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Long-term dynamics of buried organic carbon in colluvial soils

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BGD

10, 13719–13751, 2013

Long-term dynamics
of buried organic
carbon in colluvial
soils

Z. Wang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Abstract

Colluvial soils are enriched in soil organic carbon (SOC) in comparison to the soils of upslope areas due to the deposition and subsurface burial of SOC. It has been suggested that the burial of SOC has important implications for the global carbon cycle, but the long-term dynamics of buried SOC remains poorly constrained. We address this issue by determining the SOC burial efficiency (i.e., the fraction of originally deposited SOC that is preserved in colluvial deposits) of buried SOC as well as the SOC stability in colluvial soils. We quantify the turnover rate of deposited SOC by establishing sediment and SOC burial chronologies. The SOC stability is derived from soil incubation experiments and the $\delta^{13}\text{C}$ values of SOC. The C burial efficiency was found to decrease exponentially with time reaching a constant ratio of approximately 17%. This exponential decrease is attributed to the increasing recalcitrance of buried SOC with time and a less favourable environment for SOC decomposition with increasing depth. Buried SOC is found to be more stable and degraded in comparison to SOC sampled at the same depth at a stable site. This is due to preferential mineralization of the labile fraction of deposited SOC resulting in enrichment of more degraded and recalcitrant SOC in colluvial soils. In order to better understand the long-term effects of soil erosion for the global C cycle, the temporal variation of deposited SOC and its controlling factors need to be characterized and quantified.

1 Introduction

There are significant uncertainties associated with our understanding of the role of soil erosion in the global C cycle (e.g., Lal, 2003; Berhe et al., 2007; Van Oost et al., 2007). To a large extent, these uncertainties originate from the difficulties associated with quantifying the fate of the eroded SOC. The SOC mobilized by water erosion can be released into the atmosphere, re-deposited within the catchment or exported from the catchment. Various studies have been conducted to explore the fate of the SOC

BGD

10, 13719–13751, 2013

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



exported from the catchment: for instance, labile young organic matter delivered to river systems was found to be rapidly mineralized in the channel (e.g., Raymond and Bauer, 2001; Mayorga et al., 2005), while SOC reaching lakes and oceans has been shown to be well preserved over longer time scales (e.g., Galy et al., 2007; Rosen and Hammarlund, 2007).

Rather than reaching the fluvial system, where previously eroded SOC can be stored effectively in freshwater sediments, a substantial fraction of the sediment mobilized by soil erosion is re-deposited within the landscape in colluvial stores. For instance, the hillslope sediment delivery ratio, i.e. the ratio between the amount of sediment mobilized by erosion and exported to the fluvial system, for agricultural catchments in temperate climates are estimated to be between 20–50 % (Trimble, 1999; Rommens et al., 2005; Notebaert et al., 2011). This implies that 50–80 % of the eroded sediments are re-deposited on hillslopes and form colluvial soils. Also, Wang et al. (2010) found that 24–69 % of the eroded sediments were re-deposited in the same field over a period of 3 yr. Studies covering a wide range of environments have shown that depositional sites on hillslopes accumulate and protect SOC derived by soil erosion (e.g. Smith et al., 2005; Van Oost et al., 2005a; Zhang et al., 2006; Li et al., 2007; Ritchie et al., 2007; VandenBygaart et al., 2012).

Carbon burial in colluvial soils removes C from the actively cycling C pools in the surface layers to the subsoil where it continues to decompose, albeit at a slower rate. Although colluvial soils may therefore store more C than non-eroding soils, the rate at which the buried SOC cycles remains poorly quantified: on one hand, ¹³⁷Cs and C inventory measurements showed that a substantial part of the deposited C in the colluvial soils of first-order catchments is effectively protected at the time scale of 50 yr (Van Oost et al., 2007); on the other hand, studies covering millennial time scales showed that colluvial sediments on Belgian Loess Belt that were deposited several centuries to millennia ago, are typically depleted in SOC, relative to the source areas (e.g. Vancampenhout et al., 2008; Van Oost et al., 2012) indicating that the deposited C in colluvial soils is at least partially mineralized at the time scale of several centuries.

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

Further evidence is provided by studies that have addressed changes in the quality of buried SOC over time. Thomsen et al. (2008) investigated the characteristics of SOC buried for 3300 yr in a Bronze Age burial mound through nuclear magnetic resonance and soil incubation experiments. They observe that the buried soils had less C than soils at the surface, and that the quality of the buried SOC also changes with time; relative to the young surface soils, the older and buried soils are depleted in labile components and enriched in recalcitrant compositions. Berhe et al. (2008) investigated the replacement of eroded C and decomposition rates at depositional sites under natural grassland vegetation using measurements of net primary production, radiocarbon and soil incubation experiments. They find that SOC decomposition rate was 2 to 14 times slower in the depositional settings when compared to the eroding slopes and conclude that burial of C provided an effective C sequestration mechanism. However, the fate of the buried SOC in agricultural environments, where most of the human induced erosion and burial currently occurs (Doetterl et al., 2012), remains poorly quantified.

Thus, although data are available showing the potential of colluvial environments to store SOC over long (millennial) time scales precise information for deriving SOC burial efficiency is still lacking. In response to this shortfall, the main objective of this study is to quantify the timescales of SOC stabilization under aerobic depositional settings on arable agricultural land in environments where sediment deposition can precisely be dated. The study was carried out along chronostratigraphies of buried sediments in fine-textured colluvial soils of the Belgian Loess region. Using a combination of incubation experiments, isotopic measurements and a comparative analysis of depositional vs. stable profiles, we determine the stability and quality of the deposited C. Finally, we discuss C dynamics in relation to sediment burial, relevant controlling factors and the overall significance of colluvial C burial.

2 Materials and methods

2.1 Study area

The study area is located in central Belgium and has a temperate climate with a mean annual temperature of ca. 9.5 °C and an average annual precipitation of 750–800 mm (Verstraeten et al., 2006). The soils in this region are mainly loess-derived Luvisols with a high silt content (> 70 %) and relatively low clay (< 15 %) and sand (< 20 %) contents (Beuselinck et al., 2000). The study area has a rolling topography (with slopes up to 25 %), which causes a significant erosion problem (Govers, 1991; Govers et al., 1994). Today, the main crops are wheat, maize, sugar beet, potato, and chicory. The study area has a long history of agricultural land use: deciduous forests covered the catchment during the first half of the Holocene and the first agricultural crops appeared 4000–5000 yr ago. From the Roman period onwards, the human influence on the landscape became significant. Approximately 50 % of the study area was used for cropland agriculture since the Middle-Ages and agricultural use of the land remains widespread until today (Vanwalleghem et al., 2004, 2005).

2.2 Field and laboratory work

We selected three sites (Table 1) along a geomorphological gradient: (i) site A is an actively forming soil bank near a field boundary, which receives sediment from a small catchment (1.5 ha). Deposition at this site is mainly controlled by tillage erosion since the mechanization of agriculture in the 1950s. Recent deposition rates are therefore high and deposits are relatively young; (ii) site B is a colluvial profile located at the outlet of a dry valley draining 117 ha. Due to a low slope gradient, this site receives sediment that is mobilized by water erosion on the steeper slopes of the upstream area of the catchment. (iii) Site C has a similar setting than site B, i.e. it is located at the outlet of a dry valley of 103 ha, and the sediment chronology for this site is provided by Rommens et al. (2007). At these sites, soil cores covering the depth of colluvial

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

deposition were taken with a percussion coring device. In addition, upslope of each deposition location (referred to as colluvium positions), soil cores were taken at relatively flat areas at the drainage divide (referred to as reference positions). These reference profiles are assumed to represent stable conditions where little erosion and/or deposition takes place. Duplicate cores were collected at all positions for the measurements of SOC, total phosphorus (P), ^{137}Cs activity as well as optically stimulated luminescence (OSL) dating. At site A, additional 2 m soil cores were taken (i.e., one from the reference position and two from the colluvium positions) for soil incubation experiments.

2.2.1 Measurements of C content and C quality

After sampling, the soil cores were stored below 0°C for later laboratory processing. In the laboratory, the soil cores were sampled at an interval of 5 cm, and ground and passed through a 2 mm sieve after oven-drying below 60°C for further analysis of organic C and total P. For samples collected from site A, the organic carbon content and the $\delta^{13}\text{C}$ were measured with an ANCA 20-20 GSL mass spectrometer (Sercon Ltd., UK) after removal of inorganic carbon using the HCl-fumigation method proposed by Harris et al. (2001). For samples of site B and C, organic C and N were determined with a vario MAX CN Macro Elemental Analyzer (Elementar Analysensysteme GmbH, Germany). Comparison revealed that there was no difference between the C content measured by these two methods (Wang et al., 2013).

The soil cores for the incubation experiments were cut at an interval of 20 cm and soil was passed through an 8 mm sieve before air-drying. For the soil incubation experiment, two replicate samples were placed into incubation jars (1 L) which were tested to be air-tight and sprayed with de-ionized water to reach a water content of 27 %, i.e., field capacity. The jars were sealed with polystyrene stoppers and kept in a room with a constant temperature of 20°C . A 35 day pre-incubation was applied in order to avoid CO_2 pulses caused by soil sample preparation (i.e., sieving, drying and rewetting (Butterly et al., 2010)). The gases in the jars were collected to measure CO_2 concentration. When collecting the gas samples, the headspace gases were mixed by pulling and

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



pushing a 20 mL syringe 4–5 times to ensure that they were well mixed before sam-
pling. The gases were then injected into a 12 mL pre-vacuumized vial for measurement
of CO₂ concentration. After gas sampling, jars were opened and flushed with ambi-
ent air. Water loss during incubation was compensated by adding de-ionized water to
the samples until reaching a water content of 27 %. Three empty jars were taken as
controls and received the same treatments as the jars with soil samples. The CO₂ con-
centration was measured with an isotope ratio mass spectrometer (IRMS) with a cry-
ofocusing module (ANCA 2020, Sercon Ltd., UK). Difference in CO₂ concentrations
between samples and references were used to calculate the CO₂ produced during the
period of soil incubation.

2.2.2 Sediment chronology

The sediment chronology was established using four different methods: (i) *¹³⁷Cs method*: we used the fallout radionuclide ¹³⁷Cs to derive quantitative information on sedimentation rates for the period from 1954 until present (Longmore, 1982); (ii) *Total-P enrichment*: the enrichment in total P of colluvial deposits, relative to stable, non-aggrading sites, was used to quantify rates of deposition since 1910 when the P fertilizer was firstly applied (Hofman and Verloo, 1989); (iii) *OSL-dating*: optically stimulated luminescence (OSL) dating utilizes dosimetric properties of quartz and feldspar in sediments to determine the time of burial; and (iv) *AMS radiocarbon dating*: charcoals were selected from the cores for ¹⁴C dating as an supplementary to OSL dating. ¹³⁷Cs activity and total P was measured on samples from all three study sites, OSL dating was carried out at site B, and for site C, OSL and AMS radiocarbon ages from Rommens et al. (2007) were used.

(i) The majority of ¹³⁷Cs was introduced to the environment by atmospheric nuclear bomb testing in the 1950s. ¹³⁷Cs activity of parts of the samples was measured using a hyperpure lithium-drifted germanium detector coupled to a Nuclear Data 6700 multichannel g-ray spectrophotometer at the University of Exeter and an HPGe detector (Model No. GC2021) in a low-level configuration at K.U. Leuven. The maximum depth

of ^{137}Cs occurrence at depositional sites was calculated as average of the depths of the deepest sample with significant ^{137}Cs activity and the depth of the sample following below showing a ^{137}Cs activity of zero. Half the difference of these two depth values was taken as the range of error.

(ii) P fertilizer has been applied onto agricultural fields in the region since the beginning of the 20th century (Hofman and Verloo, 1989). P concentration can therefore be used to identify sediments of the past 100 yr (Steegen, 2001; Rommens et al., 2007). The method relies on the enrichment of P below the plough layer at depositional sites, relative to background P concentrations at reference sites where no significant erosion or deposition has occurred. The depth difference between the deepest layer enriched in P at a depositional site and that of the plough layer at the reference site gives the height of deposition since approximately 1910. Similar to ^{137}Cs , we took the average depth of the two neighbouring points where significant decrease occurs and took half of the difference of the two depths as the range of errors. Total P content of each sample was determined using the method of Walker and Adams (described by Olsen and Sommers, 1982, and modified by Takken and Verstraten, 1996). This method uses H_2SO_4 to extract phosphorus from ignited soil samples.

(ii) OSL dating has frequently been used to determine chronologies of hillslope deposits (e.g., Lang, 1994; Fuchs and Lang, 2009). Here we utilized a single-aliquot regenerative-dose protocol (Murray and Wintle, 2000) on fine-grained quartz (4–15 μm). Detailed procedures for sample preparation and measurement are given in Mauz et al. (2002).

(iv) ^{14}C dating of charcoals incorporated in colluvium provides a maximum age of colluvium deposition. This may be a close approximation of depositional age if charcoal production immediately precedes deposition but can represent a large overestimate if charcoal was reworked many times before arriving at the sampling location (Lang and Hönscheidt, 1999; Edwards and Whittington, 2001). Two ^{14}C dating results were adapted from Rommens et al. (2007): the radiocarbon age was calibrated using Oxcal

BGD

10, 13719–13751, 2013

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

v.3.10 (2005) (Bronk Ramsey, 2001) with the calibration curve based on atmospheric data from Reimer et al. (2004).

2.2.3 C burial efficiency

Colluvial soils are sites of deposition where, as a result of burial of former topsoil material, deep soils enriched in C develop (Quine and Van Oost, 2007). Colluvial soils therefore may be interpreted as chronostratigraphy in which young deposits are found at shallow depth and sediment age increases with depth (Van Oost et al., 2012). The efficiency of C burial can then be regarded as the fraction of deposited C that is preserved in the buried sediments. We estimated this fraction as the ratio between the SOC content of deposited sediments at the surface of depositional profiles, and the SOC content of buried sediments for a range of sediment ages:

$$CBE_z = \frac{C_z}{C_t}$$

where CBE_z denotes the C burial efficiency of sediments of a given age z , C_z denotes the C content of sediments with a given age z , and C_t denotes the C content at the surface of the depositional sites. Soils transported by water erosion are in the form of aggregates in the study area. Therefore the C selectivity by erosion is not significant and C content of deposited sediments is similar to that of the topsoil in upslope areas (Wang et al., 2010). Also, considering that the C content of the topsoil does not vary much spatially within a field and that soils are mixed homogeneously within the plough layer by tillage operation, it is reasonable to assume that the C content of topsoil at the depositional site is representative of that of the deposited sediment.

The estimation of C burial efficiency is associated with uncertainties that originate from: (i) the quantification of sediment age; and (ii) the estimation of the SOC content of the deposited sediment. Uncertainties associated with sediment ages for the 4 methods were derived from the depth sampling interval and analytical uncertainty of each age estimate, and we used the maximum range of the calculated ages, i.e., the oldest

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



and youngest possible ages to illustrate this. The SOC content of eroding soils (and hence also that of the deposited sediment) is expected to vary temporally: for example, previous studies found that the C storage in the cropland of Flanders or Belgium has experienced a decrease of 5–18% in the past decades (Sleutel et al., 2003; Lettens et al., 2005; Goidts and van Wesemael, 2007). Although it is not possible to reconstruct temporal changes in SOC content of surface soils for the last millennia, we assume that a variation of 25% with respect to the current values is a realistic range. Therefore, we considered 3 scenarios as listed in Table 2 to assess the uncertainties associated with our calculation of the C burial efficiency.

3 Results

3.1 Sedimentation chronology

The maximum depths at which ^{137}Cs occurs at depositional sites were 60.9 ± 6.3 cm, 55.5 ± 9.0 cm and 42.0 ± 4.5 cm for sites A, B and C, respectively (Fig. 1). Assuming that the tracer was homogeneously mixed in a plough layer of 25 cm, allows calculating total sediment accumulation rates. Since 1954, sediments have accumulated $35.9 \text{ cm} \pm 6.3$ cm, 30.5 ± 9.0 cm and 17.0 ± 4.5 cm at sites A, B and C respectively. This results in an average deposition rate for the last 5 decades of $6.2 \pm 1.1 \text{ mm yr}^{-1}$, $5.3 \pm 1.6 \text{ mm yr}^{-1}$ and $2.9 \pm 0.8 \text{ mm yr}^{-1}$ at sites A, B and C, respectively.

The thickness of the P enriched deposit was determined as 51.8 ± 6.1 cm, 25.0 ± 2.6 cm, and 35.0 ± 3.1 cm at sites A, B and C, respectively (Fig. 2), resulting in an average deposition rate over the last century of $5.2 \pm 0.6 \text{ mm yr}^{-1}$, $2.5 \pm 0.3 \text{ mm yr}^{-1}$ and $3.5 \pm 0.3 \text{ mm yr}^{-1}$ for site A, B and C, respectively. We do not place too much confidence on these values as identifying P decrease was not always straightforward.

The sediment chronology at the millennial scale was established using OSL and ^{14}C dating. Results for site B are listed in Table 3. Results for site C are taken from Rommens et al. (2007). Some OSL ages may represent overestimates due to insufficient

BGD

10, 13719–13751, 2013

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

light exposure of quartz grains before deposition. Ages that did not fall in stratigraphic order were excluded from chronology construction. For site B, the deposition rates for the last 3 millennia ranged from $0.6 \pm 2.6 \text{ mm yr}^{-1}$ while for site C, the deposition rates were between 0.7 and 1.6 mm yr^{-1} .

5 Combing the sediment deposition rates above, we obtained a sedimentation chronology at different time scales for the study sites (Fig. 4).

3.2 SOC quantity and quality

The depositional sites and the reference sites contained equivalent concentrations of SOC within the plough layer (top 25 cm), i.e., approximately 1% and no significant differences were found (Fig. 5, Table 5). In contrast, the SOC concentrations in the subsoil were significantly higher in the depositional profiles relative to the reference profiles, down to a depth of 1.25 m, 1.75 m and 1 m, for site A, B and C, respectively. The SOC stocks between 25 and 100 cm at the depositional sites were 2.63, 1.76 and 1.45 times of that at the stable sites for site A, B and C, respectively.

15 The results of the soil incubation experiments showed that in the plough layer (0–20 cm), there were no significant differences in the soil respiration rate between the depositional and reference sites ($p = 0.176$, Mann–Whitney U test, Fig. 6). Below the plough layer (20–200 cm) the soil respiration rate per unit of soil mass was not significantly different between the depositional and reference sites (Mann–Whitney U test, 20 $p = 0.209$, Fig. S1), however due to the fact that the subsoil C contents of the depositional sites were significantly higher than that of the reference sites (Fig. 5, Table 5), respiration rate per unit of C for the subsoil was significantly lower at the deposition sites compared to that of the reference sites ($p < 0.001$, Mann–Whitney U test). Due to the fact that the soil incubation experiment was conducted under optimal laboratory- 25 controlled conditions, the measured soil incubation rates should be considered as potential rates of mineralization. They should therefore be regarded as an indicator of the soil stability, i.e. it is an indicator how fast (or easily) the SOC can be decomposed.

BGD

10, 13719–13751, 2013

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

The $\delta^{13}\text{C}$ value can be taken as a proxy of the degree of SOC decomposition as $\delta^{13}\text{C}$ value increases with decomposition due to the kinetic fractionation, i.e. ^{12}C is preferentially mineralized due to its less atomic weight. Therefore, a high $\delta^{13}\text{C}$ value indicates a high degree of SOC decomposition and also a high degree of SOC recalcitrance (recalcitrance in this study is in term of how difficult for the SOC to decompose). Similarly to the incubation results, in the plough layer (0–25 cm) the $\delta^{13}\text{C}$ values did not show significant difference between the depositional sites and the reference site ($p = 0.10$, t test, Fig. 6), while in the subsoil (25–200 cm) the $\delta^{13}\text{C}$ values in the depositional sites were significantly higher than those in the reference site ($p = 0.00043$, t test).

4 Discussion

The observation that the sediment deposition rates for the past 50 yr, as derived from the ^{137}Cs tracer, were up to two times higher than those derived from the P profiles, which integrate the last 100 yr, is consistent with other studies. This recent increase in deposition rates can be attributed to the mechanization of agriculture since the 1950s, which was previously shown to significantly enhance rates of tillage erosion and deposition (Van Oost et al., 2005b).

The lack of significant differences in the C content between the depositional sites and the reference sites in the top soil layer (Fig. 5), is consistent with the observed similarity in C stability or quality between the depositional sites and the reference site at site A (Figs. 6 and 7). This is not unexpected: although topsoils are exposed to erosional perturbation, the C of the top soil (top 5 cm) cycles very fast and is mainly controlled by the input from the plant. As a result, the C content and C quality do not have a significant spatial variation within a field. The deposited sediments in the surface layer are exposed to the same environmental conditions (i.e., temperature, climate, management, plant inputs, soil aggregation, etc.) as the reference sites and the mineralogical characteristics are also very similar. Similar original C content and

quality, soil conditions and C cycling processes therefore explain the observed similar C content and quality in the plough layer between the depositional and reference sites.

With continuous addition of newly deposited sediments, a fraction of the plough layer at colluvial sites becomes buried under the plough layer where it is no longer mixed by tillage operations. Due to the fact that the C content of the plough layer was substantially higher than the C content of subsoils at reference sites (Fig. 5), the buried sediments under the plough layer are enriched in C when compared to the soils at the same depth at the reference sites. For a reference site experiencing no erosion or deposition, the C content at a given depth is the result of the dynamic balance between in situ C input and decomposition. Since the sites have been cultivated for several centuries, the C profiles at the reference sites can be regarded as an equilibrium condition for the environment of each study site. Our results clearly indicate that the buried sediments below the plough layer contain more C than the equilibrium amount (i.e., the C at the same depth of the reference sites). If it is accepted that the environmental conditions controlling C inputs and decomposition are the same for reference and depositional sites, the latter will lose C through post-depositional mineralization. This indicates that the depositional area loses extra SOC through mineralization in comparison to the stable site, and therefore is a local source with respect to the atmospheric CO₂ under the condition that the photosynthesis of plant is the same between the depositional and stable sites. The observation that the C content under the plough lower (25–100 cm) was significantly higher at the depositional sites than that at the reference sites (Table 5) indicates however, that the buried C was not yet completely mineralized.

The fresh C input from plants and roots is similar between the depositional sites and reference sites due to the same crop type, and similar meteorological conditions. However, the mineralization of deposited SOC will increase the fraction of recalcitrant SOC due to the fact that the labile fraction of deposited SOC is preferential mineralized. Therefore, the bulk SOC below the plough layer at the depositional sites was more recalcitrant and has a higher degree of decomposition as revealed by the results of soil incubation (Fig. 6) and stable isotopic compositions of SOC (Fig. 7) that the respiration

BGD

10, 13719–13751, 2013

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

rate per unit of C for subsoil is significantly lower at the depositional site and that $\delta^{13}\text{C}$ values of the subsoil at the depositional site were significantly higher than those in reference site. This is in line with the finding by Berhe et al. (2008) suggesting that the SOC decomposition rate of buried OC was smaller than that of C in eroding or stable profiles at similar depth. However, both SOC recalcitrance and $\delta^{13}\text{C}$ do not vary monotonously with depth and/or burial age. Rather, they appear to evolve to a new equilibrium value. We hypothesize that this is due to the fact that different SOC fractions react differently after burial. Light, labile fractions are decomposed relatively rapidly after which a set of recalcitrant, heavy fractions remain: as soon as the labile, light fraction has been mineralized, the overall quality and recalcitrance of the SOC does not change significantly anymore with further decomposition.

As discussed above, the buried sediments could not retain the amount of C as originally deposited as they contained imbalanced more C in comparison to the equilibrium C (as derived from that of reference sites at the same depth) that can be kept in the environment they stayed. However, a plot of sediment age vs. sediment C burial efficiency shows that the burial efficiency does not decrease linearly with time but instead, shows a clear exponential decrease until reaching to a constant of approximately 17% (Fig. 8). This can be attributed to two mechanisms: (i) the SOC in the buried sediment becomes more degraded and recalcitrant with increasing burial time and this results in a lower C decomposition; (ii) with time the sediments are buried deeper in the soil profile where the environmental factors controlling C decomposition (e.g., temperature, humidity and aeration) are less favourable. Although the results of the incubation experiments and isotopic characterisation provide direct evidence for mechanism 1, our estimates of burial efficiency reflect both mechanisms and we are unable to quantify their relative contribution.

Our study shows that the majority of the deposited SOC is mineralized at the time scale of centuries and that a fixed fraction (approximately 17%) of the deposited SOC is preserved over millennia. However, we should keep in mind that this value is most certainly not universal: the equilibrium C burial efficiency will also depend on the type of

crops grown, the climate and the soil type. Even within a specific agro-ecological setting the equilibrium C burial efficiency may be expected to vary with burial rate: when the sedimentation rate is high, the sediment will be buried into the depth with less time thereby spending less time in the shallower layer of the soil where the environment is favourable for SOC mineralization, which will results in a higher equilibrium C burial efficiency.

5 Conclusions

It is important to obtain a good idea on the fate of soil organic carbon (SOC) deposited within the landscape in order to understand the effect of soil erosion in global carbon cycling. This study acquires the sediment ages through sediment tracers such as ^{137}Cs and total P, and optical stimulated luminescence and radiocarbon dating. Our result shows that the C content and quality are similar in the plough layer between the depositional sites and the reference sites. However, below the plough layer the depositional sites contain significantly more SOC in comparison to the reference sites which is due to the residue of the deposited SOC. Also, under the plough layer the SOC is found to be more recalcitrant and more strongly decomposed in comparison to the reference sites, which is due to the preferential mineralization of the labile fraction of the deposited SOC. These discrepancies in both SOC quantity and quality reveal different SOC resources and cycling processes between the depositional and reference sites.

Our data show that the SOC associated with the deposited sediment decreases exponentially with time during the burial processes. This decreasing pattern of firstly rapid and continually becoming slower indicates that the role of soil erosion in global carbon cycling at the landscape scale may be temporally varying, with equilibrium being reached at the time scale of centuries. We attribute this exponential decrease to two causes: increasing recalcitrance of the buried SOC with time and the less favourable environment for SOC decomposition with increasing depth. Our data suggest an equilibrium C burial efficiency of approximately 17 % for our study sites. However, we should

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

keep in mind that this value will also depend on the type of crops grown, the climate, the soil type, and the burial rate (with larger burial rates resulting in higher equilibrium C burial efficiency). The results indicate that the fate of the deposited SOC might be mainly controlled by the depth where it is preserved and its own recalcitrance. Numerical modeling is necessary in order to clearly illustrate the SOC cycling processes within the colluvial soils as well as relevant factors controlling these processes.

Supplementary material related to this article is available online at <http://www.biogeosciences-discuss.net/10/13719/2013/bgd-10-13719-2013-supplement.zip>.

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Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

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Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



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Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



Table 1. Information on the study sites.

Site	Location	Slope (%)	Area (ha)	Land use
A	50°48′ N, 4°35′ E	< 15	1.5	Cropland
B	50°48′ N, 4°35′ E	< 20	117	Cropland
C	50°46′ N, 4°44′ E	< 28	103	Cropland

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10, 13719–13751, 2013

**Long-term dynamics
of buried organic
carbon in colluvial
soils**

Z. Wang et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)**Table 2.** Scenarios used in C burial efficiency estimation.

Scenarios	Sediment age	Temporal SOC variation
High	Oldest possible sediment age	Constant C content through time
Medium	Most likely sediment age	10 % decrease of C content than before
Low	Youngest possible sediment age	25 % decrease of C content than before

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Table 3. Sample code and depth, moisture content in % of dry wight, U, Th and K content, α -efficiency factor (a value), effective dose rate (D/dt), equivalent dose (D_e) and OSL ages.

sample	depth [cm]	moisture [%]	U [ppm]	Th [ppm]	K [%]	a value	D/dt [Gy kyr ⁻¹]	D_e [Gy]	OSL ag [kyr]
LV48	315.5	15 ± 5	4.00 ± 0.10	12.81 ± 0.24	1.63 ± 0.04	0.04	3.78 ± 0.21	11.30 ± 0.47	2.99 ± 0.21
LV48	265.5	15 ± 5	3.20 ± 0.08	10.45 ± 0.22	1.77 ± 0.04	0.04	3.49 ± 0.20	8.20 ± 0.29	2.35 ± 0.16
LV48	211	15 ± 5	3.32 ± 0.09	10.59 ± 0.23	1.98 ± 0.05	0.04	3.73 ± 0.23	7.69 ± 0.28	2.06 ± 0.15
LV48	137.5	15 ± 5	3.74 ± 0.09	12.65 ± 0.25	1.80 ± 0.04	0.04	3.86 ± 0.23	3.23 ± 0.18	0.84 ± 0.07
LV48	77.5	15 ± 5	3.10 ± 0.08	10.76 ± 0.24	1.98 ± 0.05	0.04	3.69 ± 0.22	3.25 ± 0.12	0.88 ± 0.06
LV48	37.5	15 ± 5	3.27 ± 0.08	10.12 ± 0.21	1.68 ± 0.04	0.04	3.42 ± 0.18	1.58 ± 0.09	0.46 ± 0.04

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

Table 4. Deposition rates derived from OSL and radiocarbon dating for different time periods.

Site	Phase	Deposition rate (mm yr ⁻¹)
B	980 BC–340 BC	0.78 ± 0.09
	340 BC–50 BC	1.87 ± 1.36
	50 BC–AD 1170	0.60 ± 0.16
	AD 1170–AD 1550	2.63 ± 1.18
	AD 1550–present	0.82 ± 0.10
C	600 BC–160 BC	0.80 ± 0.39
	160 BC–AD 320	0.73 ± 0.30
	AD 320–AD 1440	1.61 ± 0.17
	AD 1440–present	1.27 ± 0.09

Age information for site C is taken from Rommens et al. (2007).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

Table 5. Difference in C content (%) between the colluvium and reference positions for top- (0–25 cm) and subsoils (25–100 cm).

Site	Depth (cm)	Test	p
A	0–25	t test	0.15
	25–100	Mann–Whitney U test	< 0.001
B	0–25	t test	0.44
	25–100	Mann–Whitney U test	0.005
C	0–25	t test	0.90
	25–100	t test	0.012

Mann–Whitney U test was used if numbers were not normally distributed.

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

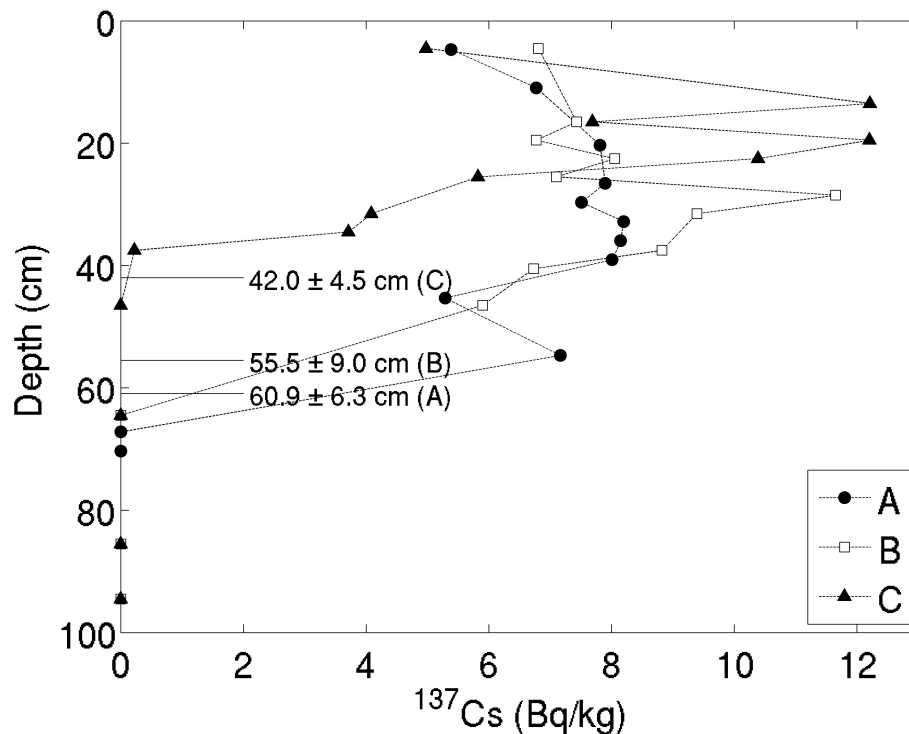


Fig. 1. ^{137}Cs activities at the depositional sites A, B, and C. The results of site A were obtained from the profile of Colluvium 1. The numbers indicate the estimated maximum depth of ^{137}Cs occurrence and half difference of the the depths of the deepest sample with significant ^{137}Cs activity and the depth of the sample following below showing a ^{137}Cs activity of zero.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

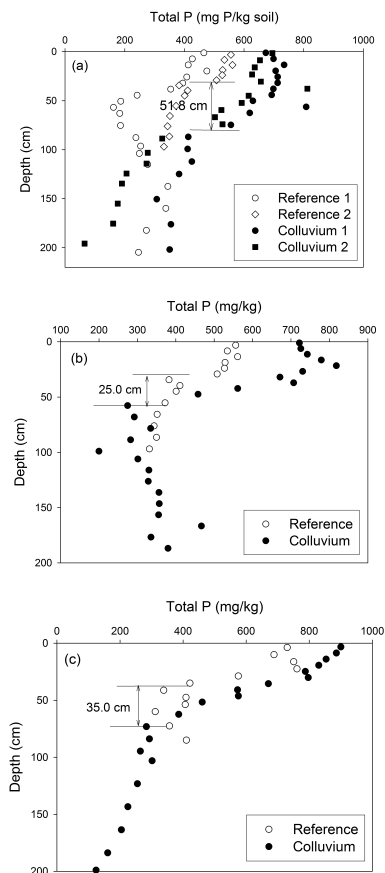


Fig. 2. P concentrations at depositional sites (filled symbols) and reference sites (open symbols) for sites A (a), B (b) and C (c). The double arrow indicates the depth difference between the original ploughing layer at depositional sites and at reference sites.

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

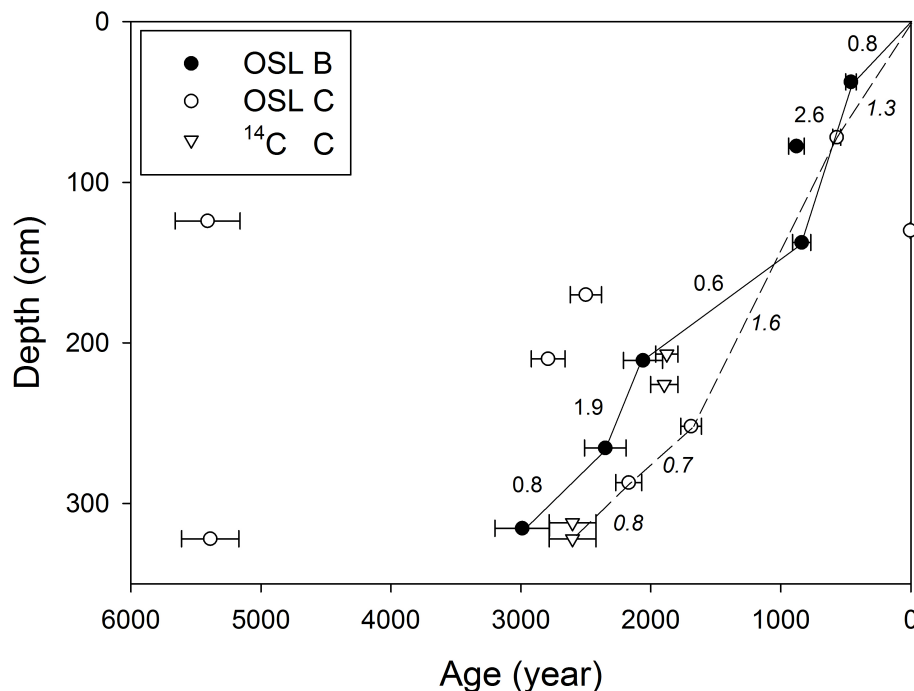


Fig. 3. OSL ages and calibrated radiocarbon ages vs. sampling depth for sites B and C. The numbers indicate the deposition rates (mm yr^{-1}) of the corresponding stages. Results of site C are taken from Rommens et al. (2007).

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

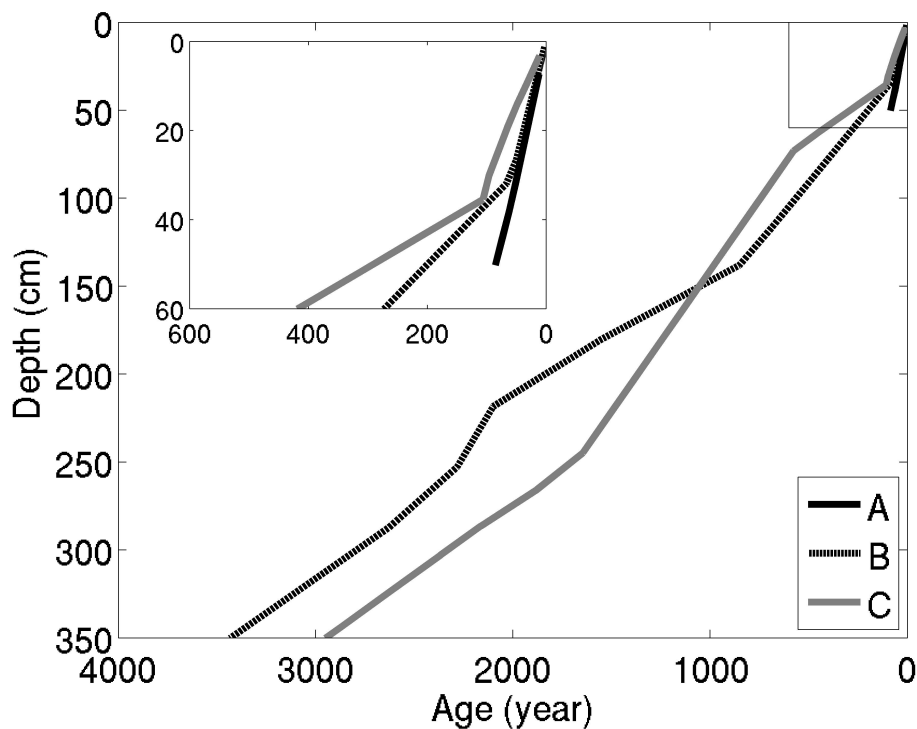


Fig. 4. Sedimentation chronologies for sites A, B, and C derived from ^{137}Cs , total P, OSL and radiocarbon dating.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Long-term dynamics
of buried organic
carbon in colluvial
soils

Z. Wang et al.

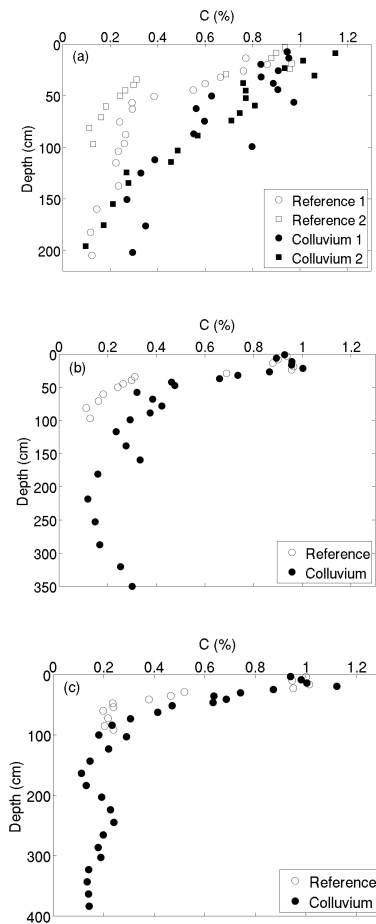


Fig. 5. C concentration at depositional sites (filled symbols) and reference sites (open symbols) for localities A (a), B (b) and C (c).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

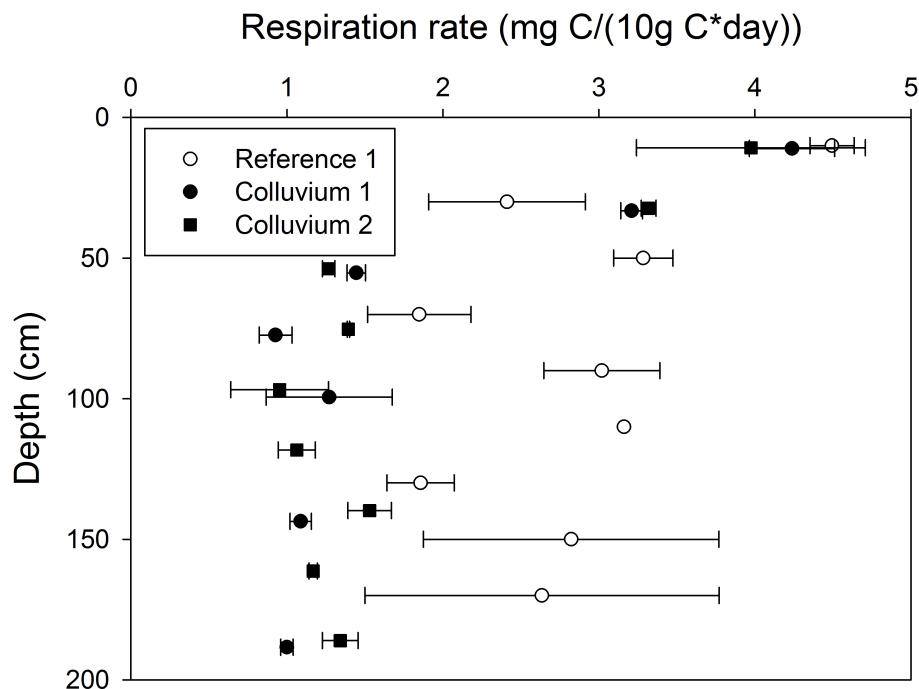


Fig. 6. Carbon respiration rates of profiles at depositional sites (filled symbols) and reference sites (open symbols) at site A during the whole incubation period. The error bar indicates the standard error of the measurements.

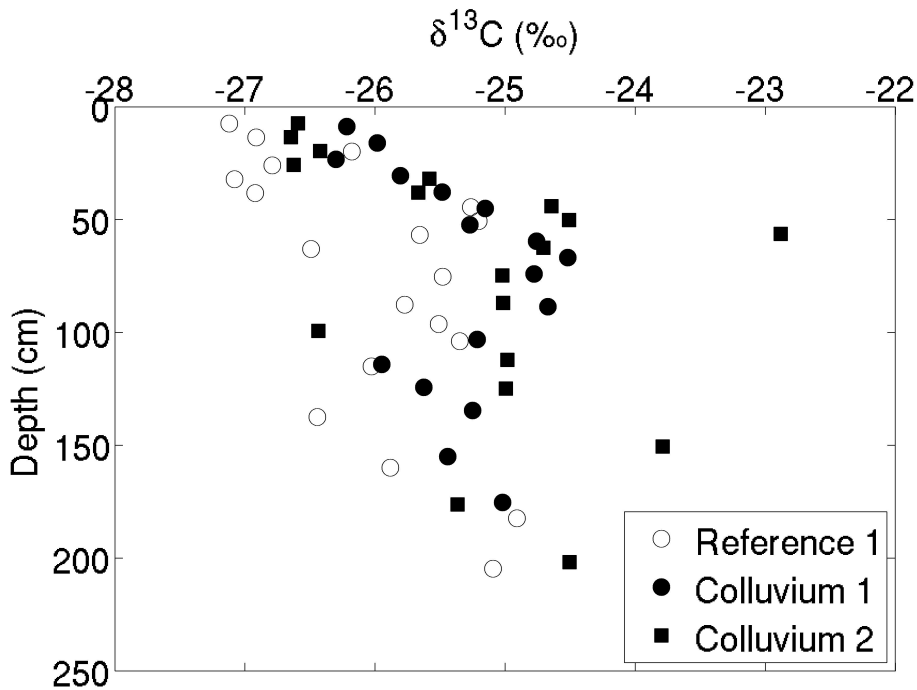


Fig. 7. Profiles of $\delta^{13}\text{C}$ at deposition sites (filled symbols) and reference sites (open symbols) at location A.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	

Long-term dynamics of buried organic carbon in colluvial soils

Z. Wang et al.

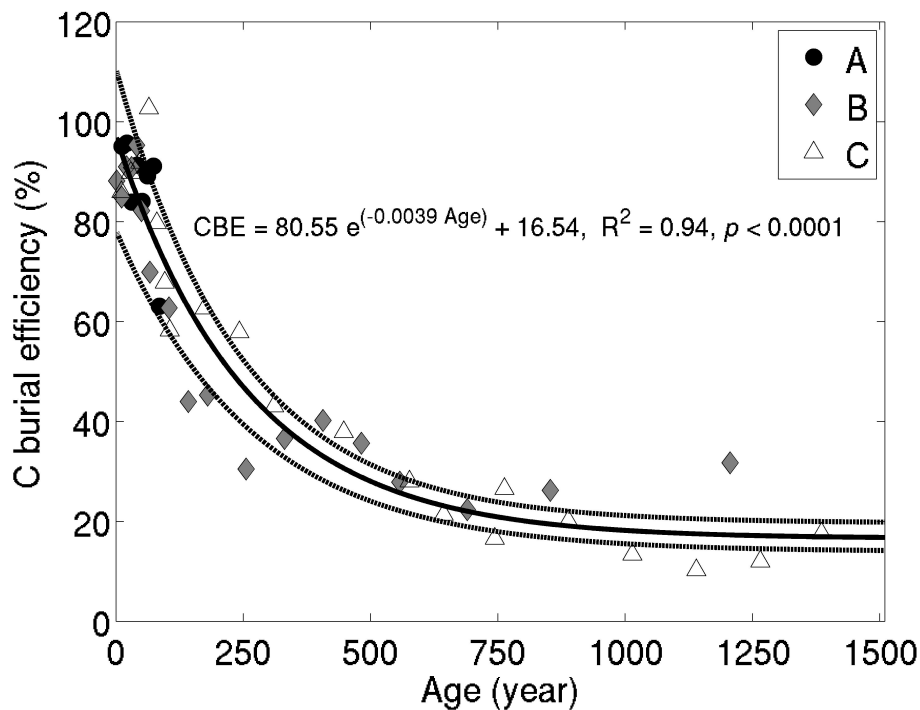


Fig. 8. Variation of C burial efficiency (CBE) with time for the study sites. The points denote the medium scenario. The solid line is fitted to the medium scenario while the dotted lines are used for the high and low scenarios.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion