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Research paper

Soil carbon and nitrogen sources and redistribution as affected by erosion and deposition processes: A case study in a loess hilly-gully catchment, China

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ABSTRACT

Understanding how organic carbon (C) and nitrogen (N) move with soil along the fluvial system and where eroded organic C and N sources occur over catchment landscape is of significant importance for evaluating accurately carbon or nitrogen budget at the catchment scale and designing proper management practice in the fragile ecosystem. In this study, we selected a dam-controlled catchment in the southwestern hilly-gully region of the Chinese Loess Plateau with severe soil erosion, and explored the catchment scale carbon and nitrogen redistribution by erosion and deposition processes as well as organic carbon and nitrogen sources in sediments retained by check dam. The physio-chemical characteristics, stable isotopic signatures (^{13}C, ^{15}N), total organic C (TOC) and total N (TN) of soils and sediments in studied catchment were determined and an isotopic mixing model was employed to quantify the relative contributions of each source type (ie., forests, cropland, and gully) to eroded sediment C and N. The results showed that the check dam intercepted 309.6 Gg of eroded soil, 1405.1 Mg of TOC, and 153.5 Mg of TN. The sediment the eroded TOC was mainly sourced from cropland, accounting for 53.54%, followed by gully (29.28%) and then forests (17.18%), respectively. Eroded TN sources was similar to C sources, showing that cropland contributed 53.53%, with gully and forests contributing 30.86% and 15.61%, respectively. Moreover, the forests contributions to eroded C and N gradually decreased in the direction of the runoff pathway at the check dam, and the C and N contributions of cropland and gullies showed the orders of mid-check dam > post-check dam > pre-check dam and pre-check dam > post-check dam > mid-check dam, respectively. Soil erosion and deposition processes induced 1569.8 Mg TOC and 146.7 Mg TN losses, with an average soil C and N erosion rate of 0.051 Mg C ha^{-1} yr^{-1} and 0.005 Mg N ha^{-1} yr^{-1} during the period (i.e., from 2004 to 2016), accounting for approximately 52.8% and 48.87% of the total amount of eroded TOC and TN, respectively. The results indicated that although the check dam served as a carbon and nitrogen storage and sequestration structure in the loess hilly-gully region, erosion-induced carbon or nitrogen redistribution might still act as a major source for atmospheric CO_2 or nitrogen oxide in our studied catchment.

1. Introduction

Soil erosion has been intensively studied as regards the impact of biogeochemical cycling of essential elements, especially elemental carbon (C) and nitrogen (N) in terrestrial ecosystems (Lal 2003; Quinton et al., 2010; Berhe et al., 2007, 2017). Accelerated soil erosion redistribute large quantities of sediment and associated soil C and N on the Earth's surface, thereby not only leading to loss of surface soil in uplands and resulting in soil quality degradation and agricultural production reduction (Lal., 2010; Kirkels et al., 2014; Li et al., 2016a,b),

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but also contributing to the aggravation of global warming and water eutrophication (Lal., 2004; Liu et al., 2017a,b). As estimated globally, soil erosion redistributes on the order of 75 Gt (1Gt = 10^{15}g) of soil and 1–5 Gt soil organic carbon (SOC) (Stallard, 1998; Berhe et al., 2007) and 23–42 Tg soil total nitrogen (TN) (1Tg = 10^{12}g) from soil ecosystem annually (Quinton et al., 2010). However, until recently, with the removal of C or N-rich topsoil from eroding slope positions and burial at a depressional and/or protected site, the redistribution of SOC and TN induced by soil erosion still have been intensely debated as to the fate of the C or N that is exported out of eroding catchments (Kirkels et al., 2014; Doetterl et al., 2016).

The lateral flows of topsoil by erosion can result in the depletion of labile C and N at eroding site and the concentration of both sediment and SOC and TN at depositional site downslope, thereby indicating a selective mobilization in the light fractions of SOC and TN at the slope scale (Kirkels et al., 2014; Berhe et al., 2017). However, the redistribution of C and N by lateral flows at the watershed scale seem to be much more complex due to the interference of other ecogeomorphological processes (Boix-Fayos et al., 2015, 2017). Erosion process, which redistributes sediment and organic matter dominated by tillage, rill, and gully erosion, will be non-selective on catchment scale (Van Oost et al., 2008). The sediment generated by non-selective erosion is considered to have identical characteristics as the soil from which it derived (Van Oost et al., 2008; Kuhn et al., 2009). At the catchment scale, the bulk of the OC and TN fractions are transported with the sediment mobilization, which lead to the average C and N enrichment ratios (including both suspended and bedload sediment) lower than 1 as reported by previous studies (Haregeweyn et al., 2008; Wang et al., 2010; Liu et al., 2017b). Hence, the fate of eroded SOC and TN still remain considerable uncertainty owing to the multiple control factors, such as depth-related soil conditions (temperature, moisture and aeration, etc.) (Kuhn et al., 2009; Quinton et al., 2010), the stability of soil organic matter (SOM) and associated stabilisation mechanisms, as well as the possible differing nature of SOM in sediments as derived from different delivering locations within a catchment (Nadeu et al., 2012, 2014; Kirkels et al., 2014).

Source pools of TOC and TN from different landform positions can affect the persistence of eroded C and N in deposition sites. For instance, soil material eroded from the surficial soils by sheet erosion might have a large proportion of relatively undecomposed OM (i.e., active OM pool which is easy to decompose and mineralize during transport or post-deposition downstream) with a high C and N contents (Wang et al., 2010; McCorkle et al., 2016). Gullies can produce a large amount of sediments, but soil materials by rill or gully erosion may contain very little C and N contents with a high proportion of relatively decomposed OM (i.e., passive OM pool which is difficult to decompose and mineralize by associating with soil minerals through aggregation or sorptive interactions during transport or after deposition downstream) (McCorkle et al., 2016). As a result, the soil material eroded from deeper soil layers should be stabilized compared to soil material eroded from surficial soil horizons during erosion, transport, and post-deposition processes (McCorkle et al., 2016; Li et al., 2017a,b; Nie et al., 2018). Moreover, although sediment OC and TN can be delivered from the terrestrial watershed (allochthonous input), the net primary production of plants on site is also likely to have a high proportion contribution to C and N pools in eroded sediments at deposition site (autochthonous input) (Liu et al., 2017a). Therefore, quantification of the fluxes of C or N between the uplands and alluvial plain induced by soil erosion, as well as identification of source materials contributing to sediment C and N within a catchment, are essential to determine C and N budgets, develop prediction models and implement soil conservation strategies at catchment scale.

Carbon and nitrogen stable isotope ratios (δ^{13}C, δ^{15}N) and elemental compositions are a potentially powerful tool to trace the contributions of catchment sources to sediment and to in-stream particulate organic matter export out of the catchment (Liu and Xing, 2012; Laceby et al., 2015; Garzon-Garcia et al., 2016, Lu et al., 2016). In addition, stable isotopes have also been used to trace the sources of eroding material occurring on catchment hillslopes (Meusburger et al., 2013). The successful employment of stable isotope compositions of carbon and nitrogen are attributed to the significant difference among ecosystem pools because of isotopic fractionation during the cycling of C and N caused by physical, chemical, and biological processes (Weihmann et al., 2007; McCorkle et al., 2016). Furthermore, other tracers, particularly elemental ratios (i.e., the C/N ratio), might also be used to complement isotopic approaches for determining organic matter sources (Kendall et al., 2001; Liu et al., 2017a).

The loess hilly-gully regions in northwestern China are the most severe soil erosion region in the world because of its precipitation characteristic, high soil erodibility, and intensive human activities in this region (Fu et al., 2011; Yue et al., 2016). More than 60% of the land in the Loess Plateau has subjected to soil erosion, with an average annual soil loss of 20–25 Mg ha^{-1} (Shi and Shao, 2000 Li et al., 2017a). Furthermore, significant amounts of nutrients associated with surface soil are lost during soil erosion in the Chinese Loess Plateau (Cai, 2001; Li et al., 2015). Approximately 0.8–1.5 kg of ammonia, 1.5 kg of total phosphorus, and 20 kg of total potassium in each ton of eroded soil are lost as estimated by Cai (2001). Carbon and nitrogen losses in the soil ecosystem not only have seriously depleted land resources and degraded the ecosystem in the Loess Plateau, but also have impacted the biogeochemical cycles of carbon and nitrogen in the terrestrial and aquatic ecosystem (Liu and Xing, 2012).

With the implementation of a series of soil and water conservation measures since the 1950s on the Loess Plateau, vast areas of cropland with a slope gradient that exceeded 25° in mountainous areas are converted to forestland or grassland in the gully and hilly zones and more than 90,000 check dams are constructed in gullies and streams (Wang et al., 2016; Zhao et al., 2016). Consequently, the intensity of soil erosion has been greatly mitigated and the sediment export to lower reaches of Yellow river has decreased significantly over the past six decades (Miao et al., 2010; Gao et al., 2010). As the most widespread and effective strategy to reduce soil and water loss, check dams not only trap all of the sediments that are derived from upstream soil erosion but also intercept massive amounts of SOC and TN in the alluvial wedges, which form an important C or N sink area (Boix-Fayos et al., 2009; Lü et al., 2012; Liu et al., 2017b). The organic matter content in sediment cores trapped by check dam can provide an important history information on soil erosion and land use change (Meyers, 2003; Chen et al., 2016). Although the information regarding the rate of sediment yield and source has been well-documented (Chen et al., 2016; Zhao et al., 2017), however, owing to the complexity and uncertainty as to the fate of the OC and TN that are exported out of eroding catchments during erosion, transport, and deposition processes, little information on soil C and N redistribution patterns and sources at the catchment scale is available on the Loess Plateau, especially as regards the N dynamic characteristics in soil erosion subsystem.

Therefore, the main objectives of this study were to: 1) determine the potential sources of eroded OC and TN in sediment cores using SIAR model and isotope tracing, 2) analyze the spatial variation of eroded OC and TN sources, 3) quantify the soil OC and TN mobilized by erosion at the catchment scale. The results will provide scientific basis on the study of C and N budgets and implementation of valid soil conservation strategies at larger scale catchment.

2. Materials and methods

2.1. Study area

The Luoyugou watershed (34°34′–34°34′N, 105°30′–105°45′E) is located in the northern suburbs of Tianshui city in the Gansu Province of China, and covers an area of 72.3 km^2. This watershed is situated in the southwestern hilly-gully region of the Chinese Loess Plateau