Erosion-induced losses of carbon, nitrogen, phosphorus and heavy metals from agricultural soils of contrasting organic matter management

Pu Shi *, Rainer Schulin
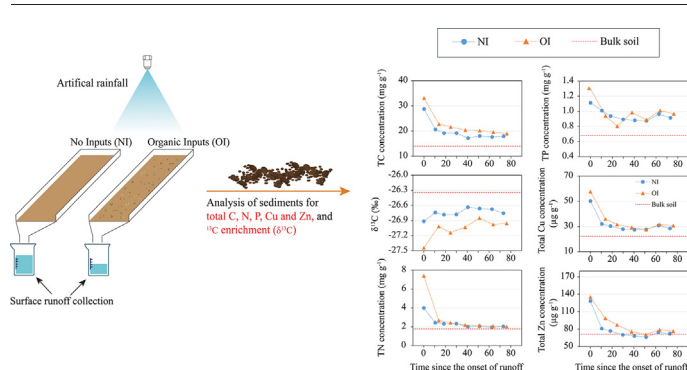
Institute of Terrestrial Ecosystems, ETH Zurich, Universitätstrasse 16, CH-8092 Zurich, Switzerland

HIGHLIGHTS

- Organic residue amendment substantially reduced the erosion-induced element losses.
- Organic residue amendment increased element concentrations in exported sediments.
- Lost organic carbon was preferentially derived from added organic residues.
- Losses of N, Cu and Zn were mostly associated with organic matter export.
- Loss of P was more associated with export of mineral particles.

GRAPHICAL ABSTRACT

ABSTRACT

Water erosion on agricultural land preferentially carries away fine particles. Due to the generally high specific density of sorption sites of these particles, their displacement can be associated with substantial particle-bound transfer also of nutrients and pollutants with low solubility. Organic matter amendments can reduce soil erosion, but to what extent they affect the erosion-induced element losses has not been studied much. Here, we carried out field rainfall experiments on three pairs of soil plots (1.5×0.75 m) after incorporating a mixture of wheat straw and grass (2.12 g C per kg soil) as organic amendment into the topsoil (0–5 cm depth) of one plot in each pair (OI treatment). The other plot was prepared in the same way but without incorporation of the amendment (NI treatment). Artificial rainfall (49.1 mm h^{-1}) was simultaneously applied on each pair of plots for approximately 2 h, and sediment samples were collected at designated time steps for the analyses of C, N, P, Cu, Zn and stable carbon isotope ratios. The organic amendment substantially reduced element losses, but to a lesser extent than soil loss, as the element concentrations were higher in the exported sediments in the OI than in the NI treatment. With and without organic amendment, the concentrations of the studied elements were consistently higher in the exported sediments than in the bulk soil. They were always maximal at the onset of discharge and then continuously decreased towards the values of the bulk soil. The δ^{13}C values revealed that the eroded C was preferentially derived from the fresh organic residue added to the soil. Pairwise correlations between elements and sediment size indicate that the export of N, Cu and Zn was primarily associated with soil organic matter loss, whereas P export was more associated with mineral fractions.

© 2017 Elsevier B.V. All rights reserved.

Editor: Charlotte Poschenrieder

1. Introduction

Soil is an essential part of the earth system, as it provides food, services and resources to fulfil basic human needs. Soil erosion is a major environmental problem and a threat to sustainable agriculture (Pimentel et al., 1995). Affecting nearly all of the world's arable land, water and wind erosion are at the same time important drivers of global biogeochemical cycles (Quinton et al., 2010; Van Oost et al., 2007). Erosion-induced lateral fluxes of carbon (C), nitrogen (N), phosphorous (P) and heavy metals can cause serious soil degradation in the eroding sites and excessive element accumulation in the depositional sites (Pimentel et al., 1995). A problem of particular concern is the transfer of nutrients and pollutants from soils to water bodies via water erosion, as it can have a major adverse impact on surface water quality (Liu et al., 2014).

In general, water erosion preferentially carries away fine particles, as these settle slower from suspensions than coarse particles. The size-selectivity of water erosion tends to increase with the magnitude of erosion events (Palis et al., 1990). On arable land water erosion can be substantial even where it is rather flat and overland flow is not very intensive. As a result, sediments exported from agricultural land into the aquatic environment are usually enriched with clay- and silt-sized particles and nutrients and pollutants bound to them due to their high specific sorption capacity compared to coarser particles (Asadi et al., 2011; Vaezi et al., 2017). Wang et al. (2013) reported that soil organic carbon (SOC) in sediments originating mostly from interrill erosion was enriched up to eight times relative to the bulk soil. They also found that the exported organic carbon (OC) was dominated by mineral-bound OC, rather than by particulate organic matter, and stressed the importance of SOC characteristics in determining the loss of SOC with water erosion. Investigating the role of soil organic matter (SOM) management in this context, Strickland et al. (2012) compared different tillage schemes and found a close relationship between sediment-associated C and N, with higher N enrichment when plant residues were incorporated into the aggregates. On the other hand, Quinton et al. (2001) found a strong correlation between clay and P contents in exported sediments, while the concentrations of copper (Cu), lead (Pb) and nickel (Ni) in sediments were found to be related to clay content as well as to SOC (Quinton and Catt, 2007).

To combat soil erosion, organic amendments have frequently been proposed to reduce soil erodibility, e.g. by protecting aggregate surfaces against rainfall impact and providing substrates for microbial transformation into compounds acting as glue between soil particles (Keesstra et al., 2016; Parras-Alcántara et al., 2016; Prosdocimi et al., 2016; Sadeghi et al., 2015; Shi et al., 2017a). However, as the effect of organic amendments could be associated with a reduction in the share of coarse particles in the exported sediments, it may at the same time lead to an increased enrichment of sediment-associated compounds, so that the decrease in the export of these compounds would be smaller than the decrease in exported mass of sediment. As a result, Kuhn et al. (2012) found that, after the conversion from conventional to organic farming, sediments exported from the organically farmed soils exhibited a greater P enrichment.

Apart from enhancing aggregate stability, the addition of new OM will also lead to a change in SOC composition. If resident SOC and added OM have sufficiently different ^{13}C signatures, the pathway of the added OC with decomposition and transformation into SOC can be monitored by analysing the ^{13}C:^{12}C ratios of SOC pools. Due to isotopic discrimination, ^{13}C is gradually enriched in older OM (Agren et al., 1996; Fernandez et al., 2003). Using density fractionation and analysing the relative enrichment of ^{13}C compared to a standard as expressed by the δ^{13}C value in the resulting OM fractions, enrichment of ^{13}C was found to increase in the following sequence of fractions: free light OM < occluded particulate OM < mineral-bound OM (Baisden et al., 2002;

Gunina and Kuzyakov, 2014). This means that stable isotope analysis could be used to detect preferential mobilization and export of these fractions in erosion studies, as demonstrated by Hu et al. (2016), who found that enhanced SOC decomposition at a footslope was associated with an elevated δ^{13}C value.

In this study, we performed artificial rainfall experiments on three pairs of soil plots after incorporating crop residues (a mixture of grass and wheat straw) into the topsoil of one plot in each pair (OI treatment), but not into the other (NI treatment), to (i) assess the effect of organic amendment on C, N, P, Cu and zinc (Zn) losses associated with the erosion events, (ii) analyze the sources of the exported OC in the OI treatment using C stable isotope ratio analysis, and (iii) investigate the association of the exported elements with different mineral and OM fractions. Cu and Zn were analyzed as representatives of heavy metals that are often present at elevated concentrations in agricultural soils, because they are widely applied in animal husbandry and get distributed with manure application on arable land. Other important sources are biowastes used as fertilizers and fungicides, especially Cu based fungicides in viticulture, where erosion is often a problem.

2. Materials and methods

2.1. Experimental design

The artificial rainfall experiments were carried out on a gently sloped (10%) arable field soil (silt loam with 19% clay, 57% silt, and 24% sand) at the Zurich-Reckenholz station of the Swiss Federal Agricultural Research Institute (Agroscope). A detailed description of the experimental soil and general set-up of the experiments is given in Shi et al. (2017a). For the study described here, three pairs of soil plots (2.5 × 1.25 m each) were installed on a seedbed after sieving the surface aggregates to smaller than 10 mm. Then a mixture of grass and wheat straw was thoroughly mixed at a rate of at 2.12 g C per kg dry soil into the top 5 cm of one plot in each pair (OI treatment). The other plot was prepared in the same way, but without incorporating any organic amendment (NI treatment). Prior to incorporation, the organic residues were chopped into pieces smaller than 1 cm size. The mixture had a C:N ratio of 22 and a δ^{13}C value of −30.4‰. The bulk density of the freshly prepared topsoil was 1.21 ± 0.05 g cm^{-3} in both treatments. Each plot was watered by applying 20 L deionized water twice a week for six weeks. During the six weeks, all plots were protected from natural rainfall by a plastic cover, leaving space between the cover and the soil surface to allow for natural ventilation. After six weeks, a core area of 1.5 × 0.75 m was isolated from the surrounding parts by pushing metal plates vertically 7 cm deep into the topsoil on the upslope side and the two lateral sides of each plot, while a triangular trough was installed at the downslope border of each of these areas to collect surface runoff and exported sediments (Fig. 1).

Prior to each rainfall experiment, 32 L deionized water was applied during 12 min onto each pair of plots using a spray can to start out from already moist conditions. Immediately after pre-wetting, artificial rainfall was applied simultaneously onto both plots through a single-nozzle type rainfall simulator for approximately 2 h. The nozzle (1/2 HH35W, Spraying Systems Fulljet, USA) was mounted at 3.6 m height, and the water pressure to the nozzle was maintained at 650 kPa to obtain a stable rainfall intensity of 49.1 ± 0.8 mm h^{-1} (Shi et al., 2017b), which is representative of extreme rainfall events in the study region (Hahn et al., 2012). The mean raindrop diameter was 1.1 mm for the selected nozzle. The Christensen Uniformity Coefficient of the rainfall was 93% in a 2-m diameter circular area.

Surface runoff was collected at designated time steps (i.e. 1st sample at onset of runoff, next four after 2-min intervals, and the rest after 4-min intervals) in graduated plastic bottles until the runoff reached steady state. Samples of 0.3–0.5 L volume were collected to ensure that the sample volume was sufficient for subsequent chemical analysis.