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Research paper

Quantifying soil loss with in-situ cosmogenic ^{10}Be and ^{14}C depth-profiles

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ABSTRACT

Conventional methods for the determination of past soil erosion provide only average rates of erosion of the sediment's source areas and are unable to determine the rate of at-a-site soil loss. In this study, we report in-situ produced cosmogenic ^{10}Be, and ^{14}C measurements from erratic boulders and two depth-profiles from Younger Dryas moraines in Scotland, and assess the extent to which these data allow the quantification of the amount and timing of site-specific Holocene soil erosion at these sites. The study focuses on two sites located on end moraines of the Loch Lomond Readvance (LLR): Wester Cameron and Inchie Farm, both near Glasgow. The site near Wester Cameron does not show any visible signs of soil disturbance and was selected in order to test (i) whether a cosmogenic nuclide depth profile in a sediment body of Holocene age can be reconstructed, and (ii) whether *in situ* ^{10}Be and ^{14}C yield concordant results. Field evidence suggests that the site at Inchie Farm has undergone soil erosion and this site was selected to explore whether the technique can be applied to determine the broad timing of soil loss. The results of the cosmogenic ^{10}Be and ^{14}C analyses at Wester Cameron confirm that the cosmogenic nuclide depth-profile to be expected from a sediment body of Holocene age can be reconstructed. Moreover, the agreement between the total cosmogenic ^{10}Be inventories in the erratics and the Wester Cameron soil/till samples indicate that there has been no erosion at the sample site since the deposition of the till/moraine. Further, the Wester Cameron depth profiles show minimal signs of homogenisation, as a result of bioturbation, and minimal cosmogenic nuclide inheritance from previous exposure periods. The results of the cosmogenic ^{10}Be and ^{14}C analyses at Inchie Farm show a clear departure from the zero-erosion cosmogenic nuclide depth profiles, suggesting that the soil/till at this site has undergone erosion since its stabilisation. The LLR moraine at the Inchie Farm site is characterised by the presence of a sharp break in slope, suggesting that the missing soil material was removed instantaneously by an erosion event rather than slowly by continuous erosion. The results of numerical simulations carried out to constrain the magnitude and timing of this erosion event suggest that the event was relatively recent and relatively shallow, resulting in the removal of circa 20–50 cm of soil at a maximum of ~2000 years BP. Our analyses also show that the predicted magnitude and timing of the Inchie Farm erosion event are highly sensitive to the assumptions that are made about the background rate of continuous soil erosion at the site, the stabilisation age of the till, and the density of the sedimentary deposit. All three parameters can be independently determined a priori and so do not impede future applications to other localities. The results of the sensitivity analyses further show that the predicted erosion event magnitude and timing is very sensitive to the ^{14}C production rate used and to assumptions about the contribution of muons to the total production rate of this nuclide. Thus, advances in this regard need to be made for the method presented in this study to be applicable with confidence to scenarios similar to the one presented here.

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1. Introduction

The economic costs of soil erosion are clear (Pimentel et al., 1995; Montgomery, 2007), but despite the substantial agro-economic research in this field, many questions of a broader scientific importance have remained unanswered. It is not actually known, for example, whether human activity accelerates soil erosion (Trimble and Crosson, 2000; Fuchs, 2007), but it is nonetheless widely assumed that it does so by at least one order of magnitude (Walling and Webb, 1996; Hooke, 2000; Hewawasam et al., 2003; Wilkinson and McElroy, 2007). The problems associated with identifying human activity induced acceleration of soil erosion are twofold. First, it is uncertain whether studies of soil erosion based on historical data, decadal soil erosion plot data, and models such as RUSLE – that all point towards an acceleration of soil erosion due to human activity (e.g., Hooke, 2000; Wilkinson and McElroy, 2007; Montgomery, 2007) – are in fact capturing the variability of background (natural) erosion rates due to climate forcing, given that climatically driven perturbations can occur over the timescales that are pertinent to these short-term soil erosion studies (Daniels et al., 1987; Alford, 1992). Second, the mismatch between sediment yield data (Milliman et al., 1987) and long-term rates of sediment production (Clapp et al., 2000; Buechi et al., 2014) does not necessarily imply recently accelerated soil erosion rates given that, as shown by Clapp et al. (2000), elevated sediment yields can be the result of rivers reworking alluvial deposits and evacuating sediment deposited in earlier periods.

Despite the role of soils and soil erosion in the dynamics of the Earth's surface, current numerical models of long-term landscape evolution treat the former in a very simplistic way (Bishop, 2007; Tucker and Hancock, 2010). A better understanding of the controls on rates and depths of soil production and erosion (Bishop, 2007, and references therein) is needed for the improvement of these numerical models. The latter have played and play an important role in our understanding of the links and feedbacks between tectonics, climate, and surface processes, and improved models will enable us to go some way towards solving the so called 'chicken and egg' paradox posed by Molnar and England (1990) more than two decades ago and debated since (Willenbring and von Blanckenburg, 2010; Herman et al., 2013).

Furthermore, soil is an important component of the global carbon cycle (Lal, 2004). The removal of soil organic carbon by accelerated erosion could be contributing to the 740 Gt of carbon in the global mass of atmospheric CO_2, with emissions of 1 Gt of C/year (Lal, 2005) not just affecting the carbon stock but also carbon mineralization. Quantifying both soil erosion and soil age will contribute to the understanding of the complex nature of soil carbon storage and release dynamics (Harden et al., 1992).

Although age-controlled process-rates data related to soils are still sparse (Schaller et al., 2004), different dating techniques, such as radiocarbon (Wells et al., 1987; Trumbore, 1993; Anselmetti et al., 2007), U–Th series radionuclides (Cornu et al., 2009; Ma et al., 2010), OSL (Fuchs and Lang, 2001), and meteoric and in-situ produced cosmogenic nuclides (Barg et al., 1997; Small et al., 1999; Heimsath et al., 1997, 1999, 2000; McKean et al., 1993; Riebe et al., 2003; Wilkinson and Humphreys, 2005; Schaller et al., 2009, 2010), have been employed successfully. Of the aforementioned dating techniques, cosmogenic nuclide analysis is perhaps the most promising in terms of quantifying soil erosion, as (i) it enables the quantification of both catchment-wide and at-a-site erosion rates, and (ii) is sensitive over the millennial timescales relevant to both soil production and soil loss.

In this study, we report in-situ produced cosmogenic ^{10}Be, and ^{14}C measurements from erratic boulders and two depth-profiles from Younger Dryas moraines in Scotland, and assess the extent to which these data allow the quantification of the amount and timing of site-specific Holocene soil erosion at these sites. Similarly to other areas affected by Quaternary glaciations, most of Scotland's soils are formed on glacial till. Unlike in the case of soils that form by the in-situ weathering of the underlying bedrock, the age of soils formed on glacial till is quantifiable, as it is coeval with the age of till stabilisation. The latter is particularly important for this study, as the cosmogenic ^{10}Be and ^{14}C-based method presented here is based on the assumption that the age of soil formation is known.

2. Theoretical background

Different cosmogenic nuclides have different production pathways, and the production rates for these different production pathways attenuate differently with depth (Strack et al., 1994; Brown et al., 1995; Heisinger et al., 1997, 2002a,b). Thus, at least in theory, the depth-profiles of cosmogenic nuclides can provide more information on the processes that operate at the Earth's surface than a single nuclide concentration obtained from a surface sample (cf. Braucher et al., 2003; Kim and Englert, 2004; Schoenbohm et al., 2004). Given the vertical nature of soil processes, most studies involving soils and employing cosmogenic nuclides have used cosmogenic nuclide depth-profiles. For example, Brown et al. (1994) and Braucher et al. (1998) have used in-situ ^{10}Be depth-profiles in lateritic tropical soils to explain the formation of certain soil deposits. Phillips et al. (1998), using a model of soil burial by colluvium and bioturbation in combination with ^{21}Ne measurements in depth-profiles, were able to estimate inheritance-corrected exposure ages in stream terraces and an alluvial fan. Further, Schaller et al. (2003) combined ^{10}Be measurements in cover bed depth-profiles and river sediment in order to determine the effect of cover beds on catchment-wide erosion rate determinations.

The examples presented above are all based on the work of Anderson et al. (1996), who showed that a cosmogenic nuclide depth-profile in an alluvial deposit can be used to calculate the depositional age of that deposit by explicitly accounting for the inherited nuclide component. In short, Anderson et al.'s (1996) method works by reconstructing the cosmogenic nuclide depth-profile of the alluvial deposit and using the shift in this profile to estimate the amount of time elapsed since emplacement of that deposit. This principle, if inverted, can at least in theory be applied to quantifying at-a-site soil erosion events in soils formed on deposits of known age. If the age of the deposit is known independently (from, for example, absolute geochronology), the expected cosmogenic nuclide depth-profile in the sediment can be generated using that independently-known age and measured or assumed bulk densities. As in the case of Anderson et al. (1996), the measured nuclide concentration profile provides an estimate of inheritance. More importantly, the profile's total measured post-depositional nuclide inventory, whether that profile is perturbed or not, should match the total nuclide inventory estimated for a deposit of that age. Any shortfall in the measured total nuclide inventory compared to the total nuclide inventory predicted for the age of the deposit must reflect loss of nuclide, presumably by loss of the nuclide-bearing clasts, which are quartzose for the cosmogenic nuclides that are currently commonly measured, namely, ^{10}Be, ^{26}Al, ^{14}C and ^{21}Ne. Such quartz may conceivably be lost from the profile by lateral or vertical translocation within the soil/sediment, but it is likely that surface erosion is a more important mechanism for loss of nuclide-bearing quartz. For the simplest case of a profile that has not been perturbed by vertical movement of clasts, such surface erosion will truncate the top of the nuclide concentration profile. If the depth-profile of nuclide concentrations has been truncated by surface erosion and is also perturbed by vertical movement of