Rock fragments control size and saturation of organic carbon pools in agricultural topsoil.

Rock fragments (RF) may severely reduce the amount of fine earth (FE) per soil volume. Here we quantified the effect of variable RF on spatial patterns of bulk soil organic carbon (SOC), particulate organic matter (POM) of three size classes, nonparticulate organic matter (nonPOM), and black carbon (BC). One hundred and twenty-nine soil samples (0–30 cm) were taken in a regular grid on an arable field nearby Selhausen (Germany). The weakly inclined site featured a strong gradient in RF, soil types covered Alfic Eutrochrepts, as well as Typic and Albaquic Hapludalfs. In addition to C-pool patterns and RF we determined texture, Fe oxides, soil moisture, as well as hillslope and elevation above sea level. Additionally, $^{137}$Cs measurements were conducted to indicate soil erosion. The reduction of SOC stocks by increasing amounts of RF on a percentage basis was smaller than attributable to mere dilution effects. Multiple regression analysis indicated BETA values of 0.65 to 0.73 between RF and FE contents of BC, nonPOM, and the finest POM fraction. The C contents of the coarse POM fractions were positively correlated with the amount of RF ($R^2 = 0.72–0.78$) and their spatial patterns were assumed to be caused by disproportionate input of plant litter to a reduced solum when the amount of RF increased. Statistical structure analysis and varigography pointed to hierarchical C saturation of nonPOM and the finest POM fraction, which was additionally regulated by Fe oxide contents. Only the spatial distribution of BC (BETA = −0.15) was affected by erosion.

**Abbreviations:** ASL, elevation above sea level; BC, black carbon; FE, fine earth; MDS, multidimensional scaling; MIRS, mid-infrared spectroscopy; PLSR, partial least squares regression; POM, particulate organic matter; RF, rock fragments; SOC, soil organic carbon; $\theta$, volumetric water content.

The pedosphere constitutes an essential compartment of atmospheric C exchange with the land surface. Evaluating the role of soils as either sink or source of atmospheric C, chemical and biological analyses are classically performed on fine soil, sieved to grain sizes <2 mm. However, many soils are rich in RF. For instance, Stendahl et al. (2009) reported that the average content of stones and boulders could be as high as 43.4% for forest soils all across Sweden. More than 60% of the Mediterranean land surface comprises major amounts of RF (Poesen and Lavee, 1994). Miller and Guthrie (1984) reported that soils with large amounts of RF comprise considerable parts of the agricultural land in the United States (~16%). Furthermore, they presume that this proportion will increase due to erosion and cultivation of marginal land. In fact, only a very limited number of soil-forming substrates are entirely free from RF. Ignoring highly variable RFs by interpreting results from sieved soil samples may thus lead to erroneous conclusions on soil C dynamics.

High amounts of RF may limit plant growth due to a reduced solum and an accelerated leaching of dissolved nutrients (Poesen and Lavee, 1994). However, in arable ecosystems, nutrient deficiencies are usually alleviated by organic and inorganic fertilization. Hence, the biological productivity of agricultural soils, and thus also the amount of added plant debris, may be less dependent on RF than the turnover...
of SOM when soil solum, and thus the supply of moisture and mineral surfaces is reduced at high amounts of RF.

Turnover models for SOC like the RothC-model are more and more initialized on the basis of measurable SOC pools: BC, POM, and humified organic matter (Skjemstad et al., 2004; Zimmermann et al., 2007). Varying chemical (Skjemstad et al., 1993; Brodowski et al., 2005a), physical (Christensen, 1996; Feller and Beare, 1997), physicochemical (Six et al., 2000), and isotope-based (Rethemeyer et al., 2007; Amelung et al., 2008) isolation procedures have been applied to calibrate and test SOM turnover models. Recently, advances in fast screening detection methods like mid-infrared spectroscopy coupled with partial least squares regression (MIRS-PLSR) also allowed quantifying these parameters in large quantities and at high spatial resolution (e.g., Zimmermann et al., 2007; Bornemann et al., 2008, 2010).

Soil clay minerals and pedogenic oxides have been identified as important parameters regulating the storage of SOC by mineral associations (Chenu and Plante, 2006; von Lützow et al., 2006; Wiseman and Puttman, 2006). Mineral associated SOC is thereby effectively sequestered and is characterized by slower turnover rates in soil C models compared to POM fractions (Balesdent et al., 1987; Skjemstad et al., 2004; von Lützow et al., 2007). Also the potential for SOC storage by micro-aggregation is significantly affected by clay and silt contents (Mayer et al., 2004), turning texture into key factor of C saturation concepts. Results of Köbl and Kögel-Knabner (2004) showed that even at field scale, the amount of SOC stored as occluded POM may reveal a significant spatial variability, depending on the spatial variation of the clay content. Results of Bornemann et al. (2010) confirmed that the amount of coarse POM in FE can be highly heterogeneous throughout a single agricultural site which was homogeneously managed but also contained variable amounts of RF. However, to our knowledge the relation between SOC pool sizes and the presence of RF has not been considered in detail, yet.

When artificially applying disproportionately high inputs of organic material, Gulde et al. (2008) and Stewart et al. (2007, 2008) found that the storage capacity of individual soils to sequester organic C was limited. In all three studies cited, the observed accumulation of organic matter was addressed to a systematic saturation hierarchy of increasingly stabilized SOC pools. In this respect, chemically and biochemically protected C pools have been observed to saturate after incorporation of high amounts of litter, and subsequent C accumulation then proceeded in the rather labile interaggregate-protected or even unprotected POM pools. However, one limitation of such studies is lacking comparability between results of the varying field trial stations as C dynamics are influenced by a range of factors as for instance climatic effects (Amelung et al., 1997; Lal, 2007), hydrology (Meersmans et al., 2008), parent material (Wagai et al., 2008), land use (Sousanna et al., 2004), management practice (von Lützow et al., 2002; Metay et al., 2009), and fertilization (Heitkamp et al., 2009, Séquaris et al., 2010). This problem could be solved by investigating a single field site with areas of highly different long-term C inputs to the fine earth.

In this study we investigate the effect of highly variable amounts of RF on the SOC dynamics in the topsoil of a homogeneously managed agricultural site. We hypothesize that the reduced solum at high amounts of RF induces saturation of mineral bound SOC like nonPOM and accumulation of weakly decomposed plant material like POM, while BC stocks are less affected.

**MATERIALS AND METHODS**

**Sampling Site**

The study was performed on a weakly inclined test site (<4° in east–west direction) of ~60 × 190 m (Fig. 1a), which has been under arable management for at least 100 yr. It is located close to Selhausen, Germany (50°52′09.34″ N; 6°27′00.58″ E) and is part of the Lower Rhine Embayment. The underlying sediments are fluvial deposits from the Rhine and Meuse River and the Rur River system, and were covered by aeolian sediments during the Pleistocene. Due to its genesis, the textural properties are highly variable throughout the test site. In the lower parts, the texture represents a slightly gravelly silt loam (<3% rock fragments). In the upper part, contents of sand and RF increase by ~20 and ~50% (gravimetric), respectively and the texture changes to a very gravelly loam (Soil Survey Staff., 1999). Long-term mean annual temperature and precipitation are 9.8°C and 694 mm (1961–2003). According to the digital elevation model as displayed in Fig. 1a, the investigated test site can roughly be divided into three geomorphological units, comprising two plain areas at the summit and the toe of a moderate inclination. Soil types cover two units and two subunits in WRB classification and were classified as Alfic Eutrochrept (Dystric Leptosol) in the upslope position, Typic Hapludalf (Orthic Luvisol) in the middleslope, and Albaquic Hapludalf (Stagnic Luvisols) in the downslope position (Soil Survey Staff., 1999; WRB, 2007).

The specific geomorphology and mixture of sediments of this particular site also causes the large heterogeneity of the solum. For the lower plane, the Aeolian substrate completely covers the underlying sediments from the rivers Rhine and Meuse, and only small gravel contents are mixed into the topsoil by solifluxion. Toward the summit, fluvial deposits with high contents of RF increasingly penetrate the Pleistocene loess layer. Here, also a gravel-stripe crosses the test site in northwestern direction. Hence, the varying content of RF as displayed in Fig. 1b roughly reproduces the geomorphologic properties. However, not only the coarse texture but also the texture of the FE is affected by this change of soil-forming substrate. The spatial pattern of the silt content (Fig. 1c) resembles the decreasing loess coverage and shows an almost reciprocal pattern to that observed for RF (Fig. 1b). Indicated by a strong negative correlation between sand and silt (R² = -0.93), the sand content distributes almost complementary to the silt content. Figure 1d reveals that the clay content covers a much smaller range, with a spatial pattern of low concentrations at the southeastern corner of the plot and high concentrations within the plane at the bottom of the slope.

Quintuple drilling cores were taken at the crosspoints of a 10 m grid (5 by 10 m at the northern border) at 0- to 30-cm depth (Fig. 1b). Soil organic carbon contents of samples F3 and F4 as well as the texture of sampling point E2 pointed to anthropogenic disturbance and the samples were thus removed from the data set. In the northeastern
corner sampling was precluded by a stabled portakabin where technical equipment for the experimental site is stored. Soil samples were packed in sealed plastic bags, and stored at $-18^\circ$C. For soil analysis samples were then dried at 60$^\circ$C and sieved to grain sizes <2 mm.

**Ground Truth Measurements**

**Texture**

Texture of the fine earth (<2 mm) was determined by a combination of wet sieving (sand fractions) and sedimentation (silt and clay fraction) after Köhn (ISO 11277, 2002). Additionally, about 0.015 m$^3$ soil of each sample was dry-sieved to determine the amount of RF (>2 mm). At two transects, five samples, which were also employed for $^{137}$Cs measurements, were additionally taken to determine bulk density. For this, cores of 25 cm diameter were drilled into the undisturbed soil to obtain samples of a given volume. After air drying, samples were sieved to 2 mm and density of the coarse texture, that is, the chert pebbles (>2 mm), and the density of the FE (<2 mm) were determined.

**Pedogenic Iron Oxides**

Contents of pedogenic Fe oxides were assessed by MIRS-PLSR. Generating a high dipole moment during vibration, a spectroscopic estimation of Fe oxides is highly promising for the mid-infrared range (Colthup et al., 1990; Janik et al., 1998). For calibration purposes we employed a sample set of 170 soils including 20 soil samples of the investigated test site at Selhausen. Amounts of Fe and Al oxides were
Soil Carbon Fractions

Bulk SOC, POM fractions, and BC were determined by a combination of lab analysis and MIRS-PLSR. Details of the employed sample sets and quality parameters of the calibrations are given in Bornemann et al. (2008, 2010). Lab analyses for the calibration samples were conducted as follows:

Total C and N content of the sieved and milled soils were determined by elemental analysis (ISO 10694, 1995). All samples were free of inorganic C as determined by gas-volumetric determination using hydrochloric acid. Physical POM fractionation was conducted by ultrasonic dispersion according to Amelung and Zech (1999). In brief, samples were gently sonicated (60 J mL–1) such that micro-aggregates were preserved from disruption. The coarse fraction (POM1: 2000–250 μm) was then separated by wet sieving, and the filtered remnant was sonicated a second time at 240 J mL–1. Intermediate (POM2: 250–53 μm) and fine (POM3: 53–20 μm) material was also gained by wet sieving and all fractions were dried at 40°C before elemental analysis. Sieving was supported by gentle agitating using small rubber paddles. Black carbon content was estimated using a molecular biomarker method (Brodowski et al., 2005b). In brief, about 500 mg of soil were digested using trifluoroacetic acid to remove metal cations and BC was oxidized to benzene carboxylic acids (BPCA) with nitric acid in a high pressure digestion unit. After cleanup using a cation-exchange resin, BPCAs were derivatized to trimethylsilyl derivatives and analyzed using gas chromatography with a flame ionization detector.

Volumetric Water Content

The volumetric water content (θ) was determined by time-domain reflectometry (Topp and Davis, 1985). As the RF on the test site consist of chert pebbles which are not capable to absorb significant amounts of water, we subtracted the volume occupied by the RF from the bulk soil volume to obtain the water content of the FE. The initial measurement was conducted at field capacity and compared with a repeat measurement after a dry period of 31 d (18 May–19 June). The difference between both measurements (δθ) was used to estimate patterns of varying soil moisture.
Spatial Distribution of Particulate Organic Matter and Nonparticulate Organic Matter

Constituting 71 to 81% of bulk SOC, nonPOM represented the quantitatively most relevant SOC fraction at this field site. The remaining 19 to 29% of total SOC were comprised by the POM fractions, with decreasing proportions in the order POM3 ≥ POM1 ≥ POM2 (calculated from Table 1). Investigating the potential of mid-infrared spectroscopy for the fast determination of SOC pools, Bornemann et al. (2010) revealed that bulk SOC, POM1, and POM2 exhibited a close spatial correlation on the investigated site, while POM3 showed a rather independent pattern. The spatial distribution of nonPOM and BC, as well as the effects of other soil properties on these patterns were, however, not investigated by Bornemann et al. (2010).

In light of the numerous parameters to be compared we computed a similarity matrix employing fuzzy-kappa statistics and visualized the determined similarities applying multidimensional scaling (MDS). As indicated by good to very good stress values (stress 1 = 0.065, stress 2 = 0.034; Kruskal, 1964), the similarity matrix was reproduced satisfactorily by the Euclidian distances of the first three dimensions of the MDS (Fig. 3). According to the first dimension, silt exhibited the highest positive values (~2.5), followed by clay (~1.5), and POM3 (0.7). All other parameters were collocated between values of 0 to ~0.6, where two distinct clusters were indicated by dimension two and three. Besides nonPOM, the first cluster comprised POM1, POM2, and SOC, whose close relation was already indicated by Bornemann et al. (2010). The MDS analysis thus indirectly supported their hypothesis of an independent distribution of nonPOM and BC, as well as the effects of other soil properties on these patterns to the patterns of the investigated SOC fractions.

Parameters that are deterministically dependent can be identified by an identical directional variability. The possibility to differentiate directional variability and stochastic heterogeneity is a prerequisite for the elucidation of any deterministic relation between C dynamics and regulating soil parameters. A classical method for the identification of spatial dependence is the semivariogram analysis (Cressie, 1993).

Due to distinct directional heterogeneity within the data set, all determined parameters were detrended by second order polynomial functions to meet the requirements of this geostatistical procedure. As summarized in Table 1, the FE contents of all SOC fractions except BC exhibit similar parameters that are collocated between values of 0 to ~0.6, where two distinct clusters were indicated by dimension two and three. Besides nonPOM, the first cluster comprised POM1, POM2, and SOC, whose close relation was already indicated by Bornemann et al. (2010). The MDS analysis thus indirectly supported their hypothesis of an independent distribution of nonPOM and BC, as well as the effects of other soil properties on these patterns to the patterns of the investigated SOC fractions.

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correlation lengths of ~30 m. Against the background of strong correlations between SOC, POM1, POM2, and nonPOM with RF (Spearman’s rank correlation coefficient: $\phi = 0.75–0.85$), the correlation length of ~60 m observed for the RF appears contradictory at a first glance. Anticipating that the varying amounts of RF resemble the main directional trend of the contents of the coarse POM fractions within the FE, the detrending procedure would largely eliminate this trend before the variogram is calculated. As a result, the spatial distribution of the detrended data of contents in FE and in bulk soil would be akin and matching correlation lengths could be anticipated. Indeed, the correlation lengths of the coarse POM fractions (POM1 and POM2) remained constant whether the variogram of the FE contents or the contents in bulk soil were computed (Table 1). As there are no mechanisms by which a high amount of RF could directly enhance the storage of coarse POM, indirect effects as for instance the reduction of the available solum has to be responsible for the observed phenomenon.

A close coherency between $\delta\theta$ and its driving forces, that is, the delimited solum, high sand contents of the fine texture, and the top-slope location (ASL) was already indicated by the MDS analysis (Fig. 3). A limited solum and reduced water holding capacity within the very gravelly topsoil likely also delimits microbial degradation, leading to the accumulation of weakly decomposed plant material. There are two indications that suggest $\delta\theta$ to codetermine the spatial distribution of the coarse POM beyond the dominating effect of the variable RF. First, the correlation lengths of the contents of coarse POM in bulk soil match the one of $\delta\theta$ (Table 1). Second, a positive relation is indicated between the content of RF and the C/N ratio of the bulk SOC ($R^2 = 0.53$), thereby documenting that SOC in the very gravelly areas of the test site is in deed enriched with weakly decomposed plant litter. Retarded decomposition and disproportionately high biomass input thus likely explain the enhanced contents of POM1 and POM2 in those areas of the test site that comprise large proportions of RF.

**Carbon Storage in Dependence of Potential Storage Capacity**

In contrast to the coarse POM fractions, the correlation lengths of bulk SOC, POM3, and nonPOM shifted considerably after their contents in FE were transformed by the amount of RF. The correlation lengths of these fractions (~50m) thus suggest other secondary control factors (apart from the RF) as indicated for POM1 and POM2. From literature, we know that the storage capacity of a particular SOC fraction is regulated by multiple protective mechanisms (von Lützow et al., 2006). Results of Wiseman and Puttmann (2006) suggest that the interaction of pedogenic Fe (Fe$_{DCB}$) and Al oxides and clay minerals play an important role for aggregation and stabilization of SOC in soils of temperate climates. According to Mayer et al. (2004), preservation of organic matter by micro-aggregation particularly includes abiotic networks of Fe and Al oxides. For our test site, the highest concentrations of Fe$_{DCB}$ in the FE were located at areas with high proportions of RFs. Nevertheless, elevated contents of Fe$_{DCB}$ also represented a random component in the spatial distribution (Fig. 1e). Indeed, the correlation length of Fe$_{DCB}$ actually matched that of nonPOM (Table 1). A stepwise multiple regression analysis proved the significant positive influence of Fe$_{DCB}$ on SOC beyond the effect of varying RF (Table 2). The SOC storage of the nonPOM, thus in part also resulted from higher Fe$_{DCB}$ contents.

**Table 2. Multiple linear regression models for the predictions of contents of black carbon (BC), nonparticulate organic matter (nonPOM), and particulate organic matter (POM3) in fine earth, from amount of rock fragments (RF), contents of dithionite soluble Fe oxides (Fe$_{DCB}$), sand, silt, and clay, bulk soil contents of the amount of rock fragments (RF), difference of volumetric soil moisture between two dates of measurement ($\delta\theta$), as well as hillslope (Slope) and elevation above sea level (ASL).**

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Independent variable</th>
<th>BETA†</th>
<th>multiple $R^2‡$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC, g kg$^{-1}$</td>
<td>RF</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe$_{DCB}$</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Slope</td>
<td>−0.15</td>
<td>0.79*</td>
</tr>
<tr>
<td>nonPOM, g kg$^{-1}$</td>
<td>RF</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe$_{DCB}$</td>
<td>0.15</td>
<td>0.68*</td>
</tr>
<tr>
<td>POM3, g kg$^{-1}$</td>
<td>RF</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe$_{DCB}$</td>
<td>−0.43</td>
<td>0.20*</td>
</tr>
</tbody>
</table>

† Partial regression coefficients of the data if standardized to mean = 0 and stdv = 1.
‡ Coefficient of determination of the multiple regression analysis.
As already pointed out above, POM3 shows the smallest variability among the investigated POM fractions. Hence, the high CV of its content in bulk soil (Table 1) is not founded on the variability of its FE contents, but rather on the variability of the FE contents of the other SOC pools. Accordingly, no close relation to any of the control variables could be identified by statistical structure analysis (Fig. 3), and even the correlation coefficient to the highly variable RF did not exceed values of 0.34.

Akin correlation lengths (~50 m) suggest that the control mechanisms observed for the nonPOM also drive the spatial distribution of POM3. In contrast to the nonPOM fraction, the individual fractionation data revealed that the C content of the isolated POM3 fraction did not change despite changing fraction yield (data not shown). Apparently, the POM3 fraction does thus not only consist of very fine, degraded POM, but also of SOM attached to the surfaces of coarse silt (20–53 μm)—an assumption that is further backed by matching correlation lengths of POM3 and silt (Table 1).

**Indications for Hierarchical Saturation of Soil Organic Carbon Fractions**

The concept of hierarchical C pool saturation implies that pools of mineral associated C fractions (i.e., nonPOM) saturate first and additional input of organic material will increase the amount of SOC fractions of larger particle size as soon as the next smaller fraction converges to the point of saturation (Stewart et al., 2007, 2008; Gulde et al., 2008). In line with this concept, nonPOM should saturate first, then POM3, while other fractions may continue to accumulate to a certain degree. According to our findings, the nonPOM fraction is close to saturation and thus also the POM3 fraction may become increasingly saturated as the SOC inputs in the gravelly areas are subjected to a limited volume of FE. The MLR model for the prediction of POM3 from content of RF and Fe$_{DCB}$ revealed a negative correlation of Fe$_{DCB}$ to the residual of the correlation between RF and POM3 (BETA = −0.43; Table 2). This finding points to lower POM3 contents at areas where the storage capacity of the nonPOM fraction is enhanced by elevated Fe$_{DCB}$ contents. In terms of a hierarchical saturation concept this indicates a more efficient C uptake by the nonPOM fraction, taking away the pressure from the POM3 to storage of SOC.

The hypothesis of hierarchical structures concerning the relation between RF and the individual POM fractions is further backed by a systematic variation of the dependency between RF and SOC fraction (Fig. 4). Here, the strong positive relation of RF to POM1 successively decreases for POM2, and POM3. In
accordance with a proposed hierarchical saturation of individual SOC pools, this points to a steady state concentration of POM3 while additional organic material is either stored in the coarser POM2 and POM1 or, also in dependence of FeDCB, within the nonPOM fraction.

Intriguingly, much of the relative distribution of SOC among different particle-size pools can be explained with the concept of hierarchical saturation. The RF influences the SOC pools because saturation of the FE is reached more rapidly when the FE content is lower at high amounts of RF.

**Spatial Distribution of Black Carbon**

Processes of C saturation are naturally limited to C species that are formed in situ and depend on the specific environmental conditions of each particular soil. However, soils also contain BC even if they are located offsite from anthropogenic point sources and when vegetation burning is of minor concern as BC deposition also takes place by aerial immission. These immissions are considered to be rather homogeneous throughout larger areas (Brodowski et al., 2007). Comprising about 6% of the total SOC (calculated from Table 1), BC constitutes an essential SOC fraction on the investigated site. Its individual spatial distribution is already indicated by the correlation length of its FE contents, which differs from that of all other investigated SOC pools and amounted to approximately 50 m (Table 1).

With respect to the small size of the field plot and generally very slow turnover times of BC (Brodowski et al., 2007; Flessa et al., 2008), BC stocks were also expected to be distributed homogeneously across the whole test site. However, the highly variable contents of RF determined the amount of FE to which supposedly homogeneous deposited BC was incorporated (plow layer). Indeed, the variability of the BC contents in FE showed the strongest variability of all SOC fractions (CV = 0.23; Table 1). It was, however, also closely correlated to the amount of RF (ρ = 0.80; data not shown). When related to bulk soil, the CV of BC contents in bulk soil was lower (CV = 0.13). While the latter probably results from a homogeneous deposition and extensive biochemical recalcitrance, the content of RF was obviously not the sole deterministic parameter driving the spatial distribution of BC. Figure 1f shows that despite the lower CV, also the BC contents in bulk soil were not homogeneously distributed. They were low at the upper end of the slope where the site had also high slope gradients. Large BC contents in bulk soil were, in turn, detected at the toe of the slope. With respect to the hillside position (up to 4° slope gradient, Fig. 1a), these results suggest that BC from the upslope may have been horizontally transported to downslope positions by erosion. This coherency to erosion processes was also corroborated by corresponding correlation lengths for ASL and BC in bulk soil (Table 1).

To investigate a potential influence of erosive translocation on C-pool patterns, we applied γ-spectroscopy to identify $^{137}$Cs as an isotopic tracer. Corresponding to the related topography, similar patterns of $^{137}$Cs activity were observed for both investigated transects (B and F; Fig. 5). Lowest $^{137}$Cs activities were apparent at the uphill positions of the test site (B18, F17). The activity then increased significantly along the inclined intersections at intermediate positions (B16, F6) and decreased again toward the bottom of the slope (B2, F2). The $^{137}$Cs activities even varied along the microlief at the sampling points at the upper part of the slope (Fig. 5: B16, B18, F14, F17). Assuming a fairly homogeneous deposition of $^{137}$Cs with the fallout event of Tschernobyl, the observed $^{137}$Cs patterns thus clearly support the assumption that erosion impacted the spatial patterns of BC. Also Rumpel et al. (2006) concluded that a preferential erosion of BC is ”a crucial process determining its fate in terrestrial ecosystems”. They attributed the potential translocation of BC by water erosion to its small density. Irrigation experiments by Rumpel et al. (2009) revealed that 7 to 55% of burned harvest residues were subject to horizontal translocation by splash erosion, which is the first step toward water erosion. Translocation of BC was also observed as a result of downslope tillage by Zhang et al. (2008), who identified significant downslope transport of bulk soil by altered $^{137}$Cs signatures of summit and toe slope following repeated hoeing of an orthic Regosol. In our study multiple linear regression analysis also indicated a significant contribution of the hillslope to the observed spatial pattern of BC (Table 2).

Besides, particularly the coarse POM fractions may also be affected by erosive downslope transport. Yet, the rather short turnover times of POM1 and POM2 likely constrain the detection of spatial patterns originating from eroded POM.

**CONCLUSIONS**

Based on our investigations we conclude that SOC stocks do not vary proportionally to the FE content of the solum, because (i) high contents of RF can result in a disproportionately high biomass input to thus smaller volumes of FE material, thereby inducing processes of SOC saturation and accumulation (ii) atmospherically deposited, biochemically recalcitrant material like BC can be heterogeneously distributed in space. Variable amounts of RF thus need to be considered when investigating SOC dynamics of agricultural topsoil.

Fig. 5. Elevation above sea level of the transects B and F (see also Fig. 1a, 1b) and corresponding $^{137}$Cs activities at five points along the individual transects.
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REFERENCES


Soil Survey Staff. 1999. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. USDA, Washington, DC.


