Legacy of human-induced C erosion and burial on soil–atmosphere C exchange

Kristof Van Oost[a,1], Gert Verstraeten[b], Sebastian Doetterl[a], Bastiaan Notebaert[b], François Wiaux[a], Nils Broothaerts[b], and Johan Six[c,2]

[a]Georges Lemaître Centre for Earth and Climate Research, Earth and Life Institute, Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium; [b]Division of Geography, Department of Earth and Environmental Sciences, KU Leuven, B-3001 Heverlee, Belgium; and [c]Department of Plant Sciences, University of California, Davis, CA 95616

Edited by Susan E. Trumbore, Max Planck Institute for Biogeochemistry, Jena, Germany, and approved October 9, 2012 (received for review July 4, 2012)

Carbon exchange associated with accelerated erosion following land cover change is an important component of the global C cycle. In current assessments, however, this component is not accounted for. Here, we integrate the effects of accelerated C erosion across point, hillslope, and catchment scale for the 780-km^2 Dijle River catchment over the period 4000 B.C. to A.D. 2000 to demonstrate that accelerated erosion results in a net C sink. We found this long-term C sink to be equivalent to 43% of the eroded C and to have offset 39% (17–66%) of the C emissions due to anthropogenic land cover change since the advent of agriculture. Nevertheless, the erosion-induced C sink strength is limited by a significant loss of buried C in terrestrial depositional stores, which lagged the burial. The time lag between burial and subsequent loss at this study site implies that the C buried in eroded terrestrial deposits during the agricultural expansion of the last 150 y cannot be assumed to be inert to further destabilization, and indeed might become a significant C source. Our analysis exemplifies that accounting for the non–steady-state C dynamics in geomorphic active systems is pertinent to understanding both past and future anthropogenic global change.

soil erosion | soil organic carbon | geomorphic cascade | human impact | global carbon cycling

Carbon emissions resulting from anthropogenic land cover change (ALCC) have drastically altered the global C cycle (1). It is estimated that ALCC released 156 petagrams (Pg) of C to the atmosphere in the period 1850–2000, equivalent to 57% of fossil fuel emissions (2). More recently, longer-term analyses of ALCC have highlighted the importance of past changes (3), with estimates of preindustrial Holocene C emissions ranging between 50 and 357 Pg C (4, 5). Current global vegetation models are capable of representing the direct effect of ALCC on the exchange of C among the atmosphere, vegetation, and soils. This includes a reduction in vegetation and changes in soil C due to increased rates of decomposition (e.g., because of tillage) and overall lower C inputs to soils. In contrast, ALCC-caused C exchange associated with the exposure of soil and C due to accelerated erosion and burial is not accounted for. However, the transition from native vegetation to row crop agriculture and erosion are tightly coupled: accelerated erosion and deposition of soil are inevitable consequences of agriculture because of the removal of vegetative cover and increased exposure of the soil surface to erosion (6). A significant portion of the earth's surface has been converted to agricultural land use, and this has accelerated erosion 10- to 100-fold (7, 8). Although recent studies have increased our understanding of the short-term response of soil C cycling to this acceleration of erosion rates (9–11), the significance of this disturbance for past and future longer-term C budgets has not been quantified (12). It is well established that C stability increases, hence C decomposability decreases, with soil depth (13). Therefore, the erosion-induced accumulation of subsoil materials with stabilized C into the top layer, and the burial of topsoil C containing more labile C, will affect C turnover (14, 15).

Soil erosion and C emissions are intimately connected because the formation of organo-mineral complexes is crucial for organic C stabilization; C retained by association with mineral surfaces has relatively longer turnover times and accounts for a large portion of the total soil organic C (16). Furthermore, mineral surfaces may quickly reach their capacity to sequester C in the upper, and biologically active, layer of the earth's surface where C from plants, especially plant roots, mixes with mineral surfaces (16, 17). In contrast, many mineral surfaces in the deeper layers of the soil profile are undersaturated with C because little C input from plants occurs in these deeper layers. Hence, the deeper soil layers have a larger saturation deficit (17, 18). The process of erosion, however, advects particles through the soil column and provides mineral surfaces with a large saturation deficit from the deeper layers of the soil profile to the biologically active layer of the earth's surface (19). This implies that eroded soils have a larger saturation deficit and a greater potential for C uptake than their noneroding counterparts. Erosion therefore may act as a C sink mechanism (20). The quantification of the net effect of erosion-induced C fluxes also requires considering the burial of previously eroded and autochthonous organic C in low-mineralization environments (20) and the chemical and physical breakdown of soil and diminished primary production following soil degradation (21).

There is growing awareness that the erosion-induced C flux may be an important factor determining global and regional net terrestrial ecosystem C balances (22). To date, however, its significance for both past and present C budgets remains poorly quantified because of uncertainty about the contribution of biotic vs. erosion-induced C fluxes as a result of their intrinsically different space and time scales. Carbon erosion research in agroecosystems traditionally has focused on short-term processes, i.e., single events to a few decades (23, 24); therefore, longer-term observations of C and sediment dynamics are rare (25). Likewise, C cycling typically is studied at the profile scale whereas erosion processes operate over various spatial scales.

Soil and sedimentary records have been used to reconstruct past sediment fluxes, and sediment budgets spanning the entire period of agriculture recently were made for some catchments (26, 27). However, few studies have evaluated accelerated C erosion through the geomorphic cascade from source to sink at longer timescales. Nevertheless, the potential exists to reconstruct C cycling responses to erosion from signatures in soils and colluvial and alluvial sediment (28). Here, we examine the effect of ALCC

Author contributions: K.V.O. and G.V. designed research; K.V.O., G.V., S.D., B.N., F.W., and N.B. performed research; K.V.O., G.V., S.D., B.N., and J.S. analyzed data; and K.V.O., G.V., and J.S. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

[1]To whom correspondence should be addressed. E-mail: kristof.vanoost@uclouvain.be.

[2]Present address: Swiss Federal Institute of Technology Zürich, Department of Environmental Systems Science, Institute of Agricultural Sciences, Sustainable Agroecosystems Group, Universitätstrasse 2, 8092 Zürich, Switzerland.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1211162109/-/DCSupplemental.

on changes in terrestrial C storage for the period of agriculture (4000 B.C. to A.D. 2000) in the Dijle River catchment. We consider the direct effect of ALCC on C storage through the reductions in vegetation cover and soil C that accompany ALCC disturbance, but more importantly, we focus on the indirect effects through the exposure of soil C to accelerated erosion and burial. Hence, we present a long-term budget for sediment and C for this large coupled upland floodplain system by including erosion, transport, and burial processes. Including these processes allows us to fully account for (*i*) the history of sediment and C erosion since the start of agriculture, (*ii*) changes in organic C stabilization due to erosion and subsoil exposure in eroding uplands, and (*iii*) changes in C stabilization due to subsequent burial in colluvial and floodplain sediments in response to ALCC.

Results

Direct Effect of ALCC on C Storage. The Dijle is a 780-km^2 catchment located between 20 and 175 m above sea level in central Belgium (Fig. 1). It is homogenous with respect to soils, and loess-derived luvisols cover more than 90% of the catchment. Deciduous forests covered the catchment during the first half of the Holocene, and the first agricultural crops appeared between 4000 and 5000 BP (27). From the Roman period onward, the human influence on the landscape became significant (Fig. 2). Cropland agriculture peaked in the Middle Ages, and agricultural use of the land remains widespread until today. It is well documented that this transition from natural vegetation to agricultural use caused a significant release of CO_2 into the atmosphere from vegetation and soils (5). Using a bookkeeping model (*Materials and Methods*), we estimate that this transition from forest to cropland and grassland covering 72% of the Dijle catchment resulted in a total net release of 7.8 megatons (Mt) of C from a reduction in vegetation and 2.2 Mt C from soils. The C release from soils is through a reduction in C inputs and higher rates of decomposition. Most of the total net release occurred before A.D. 1300: for the period 4000 B.C. to A.D. 0, the estimated net release was 5.0 Mt C, with another 4.6 Mt C released in the early Middle Ages (i.e., A.D. 0–1300). However, this analysis considers only the direct effect of ALCC on C fluxes and does not account for accelerated rates of soil and C erosion upon ALCC.

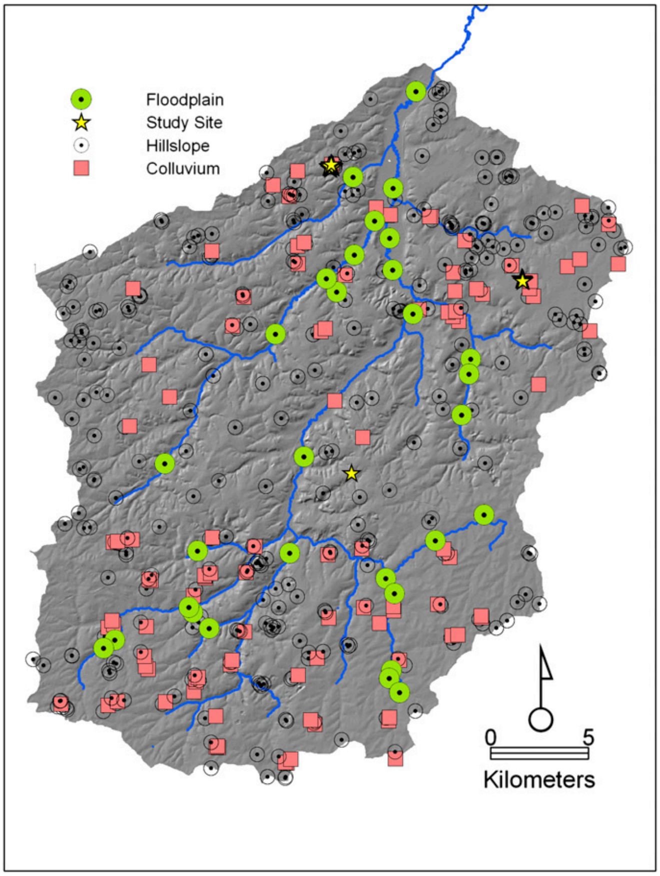

Fig. 1. Shaded relief map of the Dijle catchment, showing the fluvial network (blue line). The symbols indicate the location of the hillslope, colluvium, and floodplain C profiles and the location of the four study sites where toposequences were studied.

ALCC and Accelerated Erosion. The sediment budget for the Dijle catchment used in this study was compiled from published estimates (27). Because of the strong cohesion of the loamy soils that cover the Dijle catchment, water erosion is by far the dominant process and wind erosion is negligible (27). Age–depth curves were constructed for 15 sites in the Dijle catchment, and the uncertainties regarding the cumulative sediment mass for a given age are below 20% (Fig. 2). Hence, they may be used reliably to provide robust estimates of the mass of sediment eroded, deposited, and exported from the catchment associated with ALCC for the period 8000 B.C. to A.D. 2000. We found that most soil material has been mobilized over the past few thousand years, i.e., after the introduction of agriculture. The average preagricultural erosion rate is relatively low and equals 8 mm per thousand y (mm·ka^{-1}) when averaged over the entire catchment. After 4000 B.C., the average erosion rate increased 10-fold to 112 mm·ka^{-1} and equals 400 mm·ka^{-1} for the last 1,000 y. Massive input of eroded soil material following deforestation of the catchment changed the floodplain from a swampy environment to a meandering river with overbank deposits. More than half the total accelerated erosion took place during the past 1,000 y and almost two-thirds of colluvial deposits were formed in this period (Fig. 2). The median age of colluvial deposits is ~600 y. Floodplain sediments are older (~950 y) on average because only 55% of the floodplain sediments has been deposited during the past 1,000 y. Cumulative accelerated erosion amounted to 711 (±36) Mt in A.D. 2000, 46 (±10)% of which has been redeposited as colluvium on the slopes and another 35 (±10)% within the floodplain as alluvium. Only 19 (±6)% of the eroded sediments has been exported from the Dijle catchment.

Accelerated Erosion and C Dynamics. Accelerated erosion removes C from the topsoil and exposes C-depleted subsoil material. This reduces the C source term over time because there is less C to decompose at the eroded sites. Although erosion may reduce biomass production, plant production provides a continuous input of C into these C-depleted soils, which contributes to a net C uptake and an overall C sink at the scale of eroding uplands (20). For 25 soil profiles along four toposequences in the Dijle catchment (Fig. S1), we quantified the relationship between C removed by erosion and C replaced by plant production and stabilized into soils since the start of agriculture. We derived quantitative estimates of this relationship for a range of scenarios (*Materials and Methods*) using (*i*) observations of soil profile truncation as a measure of cumulative erosion since the start of agriculture and (*ii*) by establishing the difference between soil C inventories for a range of erosional perturbations and soil C inventories of reference sites experiencing similar land use change trajectories but no erosion or deposition (i.e., space-for-time substitution) (24). A Monte Carlo analysis suggests that this method provides robust estimates of the ratio between C removed by erosion and C replaced, with an average SD of 13% (*SI Text*). The current mean C stock for the top 1 m of eroded profiles that we examined was 5.15 (±0.89) kg C·m^{-2} (Table S1).

SUSTAINABILITY SCIENCE

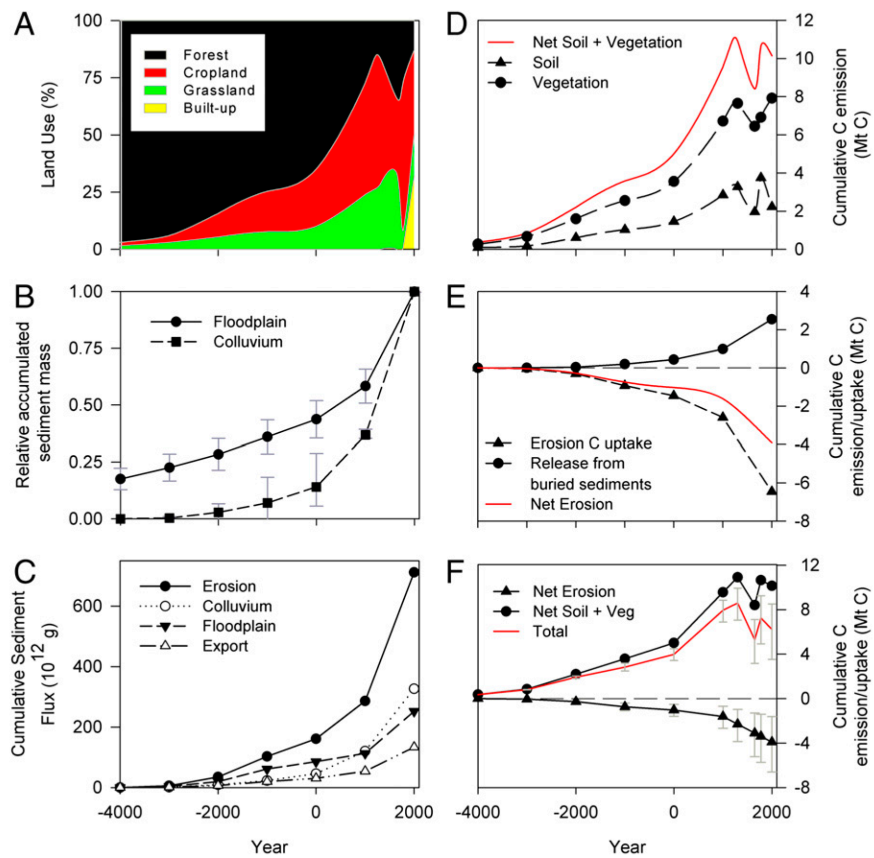

Fig. 2. (*A*) Evolution of land use in the Dijle catchment between 4000 B.C. (i.e., the start of agriculture) and A.D. 2000. (*B*) Age and average relative accumulated sediment for colluvial and floodplain sediment deposition. The line represents the average value and the error bars indicate the SD (for the 12 floodplain sites) or range (for the three colluvial sites). (*C*) Reconstructed sediment budget related to accelerated erosion including sediment mobilization on the hillslopes (erosion), deposition on slopes and in dry valleys (colluvium) and floodplains, and export from the Dijle catchment for the period of agriculture. (*D*) Estimated cumulative emission of C resulting from the direct effect of ALCC (Net Soil + Vegetation), i.e., the C release due to a reduction in vegetation (Vegetation) and soil C losses due to reduced C inputs and increased soil disturbance (Soil). (*E*) Estimated cumulative emission (positive values, to atmosphere) and uptake (negative values, to soils) resulting from the indirect effect of ALCC through accelerated erosion and burial of soil C. The combination of increased stabilization of C in the soils exposed at the surface of eroded hillslopes (Erosion C uptake) with the slower release from buried sediments in colluvium floodplain soils resulted in net erosion-induced C sink (Net Erosion). (*F*) Net release of C due to ALCC when both direct losses from soil and vegetation and erosion-induced C uptake are accounted for. The triangles indicate the best estimate of erosion-induced C uptake; the error bars indicate the uncertainty range and are derived from a low and high scenario (*SI Text*).

This is 15% lower than, but not significantly different ($P > 0.10$) from, the C inventories of noneroding profiles [6.05 (±0.65) kg $C{\cdot}m^{-2}$]. The cumulative C erosion since the start of agriculture is much greater than the current stocks and ranges between 10.4 and 44.5 kg $C{\cdot}m^{-2}$. This corresponds, on average, to 371% of the C originally present in the 0- to 100-cm profile. The eroded C and current stocks thus largely exceed the original C through both exposure of deeper soil C and continuous stabilization of C in the upper soil layers via new plant C inputs. The incorporation of subsoil C into the soil profile, which represents a nonatmospheric transport pathway that was explicitly accounted for in our calculations, plays a minor role. In contrast, we found that 71% (56–80%) of the eroded C was replaced via new plant C inputs. This confirms earlier studies, which found that erosion-induced subsoil exposure leads to C stabilization and acts as a sink for atmospheric CO_2 at the catchment scale (29). Despite a large variability in erosional forcing and the history of the eroding profiles we examined, the observed range of the ratio between C erosion and C replacement was very small (average relative SD of 12.3%). This small range indicates that C erosion is the dominant factor controlling C uptake. Hence, this ratio may be used in combination with estimates of C erosion to predict the temporal evolution of the erosion-induced C sink strength at sites of erosion in the Dijle catchment (see below).

Burial in Colluvial Profiles. Although erosion can thus promote an increased stabilization of C in former subsoil, the net effect of erosion ultimately depends on the preservation of the C that is moved laterally by erosion. The eroded C may be buried in colluvial or floodplain deposits or may be exported from the catchment through river export. Colluvial soils are sites of deposition where, as a result of the continuous burial of former topsoil material, deep soils enriched in C develop (9). Colluvial soils therefore may be interpreted as chronosequences in which young deposits are found at shallow depth and sediment age increases with depth. Carbon burial in colluvial soils removes C from the actively cycling C pools in the surface layers to the subsoil where fewer C inputs are available and where it continues to be exposed to microbial decomposition, albeit at a slower rate (29). In the four toposequences examined here, we found that the colluvial soils store significantly more C ($P < 0.001$) than noneroding soils. However, C concentrations decrease consistently with depth (Fig. S1). The %C–depth observations from the soil database (Fig. S2) provide a more representative sample of colluvial soils in the Dijle catchment and corroborate this observation. Using the age–depth relation for colluvial soils in the Dijle catchment and assuming a constant content of the initial deposited C, we found a strong effect of age on colluvial C retention, with young deposits having similar C contents as topsoils and a longer burial time accounting for a greater fraction of destabilized C. This age effect might be described by an exponential decay function (Fig. S3) whereby the catchment-averaged loss rate of buried C in colluvial soils is 0.2% per year. The validity of the loss rate estimation depends heavily on the reliability of the depth–age curve and the assumption that the deposited C has remained constant over time. The depth–age curve is poorly constrained particularly for the past 1,000 y, during which the C content of deposited soil may have changed in function of management and erosion status. We diagnosed the structural uncertainty in our estimate of burial efficiency by examining sensitivity to plausible scenarios for changes in erosion intensity and C content of deposited C (*SI Text*). This analysis shows that the overall result and interpretation are not strongly affected by these assumptions and that the loss rate is likely to be in the range of 0.1–0.3% per year. Possible mechanisms leading to destabilization of buried C are decomposition and leaching losses. The rates of C losses in colluvial soils obtained here are greater than the observed dissolved organic C export from the Dijle catchment (*SI Text*). This suggests that decomposition, and hence loss as CO_2, is the major pathway of C loss from colluvial soils.

The significant destabilization of C in colluvial soils found here, with a half-life of the buried C of ∼500 (350–730) y, does not support the findings of earlier studies reporting preservation efficiencies of 100% for buried C (11, 30). Buried C may be preserved efficiently at annual to decadal timescales, but our results indicate substantial losses of buried C at centennial to millennial timescales. This suggests that the net C uptake induced by subsoil exposure is offset, at least partially, by the loss of C buried in colluvial settings. Nonetheless, the thickest and oldest colluvial soils still store 20% more C than the noneroding reference profiles. Hence, on upland slopes where erosion and colluvial deposition occurs, the net exchange with the atmosphere is a long-term sink. The analysis presented here shows that the age of the deposits is the main control on these losses of buried C and that the exponential decay function described above may be used to predict the temporal evolution of C losses in colluvial soils.

Burial in Alluvial Profiles. At the scale of whole river catchments, the fate of eroded C stored in alluvial environments must be considered. In the Dijle catchment, the upper 2–3 m of sediment in the floodplain corresponds to typical overbank deposits resulting from accelerated anthropogenic soil erosion during the last millennium. Based on the analysis of 133 floodplain samples, we found that the soil profiles are highly variable in their C content and elemental composition. The surface layers of the floodplain had higher C values (3.3% C), relative to the source areas (1.27% C), because of locally higher net primary productivity and wetter conditions. This reflects a C input into the floodplain sediments that is derived not only from deposition of laterally transported eroded C but also from in situ produced C. The average C content of the floodplain sediments associated with accelerated erosion, however, is lower but not significantly different from the upland surface soils (1.13% vs. 1.27%). This suggests that there is no measurable net release or sequestration of C from floodplain sediments derived from accelerated erosion. However, it might be that a fraction of the transported and buried C is mineralized in an amount that is compensated for by the enrichment of the floodplain sediments with autochthonous C (22). In contrast to colluvial soils, no significant net release and age effect was thus observed; therefore, the floodplain soils in the Dijle catchment may be considered to efficiently sequester C at timescales of several millennia.

Carbon Budget Across Spatial and Temporal Scales. On the basis of the above analysis, the key controls on the temporal evolution of the sink/source magnitude were identified as (*i*) the rate of C erosion, (*ii*) the proportion of C buried in colluvial/alluvial depositional environments, and (*iii*) the age of the colluvial deposits. These have been constrained by the analysis of the temporal and spatial patterns of sediment fluxes. Averaged over the Dijle catchment, we estimated that accelerated erosion since the start of agriculture has laterally removed 9.1 Mt C, an amount equivalent to 92% of the soil C stock present before the start of agriculture in the upper 1 m of the soil profile (Fig. 3). (See *SI Text* for uncertainty estimation.) The replacement of eroded C resulted in a net uptake of 6.5 (4.2–8.3) Mt C, relative to noneroding conditions and, hence, represents a net sink of atmospheric CO_2 at the scale of the eroding hillslopes. The eroded C, on the other hand, resulted in the burial of 1.8 Mt C and 3.0 Mt C in colluvial and alluvial deposits, respectively. However, we estimated that ∼55% of the laterally derived C buried in colluvial soils was lost and limited the sink strength at the scale of the whole catchment. When the erosion-induced C uptake in uplands, burial and preservation of autochthonous C in floodplains, and mineralization in depositional stores and their uncertainties are considered, accelerated erosion resulted in a net sink of 3.9 (1.7–6.6) Mt C. This sink term is much larger than the 1.7 (1.5–2.1) Mt C that has been exported from the catchment and suggests that accelerated erosion induces a sink, irrespective of the fate of the exported C. In accordance with the timing of accelerated erosion, 60% of the sink occurred during the past 1,000 y (Fig. 2).

Discussion

Previous analysis of the influence of accelerated erosion on soil–atmosphere C fluxes, typically covering short timescales and single components of the geomorphic cascade, have resulted in opposed estimates of a global net source of 0.37–1 Pg C·y^{-1} vs. a net sink of

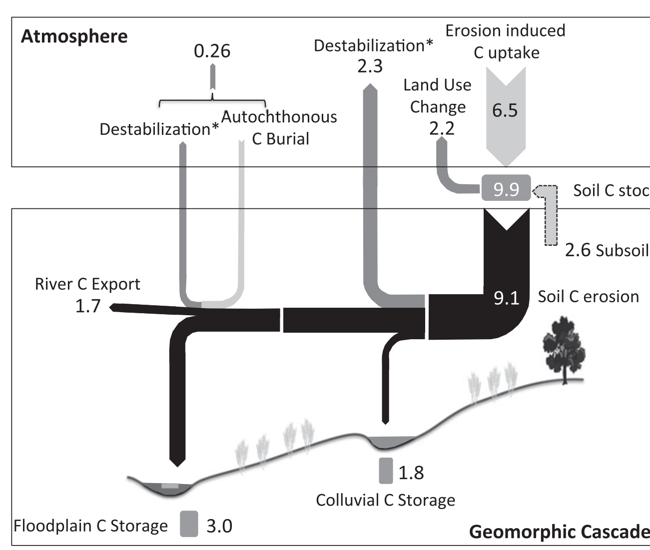

Fig. 3. Net exchange of C (in Tg C) between the soil and atmosphere as a result of accelerated erosion integrated for the period 4000 B.C. to A.D. 2000 for the Dijle catchment. Boxes represent reservoirs, black arrows represent lateral C fluxes, dark gray arrows represent mineralization of buried C in depositional environments, and light gray arrows represent soil C inputs. The land use change flux is the direct (non–erosion-related) effect of ALCC on soil C storage. The soil thus is both a source and a sink, where the sink term is greater than the source term. The soil C stock is the estimated initial C stock for the upper 1 m of the profile before the start of agriculture (4000 B.C.). *The possible mechanisms leading to destabilization of buried C are decomposition, i.e., a CO_2 flux toward the atmosphere, and leaching losses.

0.56–1 Pg C·y^{-1} (11, 21, 22). The analysis presented here for the Dijle catchment is a first assessment, which integrates the effect of accelerated C erosion for the period of agriculture and therefore balances all changes in component fluxes over space and time. Our results provide strong support for an erosion-induced sink in the long term, although the sink strength is partially offset by the net losses in colluvial environments.

Most studies of C emissions resulting from ALCC consider only the direct effect, i.e., changes in vegetation and soil disturbance that lead to lower inputs into the soil, reduce vegetation cover, and increase rates of soil decomposition (3–5). Here, we also account for the indirect effects of ALCC through accelerated C erosion and burial. The combination of increased stabilization of C in soils exposed at the surface of eroded hillslopes with the burial of eroded C in low-mineralization contexts resulted in a net C sink. For the Dijle catchment, we estimate that the direct effect of ALCC was a release of 2.2 Mt C from soils to the atmosphere since the start of agriculture. Based on our sediment and C budget calculations, this emission has been offset entirely by the C sink induced by accelerated erosion. When both direct (i.e., non-erosion-related) emissions from soils and vegetation are considered, we estimate that ALCC has released 10 Mt C since the start of agriculture. This flux is on the same order of magnitude, but opposite in sign, as the net uptake of 3.9 Mt C associated with accelerated erosion. Accelerated erosion and burial in the catchment thus has resulted in net C sink into soils, thereby offsetting 39% (17–66%) of the direct C emissions as a result of ALCC.

For the Dijle catchment, information on accelerated erosion was essential for understanding the longer-term C budget. At present, a temporally and geographically resolved global assessment of sinks and sources is hardly quantifiable for lack of reliable data and poor description of soil processes in current earth system models (4). The analysis presented here is based on high-resolution data from a 780-km^2 catchment in northwestern Europe. When corrected for catchment area, however, the floodplain sediment storage of the Dijle catchment falls within the variation reported for the much larger Rhine catchment and the observed temporal patterns of sediment deposition are in accordance with findings elsewhere in regions that have a long history of agricultural land use (28). The analysis presented here is based on data from soils derived from sedimentary substrates in which there has been a continuous supply of fine-textured subsoil, which may be less sensitive to yield decline than shallow soils overlying bedrock materials. Although recent studies have shown that accelerated erosion also may promote net C sequestration in shallow soils (11), erosion-induced yield decline should be considered in regions of the world where long-term land degradation is observed (4).

At present, the direct contribution of ALCC is considered an important component of anthropogenic climate change (1–5). Here, we suggest that not accounting for ALCC-induced C erosion and burial, particularly in regions where the erosional C flux is large relative to the soil C stock, significantly increases uncertainties not only of past but also current and future anthropogenic emissions of CO_2. By exposing subsoil to fresh organic material and burial of C in depositional settings, accelerated erosion has increased the throughput of soil C substantially. Hence, accounting for the non–steady-state C dynamics in geomorphically active systems is of utmost importance to fully understand both the historical and current exchange of C between land and atmosphere. Burial of C in depositional environments has been shown to reduce decomposition substantially at a timescale of years to decades (11, 30, 31); therefore, buried C typically is assumed to be protected from further decomposition. Our analysis, however, shows that this assumption is no longer valid when considering longer timescales and that the observed net loss in depositional environments actually limits the magnitude of the C sink. We suggest that in depositional environments, in the absence of continued plant inputs at depth, decomposition is slowed down but not completely halted. The observed loss of buried C here is consistent with recent studies suggesting that depositional profiles may have high fractions of their C stocks in active forms (32). We observed that ∼50% of buried C in colluvial stores was destabilized after 500 y and C losses therefore lag C burial. Hence, the C budget is inherently historical and there is a commitment to future climate as the result of both present and past ALCC and associated erosion and burial. This has potential implications for the contemporary C budget: most of the global agricultural development took place after 1850, with the highest rates of expansion between 1850 and 1950, followed by a sharp drop (2). Much of the world's cropland therefore is substantially younger than the cropland of the Dijle catchment. In addition to potential increases in decomposition rates of buried C as a result of global warming, desiccation of saturated soils, land use change, and reexcavation by gullying, the time lag in buried C losses implies that this large store of recently buried C cannot be assumed to be inert to further loss, and indeed might become a significant C source. The terrestrial C exchange therefore may be influenced by the legacy of this buried C. However, regional differences in rate and intensity of erosion disturbance are likely to be large; therefore, the effect of accelerated erosion on the C budget is heterogeneous within the landscape and variable across various timescales. An important step in quantifying the role of C erosion in the global C budget will require consideration of the relative contribution of colluvial C deposition vs. deposition in the aquatic system (e.g., floodplains, reservoirs, lakes).

Based on our analysis of the Dijle catchment, we conclude that (*i*) accelerated C erosion has a significant impact on both the past and present C cycle, resulting in a significant downward revision of ALCC-related CO_2 emissions, and (*ii*) the dynamic phase of buried C in terrestrial depositional stores substantially limits the erosion-induced C sink strength at centennial timescales. This highlights the need to consider past C erosion fluxes to understand the contemporary budget and the need for soil erosion control and land restoration.

Materials and Methods

ALCC and C Release. Estimates of land cover and land cover change for the Dijle catchment are derived from published reconstructions (*SI Text*). We used equilibrium C stocks ($C_{eq,luc}$, 10^6 g·ha^{-1}) for different land use classes (*luc*) in central Belgium to define the direct effect of ALCC on changes in C in vegetation and soils. The total C stock for period t (C_t, 10^6 g) is calculated as $C_t = \sum_{luc}(C_{eq,luc} {*} A_{luc})$, where A_{luc} is the area for land use class *luc* (hectares). Carbon emissions and gains during period t and t-1 are then calculated as $C_t - C_{t\text{-}1}$. The data used for C_{eq} are derived from published estimates (Table S2).

ALCC and Accelerated Soil Erosion/Deposition. The sediment budget for the Dijle catchment is compiled from published data (27). The sediment budget includes soil erosion and colluvial deposition on hillslopes and in dry valleys and alluvial deposition in floodplains. The computed difference between soil erosion and sediment deposition is then attributed to fluvial sediment export. Hillslope erosion and deposition were quantified based on an analysis of 809 augerings, whereas floodplain sediment deposition is based on 197 augerings spread over 24 cross-sections (27). A detailed database of sediment ages was used to construct cumulative sediment mass curves through time with a temporal resolution of 1,000 y. Floodplain deposition was dated at 12 sites using 62 radiocarbon dates and 11 optically stimulated luminescence (OSL) dates, whereas colluvial deposition was dated at 3 sites using 32 radiocarbon and 12 OSL dates. For each of the dated sites, an age–depth curve was created, and from these curves (27) the age–depth relation was determined for each 1,000-y interval. An average catchment-wide age–depth curve was produced as the median value of these 1,000-y interval points. In this study, we consider only the human impact on erosion and burial, and natural background rates were subtracted from the gross erosion and sedimentation rates (*SI Text*).

Derivation of Erosion-Induced C Exchange for the Toposequences. We analyzed 273 samples from 25 profiles for C, bulk density, and cumulative soil redistribution (CSR) since the start of cultivation from four toposequences covering (*i*) noneroding profiles, (*ii*) eroding profiles on the slopes, and (*iii*) depositional profiles in colluvium (Fig. 1 and Fig. S1). Samples were taken in 0.1-m intervals for a total sampling depth of 1 m for the plateau and eroding profiles, whereas sampling depth for the depositional profiles covered the whole colluvium. C was analyzed using an elemental analyzer (VarioMax; Elementar GmbH). Samples containing inorganic C were treated using acid fumigation before C analysis to remove inorganic C. Estimates of CSR were derived using the soil profile truncation method (27, 33). The method for the retrospective assessment of erosion-induced C exchange was taken from ref. 22. The change in C stock for a soil profile, down to a depth of 1 m, undergoing erosion or deposition is given by the following mass balance: $\Delta C = C_{dep} - C_{ero} + C_{sub} + C_{atm}$, where C_{ero} is the C loss by erosion; C_{dep} is the C gain by deposition; C_{sub} is the amount of subsoil C incorporated into (positive value) or exported from (negative value) the 1-m profile in the case of erosion and burial, respectively; and C_{atm} is the residual amount of C required to balance the C budget. This residual is then attributed to the difference between mineralization and sequestration processes induced by erosion whereby positive residuals are indicative of a net C sink, whereas a net source is indicated by negative residuals. The method is then based on the quantification of ΔC, $C_{dep/ero}$, and C_{sub}. An estimate for these variables is derived from C inventories and depth distributions of reference sites experiencing similar land use change trajectories but no erosion or deposition (i.e., space-for-time substitution). (See *SI Text* for a detailed discussion on the estimation procedure and uncertainty on the sink–source estimates.)

Data from the Belgian Soil Database and Floodplain Soils. From the soil database (34), we selected 379 luvisol profiles in the Dijle catchment. For these profiles, C depth profiles (up to seven depth intervals between 0 and 1.5 m) and detailed soil profile descriptions were available. From these, we selected the profiles that were under cropland (63% of the dataset) and grouped the data in colluvial vs. noncolluvial profiles. Depositional profiles in upland colluvia were selected based on their attributes (i.e., well-drained profiles without profile development). We extended this database by including the 14 %C observations from the colluvial soils of the four toposequences. This resulted in 700 and 309 depth–%C observations for noncolluvial and colluvial soils. Only a very limited number of soil profiles in floodplains are described in the soil database, and these do not cover the depth at which sediment associated with accelerated erosion is found. Therefore, 133 samples were taken at five different locations in the floodplain that are representative of the variability in floodplain sediment stratigraphy within the Dijle catchment (Fig. 1). Samples were taken at various depths (0–9 m) spanning the entire range of Holocene alluvial deposits. C and N contents were determined using the same methods described above.

C Budget Calculations and Uncertainty Estimation. We used the time-differentiated sediment budget and the relationships between accelerated erosion and C storage described in the main text to estimate human impacts on C erosion, burial, and export. (See *SI Text* for a detailed description of the implementation and assessment of uncertainties.)

ACKNOWLEDGMENTS. We thank Communauté Française de Belgique (Project Convention 09/14-022) for support. K.V.O is a research associate of the Fonds de la Recherche Scientifique, Belgium. B.N. is a Postdoctoral Fellow of the Research Foundation Flanders, Belgium.

1. DeFries RS, Field CB, Fung I, Collatz GJ, Bounoua L (1999) Combining satellite data and biogeochemical models to estimate global effects of human-induced land cover change on carbon emissions and primary productivity. *Global Biogeochem Cycles* 13 (3):803–815.
2. Houghton RA (2003) Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000. *Tellus B Chem Phys Meterol* 55(2):378–390.
3. Strassmann KM, Joos F, Fischer G (2008) Simulating effects of land use changes on carbon fluxes: Past contributions to atmospheric CO2 increases and future commitments due to losses of terrestrial sink capacity. *Tellus* 60B(2):583–603.
4. Kaplan JO, et al. (2011) Holocene carbon emissions as a result of anthropogenic land cover change. *Holocene* 21(5):775–791.
5. Stocker B, Strassmann K, Joos F (2011) Sensitivity of Holocene atmospheric CO2 and the modern carbon budget to early human land use: Analyses with a process-based model. *Biogeosciences* 8(2):69–88.
6. Lal R (2005) Soil erosion and carbon dynamics. *Soil Tillage Res* 81(2):137–142.
7. Montgomery DR (2007) Soil erosion and agricultural sustainability. *Proc Natl Acad Sci USA* 104(33):13268–13272.
8. Wilkinson BH, McElroy BJ (2007) The impact of humans on continental erosion and sedimentation. *Geol Soc Am Bull* 119(1–2):140–156.
9. Liu S, Bliss N, Sundquist E, Huntington TG (2003) Modeling carbon dynamics in vegetation and soil under the impact of soil erosion and deposition. *Global Biogeochem Cycles* 17(2):1074.
10. Jacinthe PA, Lal R, Kimble JM (2002) Carbon dioxide evolution in runoff from simulated rainfall on long-term no-till and plowed soils in southwestern Ohio. *Soil Tillage Res* 66(2):23–33.
11. Van Oost K, et al. (2007) The impact of agricultural soil erosion on the global carbon cycle. *Science* 318(5850):626–629.
12. Sundquist ET, Visser Ackerman K, Stallard RF, Bliss NB (2011) Historical influence of soil and water management on sediment and carbon budgets in the United States. *Appl Geochem* 26(Suppl):259.
13. Rumpel C, Kogel-Knabner I (2011) Deep soil organic matter-a key but poorly understood component of terrestrial C cycle. *Plant Soil* 338(1–2):143–158.
14. Fontaine S, et al. (2007) Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature* 450(7167):277–280.
15. Gregorich EG, et al. (1998) Carbon distribution and losses: Erosion and deposition effects. *Soil Tillage Res* 47(3–4):291–302.
16. Six J, Conant RT, Paul EA, Paustian K (2002) Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant Soil* 241(2):155–176.
17. Stewart CE, Paustian K, Plante AF, Conant RT, Six J (2007) Whole-soil carbon saturation: Concept, evidence and evaluation. *Biogeochemistry* 86(1):19–31.
18. Hassink J (1996) Preservation of plant residues in soils differing in unsaturated protective capacity. *Soil Sci Soc Am* 60(2):487–491.
19. Vitousek P, et al. (2003) Erosion and the rejuvenation of weathering-derived nutrient supply in an old tropical landscape. *Ecosystems (N Y)* 6(8):762–772.
20. Stallard RF (1998) Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial. *Global Biogeochem Cycles* 12(2):231–252.
21. Lal R (2003) Soil erosion and the global carbon budget. *Environ Int* 29(4):437–450.
22. Aufdenkampe AK, et al. (2011) Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. *Front Ecol Environ* 9(1):53–60.
23. Polyakov VO, Lal R (2004) Soil erosion and carbon dynamics under simulated rainfall. *Soil Sci* 169(8):590–599.
24. Quine TA, Van Oost K (2007) Quantifying carbon sequestration as a result of soil erosion and deposition: Retrospective assessment using caesium-137 and carbon inventories. *Glob Change Biol* 13(12):2610–2625.
25. Trumbore SE, Czimczik CI (2008) Geology. An uncertain future for soil carbon. *Science* 321(5895):1455–1456.
26. Trimble SW (1999) Decreased rates of alluvial sediment storage in the coon creek basin, wisconsin, 1975-93. *Science* 285(5431):1244–1246.
27. Notebaert B, et al. (2011) Changing hillslope and fluvial Holocene sediment dynamics in a Belgian loess catchment. *J Quaternary Sci* 26(1):44–58.
28. Hoffmann T, Glatzel S, Dikau R (2009) A carbon storage perspective on alluvial sediment storage in the Rhine catchment. *Geomorphology* 108(1–2):127–137.
29. Rosenbloom NA, Harden JW, Neff JC, Schimel DS (2006) Geomorphic control of landscape carbon accumulation. *J Geophys Res* 111(1):G01004.
30. Smith SV, Sleezer RO, Renwick WH, Buddemeier R (2005) Fates of eroded soil organic carbon: Mississippi basin case study. *Ecol Appl* 15(6):1929–1940.
31. Nadeu E, Berhe AA, de Vente J, Boix-Fayos C (2012) Erosion, deposition and replacement of soil organic carbon in Mediterranean catchments: A geomorphological, isotopic and land use change approach. *Biogeosciences* 9(3):1099–1111.
32. Berhe A, et al. (2012) Persistence of soil organic matter in eroding versus depositional landform positions. *J Geophys Res* 117(2):G02019.
33. Doetterl S, Six J, Van Wesemael B, Van Oost K (2012) Carbon cycling in eroding landscapes: geomorphic controls on soil organic C pool composition and C stabilization. *Glob Change Biol* 18(7):2218–2232.
34. Van Orshoven J, Maes J, Vereecken H, Feyen J, Dudal R (1988) A structural database of Belgian soil profile data. *Pedologie* 38:191–206.