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Effects of rock fragments on physical degradation of cultivated soils by rainfall

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Abstract

To understand better the role of rock fragments in soil and water conservation processes, the effects of rock fragments in maintaining a favourable soil structure and thus also in preventing physical degradation of tilled soils was studied. Laboratory experiments were conducted to investigate the effects of rock fragment content, rock fragment size, initial soil moisture content of the fine earth and surface rock fragment cover on soil subsidence by rainfall (i.e. change in bulk density by one or more cycles of wetting and drying). A total of 15 rainfall simulations (cumulative rainfall, 192.5 mm; mean intensity, 70 mm h^{-1}) were carried out. Before and after each rainfall application the surface elevation of a 19-cm thick plough layer was measured with a laser microrelief meter. In all experiments, the bulk density of the fine earth increased with applied rainfall volume to reach a maximum value at about 200 mm of cumulative rainfall. From the experimental results it was concluded that the subsidence rate decreased sharply for soils containing more than 0.50 kg kg^{-1} rock fragments, irrespective of rock fragment size. Fine earth bulk densities were negatively related to rock fragment content beyond a threshold value of 0.30 kg kg^{-1} for small rock fragments (1.7–2.7 cm) and 0.50 kg kg^{-1} for large rock fragments (7.7 cm). Initial soil moisture content influenced subsidence only in the initial stage of the experiments, when some swelling occurred in the dry soils. Surface rock fragment cover had no significant effect on subsidence of the plough layer. Therefore, subsidence of the plough layer in these experiments appears to be mainly due to changing soil strength upon drainage rather than the result of direct transfer of kinetic energy from falling drops. The relative increase in porosity of the fine earth as well as the absolute increase in macroporosity with rock fragment content will cause deeper penetration of rainfall into the soil, resulting in water conservation. Therefore, crushing of large rock fragments into smaller ones is to be preferred over removal of rock fragments from the plough layer.

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1. Introduction

In many countries of the Mediterranean basin and elsewhere, where degradation of the natural environment constitutes a serious problem leading to desertification, a large proportion of the soils contain rock fragments both at the soil surface and in the soil profile (Poesen and Lavee, 1994). Recent research in Greece has shown that soils derived from sandstones and conglomerates containing rock fragments are, despite their low fertility, less affected by dry periods than soils on marls without rock fragments, resulting in higher wheat biomass production for the first soil types (Kosmas et al., 1993). Kosmas et al. (1993) mention the higher bulk density of the fine earth in the marls and their higher water storage capacity as factors which cause penetration of rainfall into the soil to be less deep and subsequent evaporation from the soil surface to be more rapid as compared with soils containing rock fragments. These results suggest that apart from the protective role of rock fragments at the soil surface (see literature review by Poesen and Bunte, 1995), rock fragments in the soil profile play an important role in conserving soil moisture during the growing period.

In agricultural soils, which are disturbed every year by ploughing, rock fragments form a skeleton in the soil profile which protects soil structure leading to a higher macroporosity and saturated hydraulic conductivity (Saini and Grant, 1980; Magier and Ravina, 1984: Ravina and Magier, 1984; Childs and Flint, 1990: Chow et al., 1992). This is in contrast with the results of Mehuys et al. (1975), who found that in non-structured desert soils saturated hydraulic conductivity decreased with increasing rock fragment content. In addition, some authors (Childs and Flint, 1990; Poesen and Lavee, 1994) stated that in soils containing rock fragments concentration of organic matter in the fine earth fraction occurs, leading to low fine earth bulk densities at high rock fragment contents.

Freshly tilled soils are prone to physical degradation of the plough layer as a result of drop impact and percolation of water during heavy rainstorms (Onstad et al., 1984). Physical degradation refers to adverse changes in soil physical properties including porosity, permeability, bulk density and structural stability (FAO, 1979). Physical degradation results in an increase of soil bulk density (subsidence). According to Onstad et al. (1984) the most important factors responsible for subsidence of freshly tilled soils are the kinetic energy transferred to the soil surface by rainfall and changing soil strength with water content as soil water moves through the tilled layer. Soil subsidence reduces the proportion of structural pores which has a negative effect on the saturated hydraulic conductivity and on the development of the root system and a positive effect on capillary rise and evaporation of moisture from the topsoil (Ravina and Magier, 1984). Since these parameters play a crucial role in the availability of water for the vegetation and the control of soil erosion, they become more important in ecosystems with desertification hazards.

The experiments described in this paper were designed to study the influence of the content, size and surface cover of rock fragments and the initial moisture content of the fine earth, on the physical degradation of tilled soils during intense rainfall.

2. Materials and methods

2.1. Rainfall

Rainfall was simulated by a downward-oriented, single-nozzle, continuous-spray system described in detail by Poesen et al. (1990). These authors showed that at an average intensity of 71.1 mm h^{-1} (standard deviation: 3.96) and a spatial uniformity coefficient of 94%, the median raindrop diameter equals 2.2 mm. The kinetic energy of the simulated rain (fall height, 3.25 m) at the soil surface then reaches 15.8 J m^{-2} mm^{-1} of rain.

Rainfall intensity was sampled before and after each experiment. Total rainfall volume (192.5 mm) for each experiment consisted of four rainfall events lasting 15, 30, 60 and 60 min respectively. These events were separated by no-rain periods of 2, 24 and 2 h respectively. Mean intensities were 70 mm h^{-1}.

2.2. Experimental set up

The plot box used in these experiments has been described in more detail by Poesen et al. (1990). The test area of the plot box is 0.94 m long and 0.60 m wide, surrounded by a buffer area 0.33 to 0.42 m wide. The latter was treated identically to compensate for splash losses. Drainage through the 0.19-m thick layer of soil was ensured by installing at the bottom of the plot box a hollow, 1-cm thick, perforated plate covered by a wet geo-textile. The volume of the box was 0.105 m^3 (Fig. 1). The slope of the soil surface in the box equalled 15% in order to minimise the area where ponding occurs. For each experiment, the plot box was filled with a homogeneous mixture of fine earth and rock fragments simulating a freshly tilled soil (Table 1). The fine earth consisted of well-structured, homogeneous silt loam sampled in Neerijse (Belgium) at a depth of 30–60 cm. Subsoil was deliberately chosen to provide a material with a smaller structural stability than the local topsoil, since we expected the subsoil to have physical properties that were more similar to Mediterranean topsoils. A description of some soil properties (texture, bulk density, organic matter content and dry aggregate size distribution) is given in Table 2.

The small rock fragments used in these experiments are well-rounded river gravels from a quarry in Pleistocene river deposits of the Meuse. The gravels were sieved and only the fraction between 1.7 and 2.7 cm (round holes) was used. The large rock fragments ($d2=7.7$ cm) were sampled in the channel of the Durance

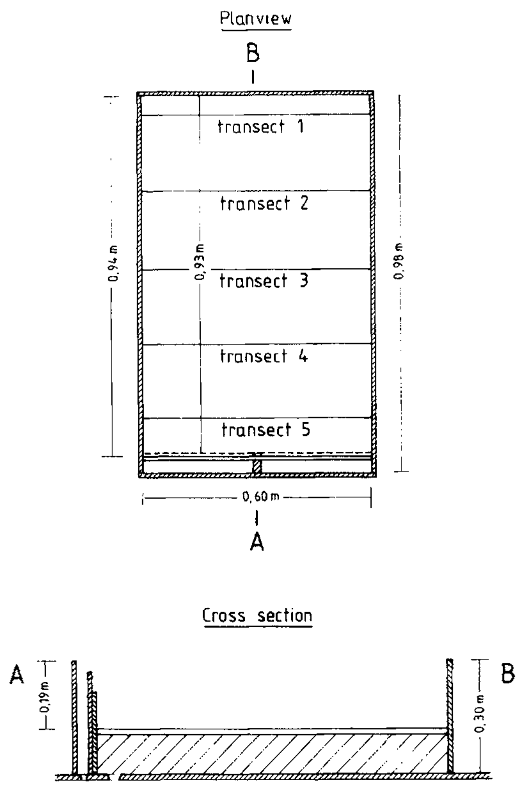


Fig. 1. Schematic view of the central test area.

river in southern France (Table 2). The small rock fragments fall in the medium to coarse gravel size class (0.5–7.6 cm), whereas the large ones are cobbles (7.6–25 cm; Miller and Guthrie, 1984). The density of the rock fragments (ρ_r in kg m^{-3}) was calculated from the increase in volume after immersion of pre-weighed amounts of rock fragments in water (Table 2).

Percolation and runoff rates were determined at regular intervals during the simulation runs. The sediment concentration was determined by evaporation of the samples. Soil moisture content was determined gravimetrically before and after the experiments. During the intervals between the showers, the soil was left to drain. A plastic sheet prevented drying out of the soil by evaporation.

2.3. Microrelief meter

Five fixed transects were selected at 20-cm intervals (see Fig. 1) along which the soil surface elevations were determined at 2-mm intervals using a Selcom laser microrelief meter (Optacor 2008, Selcom A.G., Sweden) driven by a computer-controlled motor (Römkens et al., 1988). Scans were made before the experiment and after each rainstorm (Figs. 1 and 2).

Table 1
Set-up of the experiments and volume of sediment trapped by the plot box rim

Rock fragment size (cm)	Rock fragment content		Initial moisture (g per 100 g)	Volume of sediment[c] (dm^3)
	R_m[a] ($kg\ kg^{-1}$)	R_v[b] ($m^3\ m^{-3}$)		
Control	0	0	20.0	1.38
Control	0	0	19.4	1.27
Control	0	0	18.7	1.23
1.7–2.7	0.31	0.16	20.4	0.46
1.7–2.7	0.52	0.29	19.6	0
1.7–2.7	0.52	0.28	19.1	0
1.7–2.7	0.77	0.46	21.1	0
7.7	0.23	0.11	19.7	1.51
7.7	0.52	0.30	19.7	0.64
7.7	0.74	0.47	19.2	0
Control	0	0	3.4	0
1.7–2.7	0.52	0.29	2.6	0
1.7–2.7	0.77	0.48	2.6	0.6
	Surface cover (%)			
1.7–2.7	30		20.6	1.05
1.7–2.7	50		19.0	0

[a] R_m: rock fragment content by mass.
[b] R_v rock fragment content by volume at the beginning of the experiment.
[c] Volume calculated based on the difference between the mean height of the first four transects and the fifth one.

2.4. Calculations

In order to obtain a range of rock fragment contents by volume (R_v: 0–0.15–0.30–0.50 $m^3\ m^{-3}$), the masses of fine earth and rock fragments of the simulated soil were calculated by means of Eqs. (1–5), using pre-estimated fine earth bulk densities:

$$\gamma_t = R_v \rho_r + (1 - R_v)\gamma_{fe} \qquad (1)$$

$$R_m = \frac{R_v \rho_r}{\gamma_t} \qquad (2)$$

$$m_r = R_v \rho_r V_t \qquad (3)$$

$$R_m = \frac{m_r}{m_t} \qquad (4)$$

$$m_t = m_f + m_r \qquad (5)$$

where γ_t and γ_{fe} are the total and fine earth bulk density respectively ($kg\ m^{-3}$), R_v is rock fragment content by volume ($m^3\ m^{-3}$), R_m is rock fragment content

Table 2
Characteristics of the fine earth and the rock fragments
a. Fine earth

Particle size distribution	
Sand (g per 100 g)	2
Silt (g per 100 g)	81
Clay (g per 100 g)	17
Organic matter (g per 100 g)	1.3
$CaCO_3$ (g per 100 g)	0
Field bulk density ($kg\ m^{-3}$)	1380

Dry aggregate size distribution (g per 100 g)

	>31.5	31.5–22.3	22.3–11.2	11.2–5.6	5.6–2	<2 mm
Mean	10	10	20	21	23	14
Std ($n=32$)	2	3	3	2	3	3

b. Rock fragments

1.7–2.7 cm (medium to coarse gravels)		
Size (cm)	1.7–2.7	(sieved)
Density ($kg\ m^{-3}$)	2560	std: 45 ($n=5$)

7.7 cm (cobbles)

	Length of the axes (cm)		
	*d*1	*d*2	*d*3
Size (cm)			
mean	10.8	7.7	4.4
std ($n=32$)	1.2	1.3	1.0
Density ($kg\ m^{-3}$)	2700		std: 88 ($n=5$)

std, standard deviation.

by mass ($kg\ kg^{-1}$), ρ_r is rock fragment density ($kg\ m^{-3}$), V_t is total sample volume (m^3) m_t, m_r and m_f are total mass, mass of rock fragments and mass of fine earth, respectively (kg).

According to Allmaras et al. (1967), the mean of the measured surface elevations can be used to calculate the volume of the sample before the experiment and after each shower (V_t). The bulk density of the fine earth fraction (γ_{fe}) can then be calculated rearranging Eq. (1) as follows:

$$\gamma_{fe} = \frac{m_f}{V_t - \left(\frac{m_r}{\rho_r}\right)} \tag{6}$$

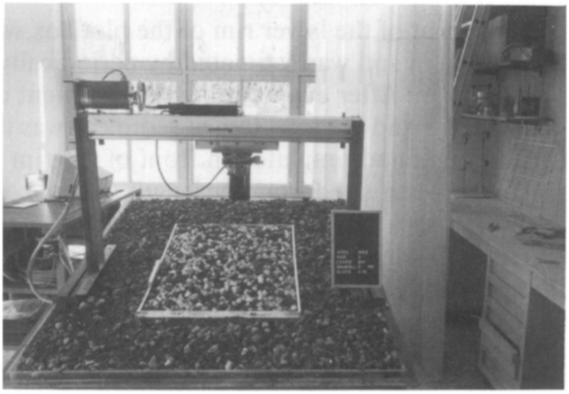


Fig. 2. Experimental set-up showing the laser microrelief meter and the plot box. Width of the central test area equals 60 cm.

The rock fragment content by volume (R_v) also changes during the experiments and can be calculated with Eq. (3).

The porosity (P: m^3 m^{-3}) of soils containing rock fragments was calculated from the density of the solid phase (d_s; kg m^{-3}) with the fine earth content by mass (F_m; kg kg^{-1}), organic matter content by mass (O_m; kg kg^{-1}) and rock fragment content by mass (R_m; kg kg^{-1}) as well as their respective densities, ρ_f: 2650 kg m^{-3}, ρ_o: 1470 kg m^{-3}, and ρ_r (see Table 2) using Eqs. (7–8):

$$d_s = \frac{1}{\frac{F_m}{\rho_f} + \frac{O_m}{\rho_o} + \frac{R_m}{\rho_r}} \qquad (7)$$

$$P = \left(1 - \frac{\gamma_t}{d_s}\right) \qquad (8)$$

The macroporosity at the end of the experiments (192.5 mm cumulative rainfall) was estimated from the difference between the total porosity and the volumetric water content of the fine earth (θ; m^3 m^{-3}) after the plot box was allowed to drain for 1 h. This parameter was calculated from the gravimetric moisture content (w; kg kg^{-1}) of the fine earth and the density of water (ρ_w; 1000 kg m^{-3}) using Eq. (9).

$$\theta = \frac{w \times \gamma_{fe} \times (1 - R_v)}{\rho_w} \qquad (9)$$

2.5. Sources of error

There are two sources of error associated with the experimental set-up. The first is caused by loss of soil material by runoff or percolation, and the second is due to sedimentation in front of the lower rim of the plot box when the soil surface has subsided. The loss of soil was estimated by periodically taking samples of the runoff and percolation. After evaporation, the sediment concentration in these samples was calculated and the total loss of sediment was thus estimated.

The volume of the sediment accumulated in front of the rim (V; dm^3) at the end of each experiment was estimated from the length (l_d; cm) of the zone where deposition occurs and its thickness ($=0.15\times l_d$ at a slope angle of 15%). The length and the volume of the deposition zone were calculated from mean height of the first four transects (h_m; cm) and the fifth transect (h_5; cm) at a distance of 10 cm from the rim using Eqs. (10) and (11); (Fig. 1):

$$l_d = 10 + \frac{(h_5 - h_m)}{0.15} \tag{10}$$

$$V = \frac{l_d^2 \times 0.15 \times 60}{2 \times 1000} \tag{11}$$

3. Results and discussion

3.1. changes in γ_{fe} during rainfall

Both the total bulk densities (γ_t) and the bulk densities of the fine earth fractions (γ_{fe}) for the different experiments are listed in Table 3. In standard soil physical procedures the total bulk density is usually measured (Childs and Flint, 1990). However, for a better understanding of the behaviour of a soil during heavy rainstorms, the distribution of pores in the fine earth is far more important. This parameter is reflected by the bulk density of the fine earth. A low γ_{fe} means a high porosity, which improves infiltration, can reduce capillary rise and hence the subsequent loss of water by evaporation and facilitates rooting (Childs and Flint, 1990; Poesen and Lavee, 1994). In practice, γ_{fe} can be calculated from the γ_t and the rock fragment content by volume (R_v) with Eq. (1). This was illustrated by Childs and Flint (1990), who produced diagrams of γ_{fe} against R_v for different γ_t values.

The relationships between γ_{fe} and the cumulative rainfall for the different treatments are plotted in Fig. 3. Rock fragment content by mass (R_m) is given in these graphs because rock fragment content by volume (R_v) increases during the experiments due to subsidence of the fine earth. In these graphs cumulative rainfall was used rather than its kinetic energy, because the cause of the changes in bulk density is considered to be a combination of destruction of aggregates by falling raindrops and changing soil strength with changing water content as soil water moves through the tilled layer (Onstad et al., 1984; Gusli et al., 1994). For moist soils, γ_{fe} increases rapidly during the initial phase, after which it seems to approach a constant value. For dry soils, swelling and subsidence seem to interact

Table 3
Bulk density of the fine earth (γ_{fe}) and total bulk density (γ_t) during rainfall simulations where rock fragment content by mass (R_m), rock fragment size, rock fragment cover at the soil surface (R_c) and initial moisture content are variables

a. Bulk density (γ) of control soils

Rock fragment size	R_m ($kg\ kg^{-1}$)	Initial moisture (g per 100 g)	γ ($kg\ m^{-3}$) at cumulative rainfall (mm)				
			0	17.5	52.5	122.5	192.5
Control	0	20.0	1135	1366	1389	1407	1405
Control	0	19.4	1102	1238	1292	1366	1367
Control	0	18.7	1126	1298	1349	1367	1375
Mean	0	19.4	1121	1301	1344	1380	1382
Control	0	3.4	1150	1156	1180	1216	1243

b. Bulk density (γ) of soils with surface rock fragment cover only

Rock fragment size (cm)	R_c (%)	Initial moisture (g per 100 g)	γ ($kg\ m^{-3}$) at cumulative rainfall (mm)				
			0	17.5	52.5	122.5	192.5
1.7–2.7	30	20.6	1089	1237	1271	1325	1334
1.7–2.7	50	19	1105	1286	1306	1360	1379

c. Fine earth bulk density (γ_{fe})

Rock fragment size (cm)	R_m ($kg\ kg^{-1}$)	Initial moisture (g per 100 g)	γ_{fe} ($kg\ m^{-3}$) at cumulative rainfall (mm)				
			0	17.5	52.5	122.5	192.5
1.7–2.7	0.31	20	1105	1316	1364	1381	1392
1.7–2.7	0.52	20	989	1188	1246	1264	1266
1.7–2.7	0.52	19	945	1187	1221	1242	1247
1.7–2.7	0.77	21	652	790	794	799	803
7.7	0.23	19.7	1107	1274	1339	1350	1357
7.7	0.52	19.7	1081	1261	1300	1320	1328
7.7	0.74	19.2	854	945	968	978	986
1.7–2.7	0.51	2.6	974	998	1098	1138	1149
1.7–2.7	0.77	2.6	651	698	725	735	735

d. Total bulk density (γ_t)

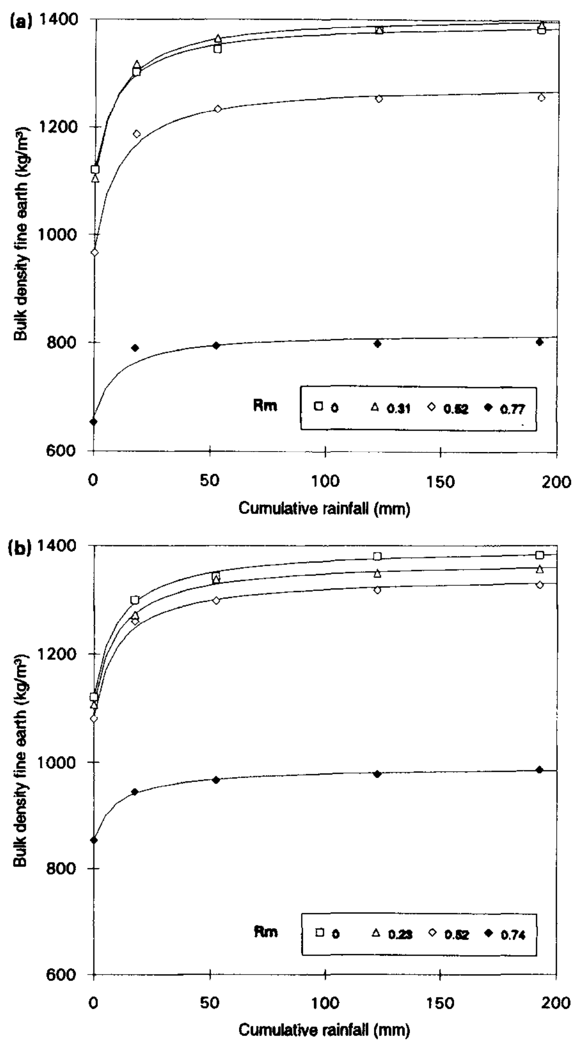
Rock fragment size (cm)	R_m ($kg\ kg^{-1}$)	Initial moisture (g per 100 g)	γ_t ($kg\ m^{-3}$) at cumulative rainfall (mm)				
			0	17.5	52.5	122.5	192.5
1.7–2.7	0.31	20	1329	1544	1595	1612	1622
1.7–2.7	0.52	20	1451	1646	1699	1714	1716
1.7–2.7	0.52	19	1404	1644	1675	1694	1698
1.7–2.7	0.77	21	1532	1691	1696	1701	1705
7.7	0.23	19.7	1277	1446	1511	1522	1528
7.7	0.52	19.7	1570	1743	1779	1797	1804
7.7	0.74	19.2	1726	1818	1840	1850	1857
1.7–2.7	0.51	2.6	1429	1454	1554	1593	1603
1.7–2.7	0.77	2.6	1526	1584	1615	1626	1626

during the initial phase (up to 17.5 mm rainfall), after which γ_{fe} increases (Fig. 3).

Onstad et al. (1984) proposed a model describing the evolution of bulk density due to water application to non-stoney soils. This model was applied to describe the relationship between bulk density of fine earth (γ_{fe}; kg m^{-3}) and cumulative rainfall (R_t; cm) using the initial fine earth bulk density $(\gamma_{fe})_0$ and a regression coefficient (β_b; kg m^{-3}) in Eq. (12):

$$\gamma_{fe} = (\gamma_{fe})_0 + \beta_b \left[\frac{R_t}{(1+R_t)} \right] \tag{12}$$

The results of the regression analyses for the different experiments show that



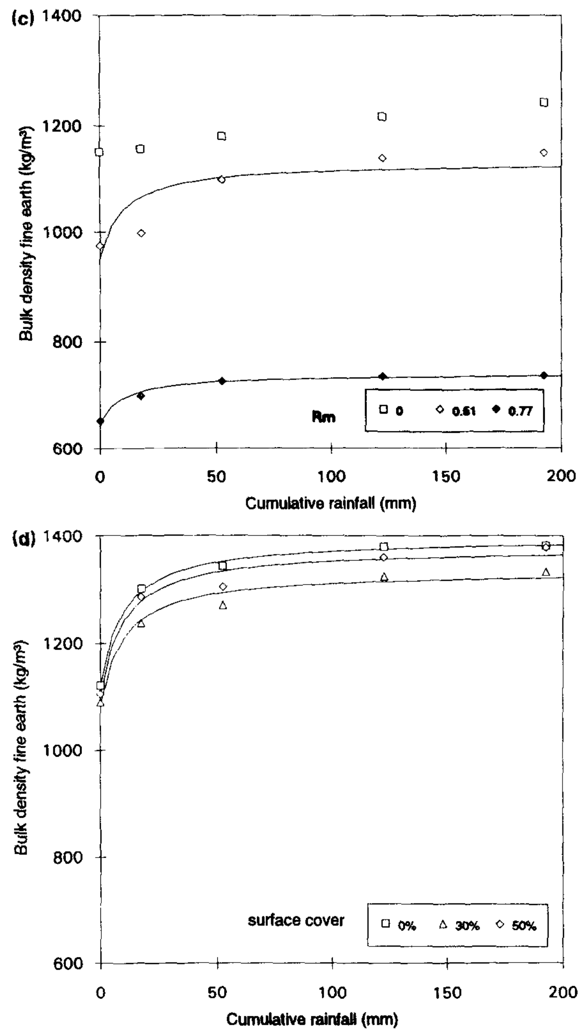


Fig. 3. Bulk density of the fine earth (γ_{fe}) as function of the cumulative rainfall applied for different rock fragment contents by mass (R_m; kg kg^{-1}). The regression lines were plotted using Eq. (12) and the parameters in Table 4. Four sets of experiments were performed using: (a) Small rock fragments (1.7–2.7 cm) in a moist soil (20 g per 100 g); (b) Large rock fragments (7.7 cm) in a moist soil (20 g per 100 g); (c) Small rock fragments (1.7–2.7 cm) in a dry soil (3 g per 100 g); (d) Small rock fragments (1.7–2.7 cm) only at the surface of a moist soil (20 g per 100 g).

the model of Onstad et al. (1984) is very suitable for moist soils (Table 4 and Fig. 3). For dry soils, in particular with low rock fragment contents, the initial swelling is not accounted for. The rate of subsidence, expressed by the regression coefficient (β_b), was greatly reduced when R_m was more than 0.7 kg kg^{-1} (Table 4). According to Eq. (12), the maximum γ_{fe} can be estimated from the $(\gamma_{fe})_0$ and β_b. A comparison of the γ_{fe} (Table 3) and $(\gamma_{fe})_{final}$ (Table 4) indicates that after 192.5 mm rainfall virtually no further change in bulk density (maximum 2%)

Table 4
Regression analyses of fine earth bulk density (γ_{fe}) against cumulative rainfall (R_t; cm) using the initial bulk density, $(\gamma_{fe})_0$ and a regression coefficient (β_b) for different rock fragment contents by mass (R_m) (Eq. 12; Onstad et al., 1984)

Run[a]	R_m (kg kg^{-1})	β_b (kg m^{-3})	$(\gamma_{fe})_0$ (kg m^{-3})	r^2	$(\gamma_{fe})_{final}$[b] (kg m^{-3})
SM	0	274.2	1122	0.99	1396
SM	0.31	301	1110	0.99	1411
SM	0.52	307.7	973	0.99	1281
SM	0.77	159.3	661	0.94	820
LM	0.23	265.3	1107	0.99	1373
LM	0.52	258.6	1085	0.99	1343
LM	0.74	136.2	855	0.99	991
SD	0	76.2	1138	0.57[c]	1214
SD	0.51	178.1	952	0.76[d]	1130
SD	0.77	89.4	649	0.98	738
	Surface cover (%)				
SU	30	248.6	1085	0.98	1333
SU	50	272.5	1105	0.98	1377

[a]SM, small rock fragments in moist soil; LM, large rock fragments in moist soil; SD, small rock fragments in dry soil; SU, surface rock fragment cover.
[b]Final fine earth bulk density.
[c]Not significant.
[d]Significant at $P<0.1$

will occur. The behaviour of dry soils containing rock fragments deserves some more attention (Fig. 3c). In the initial phase (up to about 17.5 mm rainfall) swelling is an important feature which is most prominent in dry soils without rock fragments because of the large proportion of fine earth. After this stage, the trend for dry soils is comparable with that of moist soils, although swelling in the initial stage makes it difficult to calculate reliable regressions (Table 4 and Fig. 3c).

During the experiments the surface is washed by the simulated rainfall, increasing the rock fragment cover (Fig. 4). In the initial phase, soil is washed mainly vertically into the top layer, while during the final stage of the experiment some erosion as well as deposition within the plot box occur (Tables 1 and 5). It should be noted that sediment loss by erosion and deposition of sediment within the plot box were responsible for only at the most 3% of the weight loss and 1.5% of the change in volume.

3.2. *Effects of rock fragment content and size*

The effects of rock fragment content and size on subsidence rates can be estimated from the relation between the regression coefficient (β_b; Eq. 12) in the model of Onstad et al. (1984) and the rock fragment content by mass (R_m). For both soils with small and large rock fragments, the subsidence rate increases up

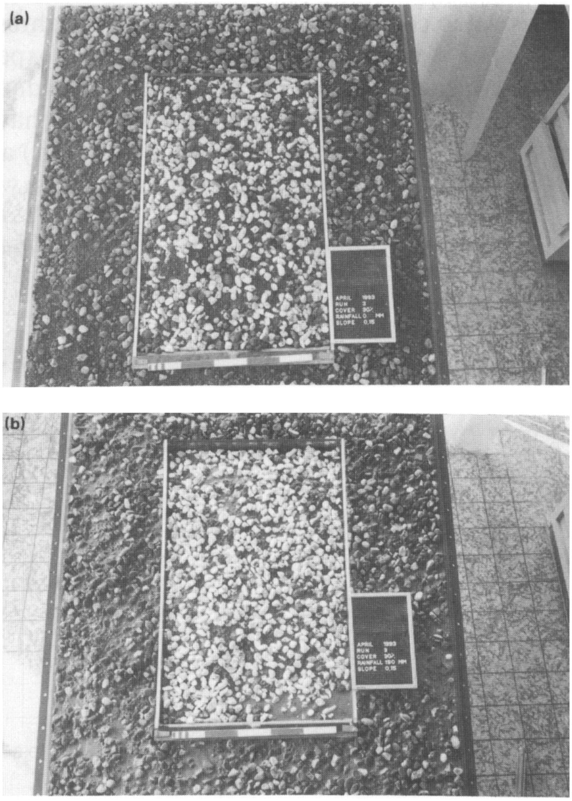


Fig. 4. Surface of a moist soil with 0.52 kg kg^{-1} rock fragments: (a) before the experiment; rock fragment cover 35%; and (b) after 190 mm of cumulative rainfall; rock fragment cover, 44%. Length of scale equals 50 cm.

Table 5
Total soil loss by runoff and percolation as well as moisture content after the experiments

Rock fragment size	R_m (kg kg^{-1})	Rainfall (mm)	Runoff (mm)	Percolation (mm)	Sediment (g)	Moisture (g per 100 g)
Control	0	205.3	139.8	6.8	555	24.7
1.7–2.7	0.52	190.3	0	136.4	399	27.4
7.7	0.74	197.3	0	155.0	354	27.2
Control	0	205.8	115.5	0	2726	28.8
1.7–2.7	0.51	193.8	105.5	0	1098	30.1
1.7–2.7	0.77	195.3	0	111.3	95	34.6

to R_m values of 0.52 kg kg^{-1}. For higher R_m values subsidence rates decrease (Table 4). According to Ravina and Magier (1984) the decrease in subsidence rates at high rock fragment contents can be explained by the formation of a skeleton of rock fragments which sustains the soil structure. Childs and Flint (1990) draw the limit between non-skeletal and skeletal soils at a rock fragment content of 0.35 m^3 m^{-3}. This value corresponds very well with the threshold rock fragment content of 0.50 kg kg^{-1} at which a skeleton forms in our experiments (Table 1). The increased effectiveness of small rock fragments in reducing soil subsidence reported by Saini and Grant (1980), who studied the behaviour of agricultural soils with small (0.64–1.27 cm), medium (1.27–2.54 cm) and large (2.54–3.81 cm) rock fragments during application of dynamic loads, was not found in our experiments.

The effects of rock fragment content and size on final bulk density can be ob-

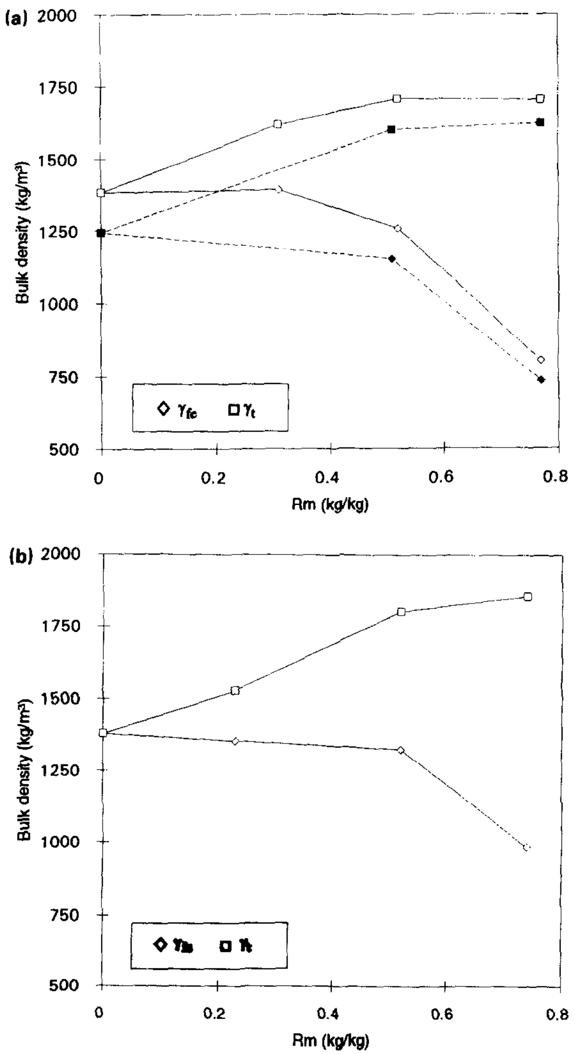


Fig. 5. Relationship between bulk density (γ_{fe} and γ_t) and rock fragment content by mass (R_m) after the application of 192.5 mm of rainfall for: (a) Small rock fragments (1.7–2.7 cm) in a moist soil (20 g per 100 g, open symbols) and in a dry soil (3 g per 100 g, closed symbols); (b) Large rock fragments (7.7 cm) in a moist soil (20 g per 100 g).

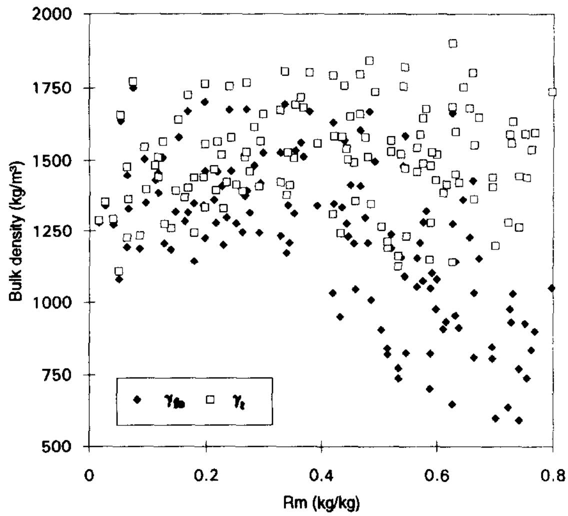


Fig. 6. Relationship between rock fragment content by mass (R_m) and bulk density (γ_{fe} and γ_t) for a brown cultivated soil with limestone fragments developed on a river terrace (Ebro basin, Spain). Data extracted from Alberto 1971. Figure reproduced with permission from Poesen and Lavee, 1994, Catena, 23:7.

served by plotting bulk densities after 192.5 mm of cumulative rainfall against rock fragment content (Fig. 5). As expected, total bulk density (γ_t) increases with increasing rock fragment content (Fig. 5). However, γ_{fe} is negatively influenced by rock fragment content beyond a critical value for R_m: 0.30 for small and 0.50 kg kg^{-1} for large rock fragments (Fig. 5). Furthermore, at comparable R_m values, γ_{fe} and γ_t are generally lower for soils containing small rock fragments.

The decrease of γ_{fe} with rock fragment content found during the final stage of our experiments is corroborated by the results from field studies both in cultivated fields (Fig. 6: Alberto, 1971 after Poesen and Lavee, 1994) and in non-cultivated, forest soils (Fig. 7; Van Wesemael and Veer, 1992). The scatter in the graphs from field measurements is very large (Figs. 6 and 7). This is inevitable since the results are obtained from rather large areas, where soil conditions are variable.

3.3. Effects of initial moisture content of the fine earth

The aggregate stability of dry soils is in general lower than that of moist soils (e.g. Cernuda et al., 1954; Haynes and Swift, 1990; Le Bissonais and Singer, 1992). The low aggregate stability might also influence subsidence of the plough layer, when rain falls on a dry, tilled soil, as is often the case in Mediterranean environments. From the experiments it can be concluded that low initial moisture content (2.6–3.4 g per 100 g) of the fine earth limits subsidence (Fig. 3c). This is attributed to swelling of the fine earth during the first 17.5 mm of rainfall (Table 3). Apart from the lower γ_{fe} and γ_t in dry soils, attributed to swelling of

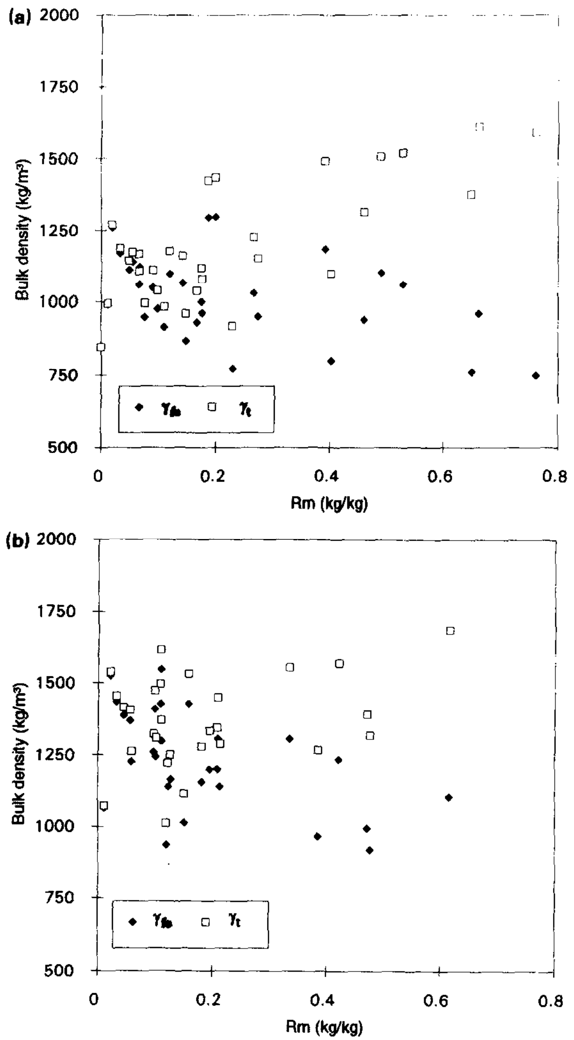


Fig. 7. Relationship between rock fragment content by mass (R_m), fine earth bulk density (γ_{fe}) and total bulk density (γ_t) in forest soils on phyllite (Tuscany, Italy). Data extracted from Van Wesemael and Veer (1992). Samples were taken at two depths: (a) 0–5 cm and (b) 10–15 cm.

the fine earth, the effects of rock fragment content are comparable with those in moist soils (Fig. 5a).

3.4. Effects of a surface rock fragment cover

Rock fragments at the soil surface, which dissipate the kinetic energy from falling raindrops, do not seem to have a significant influence on subsidence of the plough layer (Table 4). Therefore, it can be stated that the changing soil strength with changing water content, mentioned by Onstad et al. (1984) and Gusli et al. (1994), is the most important process in physical degradation of the plough layer.

It has to be noted that in this paper physical degradation of the entire plough layer is treated. A rock fragment surface cover does influence the degree of subsidence in the uppermost millimetres resulting in surface sealing and the formation of a thin, dense crust (Poesen and Ingelmo-Sanchez, 1992).

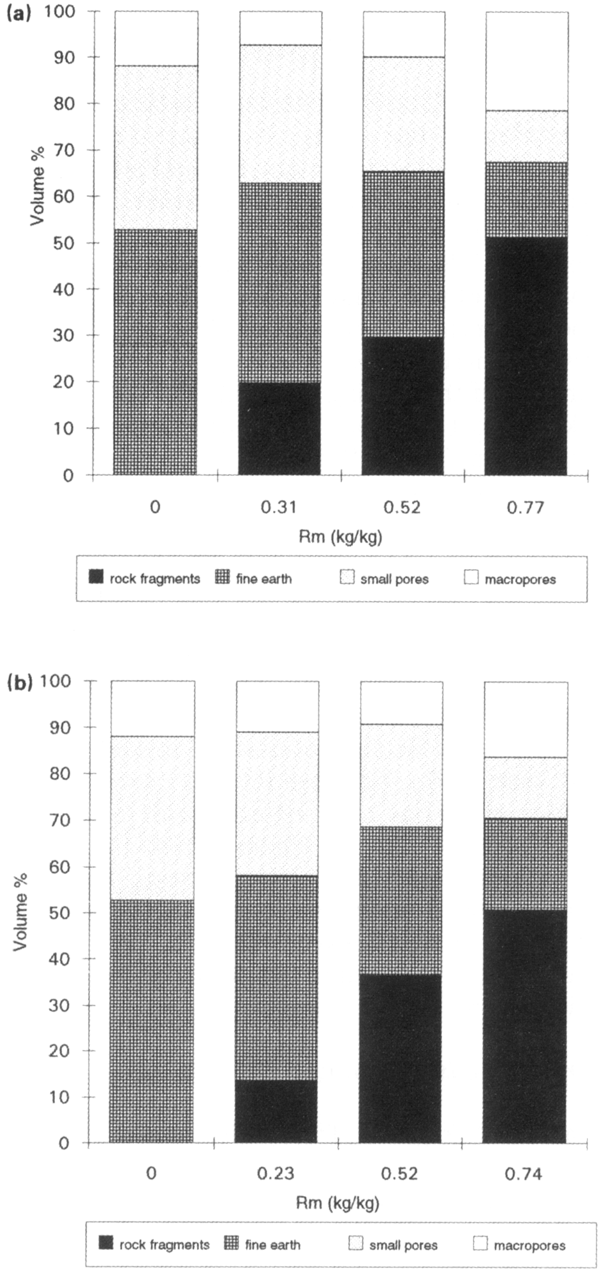
3.5. Physical characteristics of soils containing rock fragments

Fig. 8 depicts the distribution of the volumes occupied by rock fragments, fine earth and pores after the fine earth/rock fragment mixtures had received 192.5 mm of rainfall. Although the distinction between small pores and macropores is not based on soil moisture retention characteristics, it gives a practical indication of the capacity for rapid drainage after rainstorms. At low and medium rock fragment contents ($R_m < 0.50$ kg kg^{-1}), the total pore volume decreases and the ratio between the volume of pores and volume of fine earth increases with R_m (Fig. 8). At high rock fragment contents ($R_m > 0.50$ kg kg^{-1}), there is a strong increase in macropores with increasing R_m (Fig. 8). Both effects at low and high R_m cause deeper penetration of the wetting front into the soil with rock fragments compared to rock-fragment-free soils; reducing evaporation losses and enhancing ground water recharge. These effects are particularly important in dry climates, where wheat biomass production, for example, is directly related to amount of rainfall (Kosmas et al., 1993).

An additional effect of rock fragments is the concentration of inputs in the fine earth fraction (e.g. rainfall, organic matter and fertilizers; Childs and Flint, 1990; Poesen and Lavee, 1994). The more intense flow of water through the fine earth fraction in the soils with large amounts of rock fragments apparently does not have a negative effect on the stability of the soil structure. The effect of organic matter concentration on γ_{fe}, however, can clearly be seen in forest soils with slowly decomposing litter, as in the pine forest stand in southern Tuscany (Fig. 9; Van Wesemael and Veer, 1992). Although there is a considerable variation, the carbon concentration of the fine earth increases with increasing rock fragment content (Fig. 9). The data of Flint and Childs (1984) from 40 topsoils in southwest Oregon do not show a relationship between organic matter content and R_v. This can be explained by the differences in conditions which determine the accumulation of soil organic matter between the sites. The data from the site of Van Wesemael and Veer (1992) used in Fig. 9 can be considered to be quite homogeneous in this respect.

3.6. Management of soils containing rock fragments

The removal of rock fragments from agricultural soils, if economically feasible, is practised in order to facilitate tillage and to reduce damage of root crops (e.g. potatoes and sugar beets; Saini and Grant, 1980; Witney, 1984). From our experiments it can be concluded that large amounts of rock fragments have a positive effect on soil structure. In particular small rock fragments (1.7–2.7 cm) are responsible for maintaining low γ_{fe} and high macroporosity in topsoils (Figs. 5 and 8). Therefore, size reduction of rock fragments rather than removal seems to be a promising management technique. Chow et al. (1992), however, demonstrated that in practice there are some disadvantages in mechanical rock crushing. They concluded that care should be taken to avoid too severe crushing of



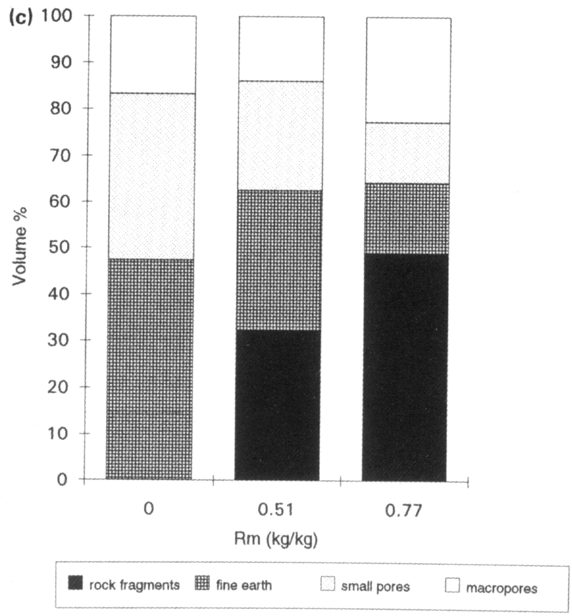


Fig. 8. Volumes occupied by rock fragments, fine earth, small pores and macropores as a function of rock fragment content by mass (R_m) after 192.5 mm of rainfall: (a) Small rock fragments (1.7–2.7 cm) in a moist soil (20 g per 100 g); (b) Large rock fragments (7.7 cm) in a moist soil (20 g per 100 g); (c) Small rock fragments (1.7–2.7 cm) in a dry soil (3 g per 100 g).

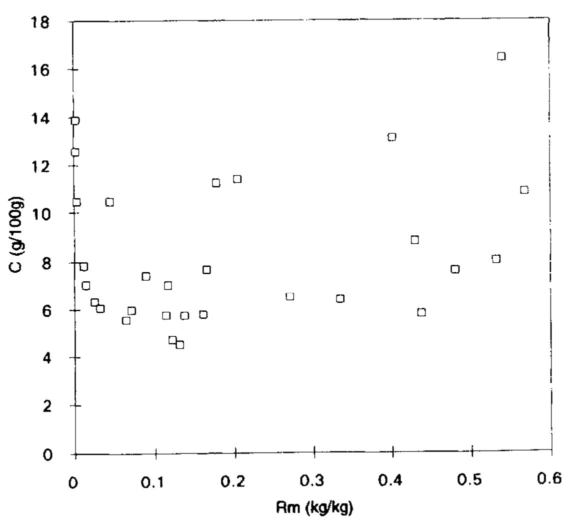


Fig. 9. Relationship between carbon content (C) in the fine earth and rock fragment content by mass (R_m) for the topsoil (0–5 cm) of a Mediterranean pine forest. Data extracted from Van Wesemael and Veer (1992).

rock fragments (2–3 mm) and to separate large soil aggregates from rock fragments before crushing.

4. Conclusions

Soil subsidence, expressed by the increase of bulk density of tilled soils, due to rainfall is rapid during the initial stage (up to 17.5 mm of cumulative rainfall) and after that becomes negligible (up to 192.5 mm cumulative rainfall). For soils containing rock fragments, the relation between bulk density of the fine earth and cumulative rainfall can be well represented by Eq. (12).

The distinction between skeletal soils (rock fragment content of more than 0.35 $m^3 m^{-3}$) and non-skeletal soils appears to be useful, since the influence of rock fragments on subsidence is visible only beyond a threshold rock fragment content. Rock fragments at the soil surface do not influence subsidence of the entire plough layer, which points to the dominance of water passing through the soil over transfer of kinetic energy by falling raindrops as the main mechanism of subsidence of the plough layer. The effect of rock fragments on final bulk density of the fine earth is strongest when rock fragments are small (1.7–2.7 cm) and dispersed throughout the soil profile.

The high macroporosity of soils containing more than 0.50 kg kg^{-1} rock fragments will enhance deeper penetration of rainfall into the soil compared with soils without rock fragments. In addition, the concentration of organic matter in the fine earth fraction has a beneficial effect on soil structure. Therefore, the removal of rock fragments from agricultural fields should be discouraged. If economically feasible, mechanical reduction of their size to 1.7–2.7 cm seems to be a good alternative.

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