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Novel application of Compound Specific Stable Isotope (CSSI) techniques to investigate on-site sediment origins across arable fields

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ABSTRACT

In recent years, Compound Specific Stable Isotope (CSSI) techniques have enabled promising new tracers to track land-use-specific sediment sources. However, empirical data exploring the technique, particularly under controlled conditions, is still scarce. Hence, the main goal of this study is to explore the suitability of CSSI to identify sediment sources under different land use in the small agricultural site of Mistelbach (8.7 ha) located in Austria. In a previous study, the authors quantified, with a ^{137}Cs-based reconnaissance approach, a sedimentation magnitude of 4 mm year^{-1} in the deposition zone at the outlet of that study site. To obtain detailed information on the sediment provenance, CSSI techniques based on the measurement of δ^{13}C signatures of natural fatty acids (FAs), were used. A cost effective sampling approach involving composite sampling, identified potential sediment source materials from the four main agricultural fields. Two long-chain FAs (i.e. C22:0 = behenic acid; C24:0 = lignoceric acid) as well as bulk δ^{13}C allowed the best statistical discrimination for apportioning the origin of the sediments. Four mixing models (i.e. IsoSource, SIAR, MixSIAR and SIMMR) applied to the data generated similar results. IsoSource performed as well as the other Bayesian models tested.

The main grazed waterway of the basin, identified as one of the four sources of the sediment, was evaluated to have contributed 55.1 ± 5% (IsoSource), 53.9 ± 2.7% (SIAR), 53.9 ± 2.7% (MixSIAR) and 54.0 ± 2.7% (SIMMR) to the sediment. The estimated contributions of the sources to the sediment are consistent with the land use information and the distance of the sources to the outlet. More than 80% of the sediment deposited at the basin exit originates from the two sources which had maize cultivation, one of the more erosive crops, in particular at the beginning of the growing season. This study emphasizes that CSSI and ^{137}Cs techniques are complementary for establishing land sediment redistribution. Their combined use could provide key decision support knowledge for optimised decision-making of land managers to ensure the sustainability of agro-ecosystem management.

1. Introduction

Climate change poses a clear challenge to worldwide food security (Branca et al., 2013; FAO, 2015; HLPE, 2012). The Economics of Land Degradation (ELD) Initiative stressed that each year land degradation cost over USD 10 trillion and that worldwide 1.4 billion people are already affected in their daily life (ELD Initiative, 2015).

Predicted extreme weather events will increase soil degradation processes and hence impact natural resource sustainability (FAO, 2013, 2017; IPCC, 2014; Nearing et al., 2004; WMO, 2005). As a result of climate change, by the year 2050 the European water erosion risk will increase by around 80% (EEA, 2002). Extensive soil degradation processes are occurring in Europe (Boardman and Poesen, 2006). European soil erosion losses are much above soil formation rate and the yearly costs of soil erosion was recently evaluated at around US$20 billion (Panagos et al., 2015).

Current European concerns for proper soil & water resources management have generated a crucial necessity to establish precise fertile

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soil loss rates. This information is needed (1) for evaluating the various impacts of soil erosion, (2) to reinforce our understanding of key driving processes, (3) to confirm soil redistribution magnitudes predicted by models, and (4) to propose scientifically sound and effective soil conservation strategies (IAEA, 2014).

Moreover, as climate change is expected to further increase soil erosion magnitude (García-Ruiz et al., 2017; Li and Fang, 2016; Nearing et al., 2004), an improved knowledge of erosion processes and pathways is required to reduce soil loss related agro-environmental issues.

Traditional methods to investigate agricultural soil redistribution involving modelling and monitoring techniques (e.g. erosion pins, erosion modelling, erosion plots, sediment quantification and records) have several limitations in terms of validation, data acquisition and involved costs. The quest for innovative approaches for assessing soil redistribution processes has directed the attention of multidisciplinary scientists to the use of fallout radionuclide (FRN) tracers which could inform about the magnitude and pattern of erosion and sedimentation (Alewell et al., 2014, 2017; IAEA, 2014; Mabit et al., 2008, 2013, 2014; Taylor et al., 2013; Walling, 2013).

However, these anthropogenic (i.e. ^{137}Cs, $^{239+240}$Pu), geogenic (i.e. ^{210}Pb$_{ex}$) and cosmogenic (i.e. ^{7}Be) soil radiotracers have limited ability to provide precise knowledge regarding the contribution of the different agro-environmental sources of sediment that could be accumulated and deposited along the landscape (Blake et al., 2012; Guzmán et al., 2013; IAEA, 2014). Furthermore, other existing isotopic techniques used as fingerprints such as bulk information of stable isotopes (^{13}C and/or ^{15}N) are limited in their ability to deliver such specific information (Alewell et al., 2008; Fox and Papanicolaou, 2007; Laceby et al., 2015; Schaub and Alewell, 2009; Schindler Wildhaber et al., 2012).

In this context, compound-specific stable isotope (CSSI) techniques, also termed in the literature as compound-specific isotope analysis (CSIA), appear as a new effective isotopic fingerprinting approach for land-use-specific sediment source identification (Owens et al., 2016; Reiffarth et al., 2016). Indeed, CSSI signatures of inherent soil organic biomarkers (e.g. natural fatty acids (FAs), *n*-alkane (e.g. Cooper et al., 2015; Glaser, 2005) allow discriminating and apportioning of the source soil contribution originating from various land uses. The concept behind the CSSI method is that “land use” is usually defined by the plants growing on that land. Plant communities “label” the soil where they grow by exuding organic biomarkers (Mabit et al., 2015). Plants generate various organic compounds that “leak” from the roots or leach from leaves into the soil. Different plant species produce a similar range of organic compounds, but with different isotopic δ^{13}C (i.e. ^{13}C/^{12}C ratio) values (Gibbs, 2008; Tolosa et al., 2013). According to Mabit et al. (2015) “By linking fingerprints of land use to the sediment in deposition zones, this approach has been shown to be a useful technique for determining the source of eroded soil and thereby identifying areas prone to soil degradation”. For agro-environmental investigations, the CSSI technique relies on the determination of the δ^{13}C signatures of particular soil organic compounds (i.e. FAs). Applied research studies pioneered in New Zealand were the first to demonstrate the usefulness of CSSI focusing on FAs to quantitatively address sediment provenance from soils to adjacent freshwaters (Gibbs, 2008). One has to admit that although it started around 10 years ago, this method optimising the use of the FAs carbon isotopic signature is still in its infancy to investigate agroecosystems with various land use. Indeed for this specific purpose, peer-reviewed publications reporting applied CSSI studies using FAs are rare. Blake et al. (2012) reported that CSSI techniques – supported by additional geochemical mineral tracers – offer key information for land management policies and for protecting surface water bodies against over-siltation processes. More recently, Hancock and Revill (2013) and Brandt et al. (2018 and 2016) successfully applied the CSSI techniques in a 3860 km^2 rural Australian catchment of the Logan and Albert rivers, and in the agricultural upland areas surrounding the Chieng Khoi Lake (northwest Vietnam), respectively. In Switzerland, when investigating the Enziwigger catchment dominated by C$_3$ vegetation, Alewell et al. (2016) recommended focusing on long chain saturated FAs exclusively of plant origin for sediment source attribution, and suggested using compound content/concentration rather than soil organic matter to convert the measured δ^{13}C signature of the FAs into soil proportion estimates. Recent reviews of literature from Upadhayay et al. (2017) and Reiffarth et al. (2016) will provide the readers an up-to-date state of knowledge of the limitation and challenges when using CSSI techniques for FAs to investigate soil and sediment fingerprinting.

Here we propose an advancement of the above described technique of tracing soil sediments to freshwaters, we aim to track terrestrial sediment movement on-site within the small Austrian basin of Mistelbach, where the authors have already demonstrated the complementarities of conventional erosion plots and FRNs to evaluate erosion and sedimentation magnitudes (see Mabit et al., 2010; Mabit et al., 2009). More specifically, our objectives were to test the ability of CSSI based fingerprinting to apportion the different sediment sources contributing to an adjacent terrestrial deposition area, by (a) distinguishing the best FAs indicators according to the land use of the sources and the sedimentation area and by (b) applying the CSSI techniques under Austrian agro-climatic conditions to quantify the relative contribution of each connected source to the on-site deposition area according to the land use and their specific stable isotopic signatures.

2. Material and methods

2.1. Site description and background information

Characterized by moderate slopes (5–20%), the 8.7 hectare investigated sub-basin of Mistelbach is situated in Austria 60 km north of Vienna (Fig. 1). Under continental temperate climate, the yearly precipitation reaches 643 mm and the average air temperature is 9.6 °C. The soil of the area, which is developed on parental loessic material, has been classified as typical Argiudoll with a silt loam textural class (Klik, 2003; Klik et al., 2004).

The effectiveness of various soil conservation strategies (i.e. conventional tillage, conservation tillage and direct seeding) has been already assessed by the authors in this small basin using FRN and conventional techniques (Mabit et al., 2010; Mabit et al., 2009).

During these previous investigations, the evaluation of soil redistribution magnitudes and the basin geomorphology identified the lowest part of the sub-basin as localised a small deposition area.

Using the ^{137}Cs technique, Mabit et al. (2009) reported a local maximum sedimentation rate reaching 50 t ha^{-1} year^{-1}. However, this pilot FRN study did not provide information regarding the origin of the deposited sediment. According to its geomorphological local condition, a total of four soil sources could be considered as contributors to the sedimentation process occurring in this basin (Fig. 1). For the sampling, “Sources” are defined as the soils from a well-defined land use/agricultural field, which should be connected to the sedimentation area and could potentially contribute to it. Subsequently, the deposited sediment (hereafter termed the “mixture”; the mixture being defined as the sample of sediment from a downslope location in the specific catchment) and representative soil samples from the four main agricultural fields - expected to be the source soils based on the geomorphology of the basin and fields reconnaissance such as the runoff generation location - of the site were investigated (see Section 2.2 and Fig. 1).

2.2. Sampling strategy

In 2012, the CSSI technique was tested under our experimental condition in collecting representative samples in the agricultural fields of Mistelbach which, based on the characteristics of the area and on field surveys, can be considered as major contributors to the