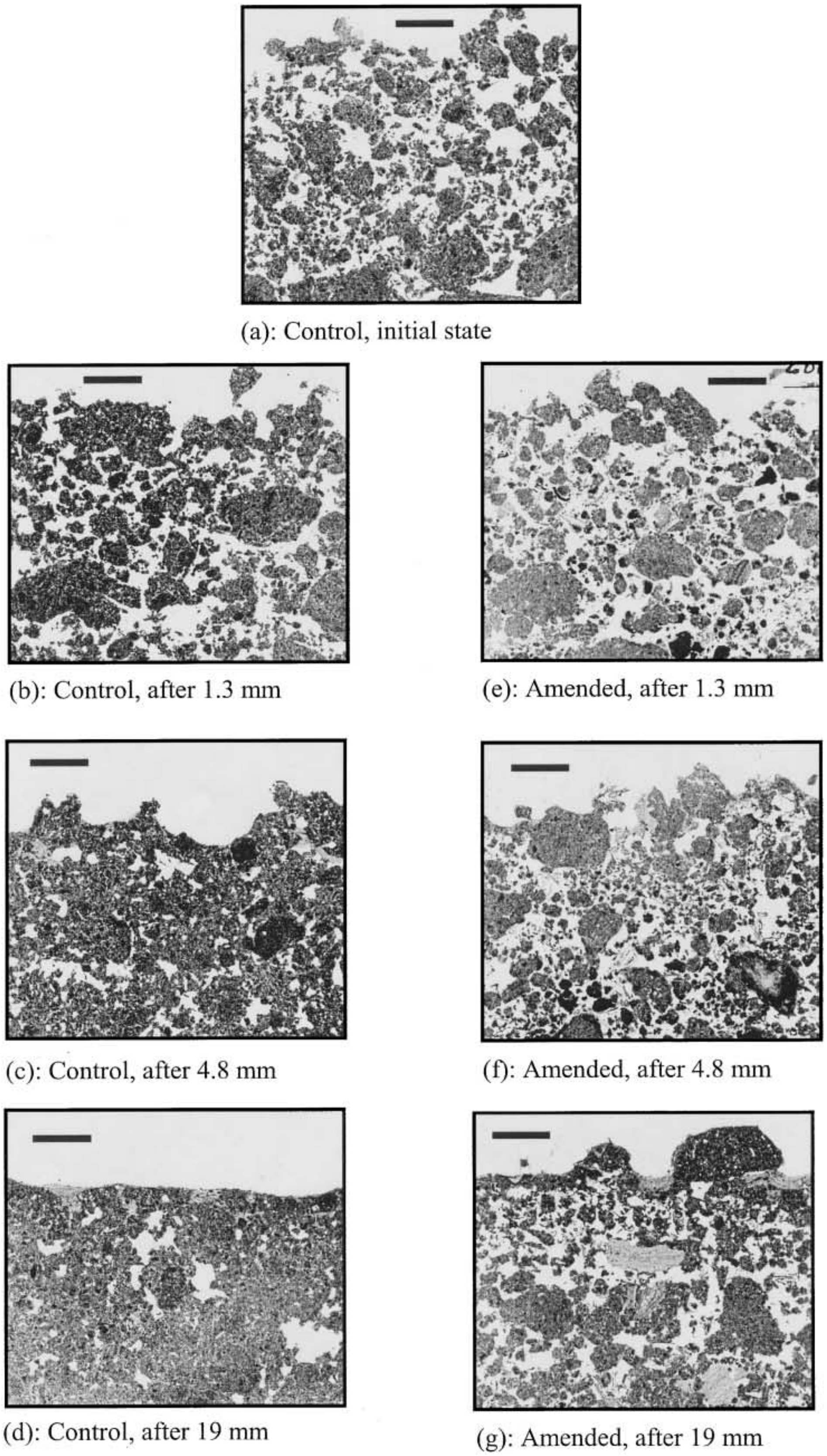

Fig. 2. Micromorphological evolution of the seedbed structure in the (a, b, c, d) control and (e, f, g) amended soil after 1.3, 4.8, and 19 mm of cumulative rainfall (plain light, bar length 10 mm).

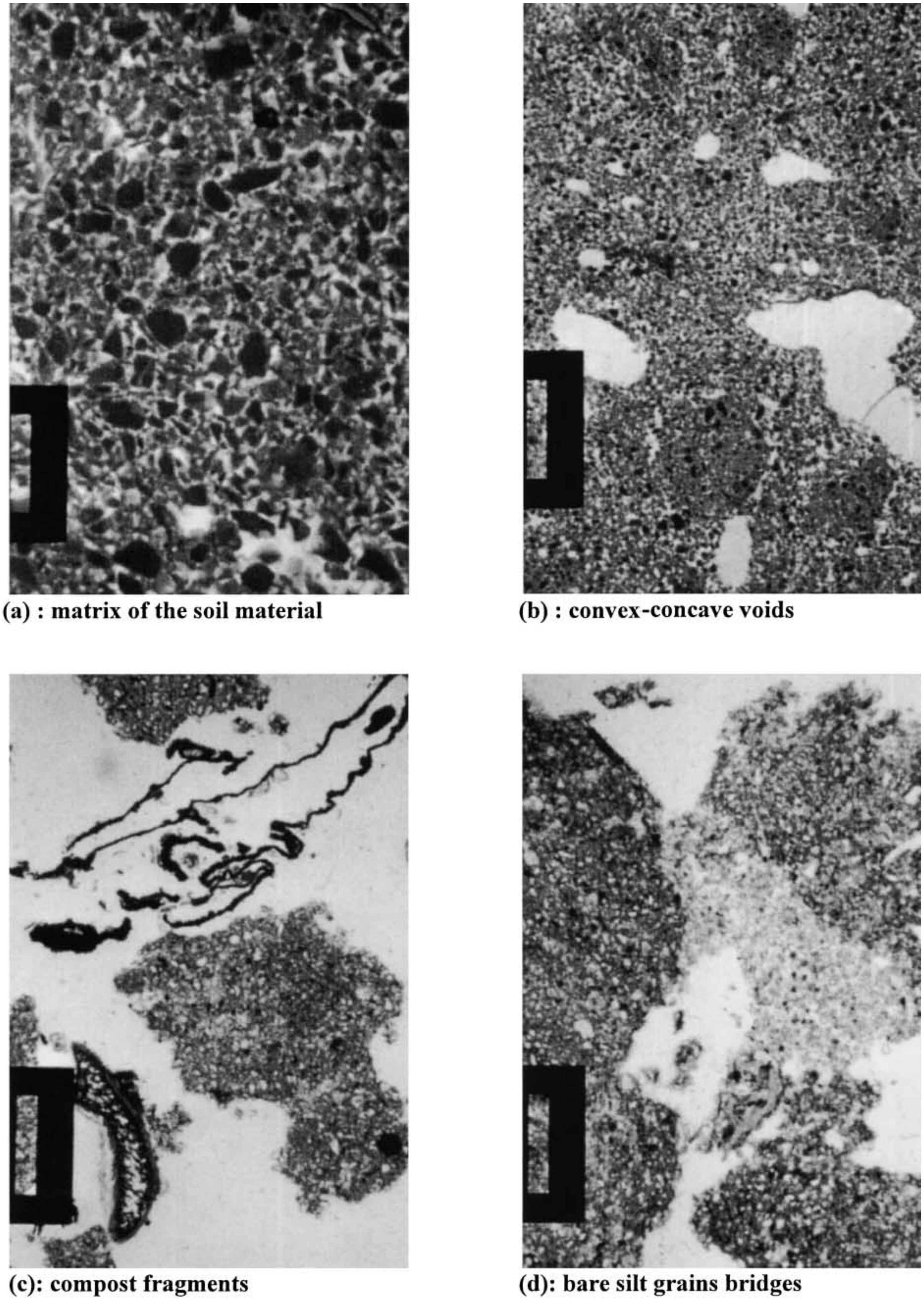

Fig. 3. Micromorphological features of the processes involved in structure degradation. Control soil (UV light): (a) initial state (bar length 200 μm), (b) after 4.8 mm of rainfall (bar length 800 μm). Amended soil (plain light): (c) initial state (bar length 800 μm), (d) after 4.8 mm of rainfall (bar length 800 μm).

pressions of the surface which remained rather rough. In some places, depositional material was observed below the surface. It differed significantly from silt illuviation by a clearly bedded microstructure. This internal depositional crust indicates the persistency of some macroporosity at the soil surface even after runoff had begun.

The stabilizing effect observed cannot be mistaken for the increase in bulk density commonly reported in the literature and usually ascribed to a mixing effect, i.e., the dilution of the soil material by a less dense organic material (Khaleel et al., 1981). The above description of porosity deals with a low magnification, which means that compost particles and soil are not distinguished. In turn, this description cannot account for the mixing effect but for the interaction effect instead, i.e., the change in soil structure.

The slowing down of aggregate coalescence induced by compost application probably results from an increase in wet cohesion. Chenu and Guérif (1991) found that polysaccharides greatly increased tensile strength of dry clay aggregates, and this effect might also be true in wet aggregates, as shown for polyvinyl alcohol (PVA) (Williams et al., 1967). Entanglement of primary particles or microaggregates by fungal hyphaes has been shown to play a great role in sludge amended soils (Metzger et al., 1987), but microscopic evidence of such a process could not be found in the experiment reported here, possibly because of its short duration (1 wk).

Hydrological Behavior

On the control runoff trays, runoff started after 2.5 mm of cumulative rainfall (Table 2) and reached a steady state after about 13 mm of cumulative rainfall. Final runoff rate was 17.1 mm h^{-1}, i.e., a runoff coefficient of 90.2%, which is greater than the values measured in the field at the same scale on a similar soil material (Le Bissonnais et al., 1995; Le Bissonnais et al., 1998). On the amended runoff trays, compost application changed the hydrological behavior (Table 2). Runoff started significantly later (9.2 vs. 2.5 mm of cumulative rainfall) and drainage persisted (3 mm h^{-1}) at the end of the simulation. These results are consistent with the observed change in structure, i.e., delay of crust formation and prevention of slumping.

Sediment concentration in the incipient runoff (Table 2) was high on the control runoff trays (36.3 g L^{-1} after 6 mm of cumulative rainfall) and stabilized at 13.3 g L^{-1} at the end of the experiment. Such data measured on runoff trays cannot be extrapolated at the catchment scale because of differences in flow velocity and redeposition processes (Le Bissonnais et al., 1995; Le Bissonnais et al., 1998). However, they are consistent with the data measured in the field on the same soil and at the same scale (Le Bissonnais et al., 1998) and therefore may provide relevant information on the stabilizing effect of compost application. Compost application decreased the sediment concentration in the incipient runoff (11 g L^{-1} after 13 mm of cumulative rainfall). This low sediment concentration is even lower than the one measured in the control soil after the same amount of cumulative rainfall when runoff had already reached a steady state (16.7 g L^{-1} after 13 mm of cumulative rainfall).

Compost application decreased soil loss from 54.6 to 18.3 g (Table 2), mainly by decreasing the flush of sediment related to the incipient runoff. As indicated by microstructure observation, particles detached from the top aggregates when rainfall had started were allowed to illuviate a few millimeters below the surface where they were protected against further entrainment by surface runoff.

CONCLUSIONS

Composted municipal waste application was efficient in combating surface structure degradation in a highly unstable soil prone to surface crusting and seedbed slumping. Amendment decreased aggregate coalescence so that the whole seedbed maintained its aggregate framework. As a result, runoff was delayed and soil loss decreased. Moreover, delaying crust formation allowed particles detached from the top of surface aggregates to infiltrate a few centimeters below the surface where they were protected from further erosion. Such a protection might contribute to decrease risks of surface water contamination by pesticides or fertilizers applied at the soil suface after sowing, and further experiments are required to assess the impact of compost application at the field scale.

This study shows that the effect of compost application on soil bulk density reported in the literature was not a mixing but an interaction effect. Interaction occurred within 1 wk after compost application but its nature and the way it prevented coalescence are still to be established.

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Table 2. Time to runoff, sediment concentration in the incipient runoff and soil loss for the control and amended soils (mean of three replicates, standard deviation and probability level of significance).

	Control		Amended		Probability level of significance†
	Mean	SD	Mean	SD	$P(T <= t)$
Cumulative rainfall when runoff began, mm	2.5	0.1	9.2	2.4	0.041
Sediment concentration in the incipient runoff, g L^{-1}	36.4	9.7	11	1.7	0.067
Soil loss, g	54.6	24	18.3	9.1	0.110

† Unpaired, two tailed Student's *t*-test run after comparison of variances using a *F*-test.

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