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Compound-specific δ^{13}C isotopes and Bayesian inference for erosion estimates under different land use in Vietnam

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ABSTRACT

Recent studies have pointed out the potential of the compound specific stable isotope (CSSI) technique based on long-chain fatty acids methylester (FAME) to identify hot spots of soil erosion by means of land use types. We tested the applicability of the CSSI technique on the basis of soil and sediment samples derived from a small agriculturally used catchment in Vietnam which is exemplary for many mountainous areas in Southeast Asia. Following CSSI analysis we set up a statistical decision sequence to identify hot spots of soil erosion by i) testing for significant differences between δ^{13}C values of fatty acids (FA) of different contributing land use types and thereafter ii) examining the data using a Monte Carlo simulation of mixing polygons to provide a quantitative basis for model rejection and exclusion for sediment samples which violate the point-in-polygon assumption and iii) applying a Bayesian model with a Markov chain Monte Carlo (MCMC) model fitting using "SIAR" (Stable Isotope Analysis in R), which produces simulations of plausible values and therefore representing a true probability density for the proportional contribution of source soils. Our results confirmed that there were significantly different δ^{13}C values for identical FAMEs extracted from soils under different land uses. Most fatty acids with significantly different δ^{13}C values were found between soils under C_3 (protected and secondary forest, teak and fruit plantations) and C_4 (maize) plants but also within different soils of land use types which consisted only of C_3 plants (e.g. protected forest, fruit plantation and teak). The resulting soil proportions were plausible for the six investigated sedimentation areas and suggested that fields under crop production such as maize and cassava, but also teak plantations were the main sources of eroding soil in the upland area surrounding the Chieng Khoi reservoir. Based on our data, we can conclude that the developed integrated Bayesian SIAR-CSSI approach represents a unique tool to identify and apportion soil sources to major land use types in small heterogeneous catchments by linking biomarkers of land use types to the sediment in deposition zones.

1. Introduction

Water erosion and accompanying loss of soil organic carbon (SOC) is a global driver of land degradation (Lal, 2003). Water erosion leads to a serious decline in soil productivity and crop production in intensively managed tropical mountainous catchments, where exceptional topographical and climatic conditions prevail (El-Swaify et al., 1982). In particular, in mountainous regions of Southeast Asia (e.g., Vietnam, Thailand), land use intensification has been promoted by increased population pressure and agricultural commercialization. Hence, farmers expanded crop cultivation into marginal forested upland regions, where large scale cultivation of maize and cassava as cash crops was introduced (Valentin et al., 2008). As a consequence of resulting loss of soil cover and intensive soil tillage, severe erosion on steep slopes (up to 174 Mg ha^{-1} yr^{-1}) was induced resulting in associated soil degradation through soil relocation (e.g., SOC, nutrients) from uplands to lowlands (Dung et al., 2008; Lam et al., 2005; Pansak et al., 2008; Tuan et al., 2014). This soil relocation process increased sedimentation yields in paddy fields and in local reservoirs as well as enhanced sediment loads in rivers (Dung et al., 2009; Lippe et al., 2014; Schmitter et al., 2012).

To counteract this development and to design soil conservation measures at designated soil erosion hot spots, accurate analytical methods are required to trace predominant sources of soil erosion. So far, fallout radionuclides (FRN; e.g., caesium-137, excess lead-210, beryllium-7) proved to be most suitable for generating soil redistribution patterns at catchment scale (Dercon et al., 2012; Mabit et al., 2008).

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Although FRNs estimate accurately the quantitative sediment budget for a specific location, they do not assign a denudation rate to a specific upland land use type (Blake et al., 2012; Hancock and Revill, 2013).

Alternatively, lipid biomarkers (e.g., fatty acids (FA)) were recently introduced as promising indicators for tracking land use types (i.e., sources) that contribute to downstream sediment materials (Mead et al., 2005; Ratnayake et al., 2011). FAs are ubiquitous in soil and originate from root exudates, above ground plant biomass and microorganisms (Badri and Vivanco, 2009; Ibekwe and Kennedy, 1999; Wiesenberg et al., 2010). Due to their polarity, FAs are partially water soluble and after percolation into soil, they can form associations with clay minerals (Williams et al., 2006).

The newly formed FA-clay mineral associations serve as a biomarker, which, after surface run-off and deposition in sedimentation areas, provide the link between eroding soil material from distinct land use types and respective sediments. An important criterion to use FAs as erosion biomarkers is their individual $\delta^{13}C$ isotopic signature creating a unique fingerprint which allows identifying erosion sources without relying on the amount of FAs present. It is worthwhile emphasizing that this isotopic signature does not alter to a great extent over time as non-degradative processes including volatilization, dilution, dispersion, and equilibrium sorption do not cause significant isotope fractionation (Blessing et al., 2008). Hence, it can be manifested that compound specific stable isotope (CSSI) analysis based on long-chain FAs (i.e., C12:0 to C24:0) represents a major advancement to tackle source-sink relationships at catchment level (e.g., Chikaraishi and Naraoka, 2003; Gibbs, 2008).

Gibbs (2008) using the CSSI approach successfully assessed the contributions of soils under natural forest, pine forest, pasture, agricultural land and urban areas to sediment bodies in an estuary of the Mahurangi catchment (117 km^2) in New Zealand. Blake et al. (2012) applied the CSSI approach in a small agricultural catchment (i.e., 145 ha, Furze Brook, UK) to successfully apportion the relative sediment contribution of harvested fields (maize, wheat), grasslands and forests to downstream sediments. Moreover, Hancock and Revill (2013) investigated the sediment provenances of the Logan River Basin in Australia (3860 km^2).

Although these examples justify the successful application of FA-based CSSIs at larger catchment scales, their applicability was never corroborated in erosion prone small tropical catchments which are characterized by very heterogeneous land use types. Hence, we used a representative catchment in Northwest Vietnam with various annual and perennial crops, fruit trees and commercial and natural forests to test the hypothesis if the CSSI analysis approach is suited to derive significant differences of individual soil FA $\delta^{13}C$ values in source soils allowing the clear distinction of various upland land use types. We further hypothesized that, when bound to clay minerals and translocated by erosion, FAs with land use type specific $\delta^{13}C$ values enable the identification of source soil composition of sediments and hence the determination of SOC-related source-sink relationships at catchment levels smaller than one hectare. Our objective was thus to develop a statistical procedure to identify erosion prone land use types based on their proportional isotopic contribution to sediment deposition areas in a heterogeneous small agricultural catchment.

2. Materials and methods

2.1. Study area

The model catchment was located in the Chieng Khoi commune (21° 7′60″N, 105°40′0″E), Son La province in Northwest Vietnam. The climate is characterized by tropical monsoons, with a rainy season from May to October and a relatively dry, cold season from November to April. The average annual temperature is 21 °C, with a maximum of 27 °C in August and a minimum of 16 °C in February (Thao, 1997). Average annual precipitation amounts to 1110 mm (Hien et al., 1995).

The commune covers a total area of 3189 ha and has an altitudinal range of 320 to 1600 m above sea level (a.s.l.). Steep mountain limestone ridges and areas of more undulating hills characterize the topography of the catchment. The geological bedrock material derived from the Yen Chau Formation deposited during the upper Cretaceous period. The dominating bedrocks are made of limestone and schist (Bao, 2004). Upland soils in the Yen Chau area belong mostly to Ferralsols and Leptosols (FAO classification) (Wezel et al., 2002). Clemens et al. (2010) reported that the most common soil types within the upland area of the Chieng Khoi commune were characterized as Luvisols and Alisols (FAO classification). Leptosols were mostly found on top-slope position and showed considerable signs of severe soil erosion, especially on hills under maize production. Exposed parent rocks on hilltops as well as sheet and gully erosion on the upper and middle slopes are common for maize fields in the region.

An irrigation lake was constructed to regulate the supply of water to downstream paddy rice fields in the catchment. It covers approximately 12% of the Chieng Khoi catchment. Originating from the dammed stream Doi Ban, the Chieng Khoi Lake of about 26 ha is situated in a karstic depression, surrounded by a chain of calcareous mountains and has a catchment area of about 207 ha. The stream was initially dammed in 1963, while the present concrete dam was finished in 1974. Elevation of the area around the Chieng Khoi Lake ranges from 429 to 493 m a.s.l. with slope steepness up to 86%. Since 1963, the primary forest decreased by >50% and nowadays almost 25% of the total catchment area is under agricultural use.

The Chieng Khoi catchment has been characterized by traditional shifting cultivation and secondary forests. The latter are 10 to 30 years of age and consist mainly of small deciduous broad-leaved trees mixed with bamboo and bushes. The remnants of the protected natural forests were never cultivated. In the last decades, most traditional shifting cultivation systems with fallow periods were replaced by permanent crop monocultures and commercial fruit trees and forests.

2.2. Sample collection

Characteristic land use types of the upland area surrounding the Chieng Khoi Lake were identified as potential soil source sites. These land use types included field crops such as maize (M; *Zea mays* L.) and cassava (C; *Manihot esculenta* Crantz) as well as commercial forests (T) consisting of teak (*Tectona grandis* L.) or Chukrasia (*Chukrasia tabularis* A. JUSS.). Moreover, fruit tree plantations (FP) including mango (*Mangifera indica* L.), jackfruit (*Artocarpus heterophyllus* LAM.), tamarind (*Tamarindus indica* L.), and longan (*Dimocarpus longan* LOUR.) were determined. Furthermore, secondary (SF) and protected natural (PF) forests surrounding the lake were considered as potential sources of soil erosion. Soil and sediment samples were collected in July to September 2010 and March to May 2012. At the time of sampling maize and cassava were cultivated either as mono crops or as maize-cassava intercrop. We obtained soil samples only from fields with monocrops. Crop-fallow rotation systems and also maize-cassava rotation systems were abandoned in favor for permanent cropping systems with high yield varieties in the 1990s.

Top soil (0–2 cm) samples of each individual land use type were collected from at least 3 discrete plots of each land use type within the upland area around the Chieng Khoi Lake. In each plot, soil samples were obtained from 3 different positions (e.g., lower, middle, upper slope). At each position, 20 sub-samples from an area of 20 m^2 were combined to a composite sample of each land use. Collecting spatially-integrated mixtures allowed us to obtain representative soil samples of each land use type but the degree of variability in the source samples might still be under- estimated in most cases. Analyzing all individual sub-samples would have provided better insight on the variability of each CSSI value from that explicit land use type and improved most likely the interpretation and statistics using SIAR. However, these advantages stand in contrast to the analytical costs which would have been soared. Using