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Integrating compound-specific $\delta^{13}C$ isotopes and fallout radionuclides to retrace land use type-specific net erosion rates in a small tropical catchment exposed to intense land use change

Christian Brandt[a], Moncef Benmansour[b], Leander Walz[a], Lam T. Nguyen[c], Georg Cadisch[a], Frank Rasche[a,*]

[a] Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute), University of Hohenheim, Stuttgart, Germany
[b] Centre National de l'Energie, des Sciences et des Techniques Nucléaires, Rabat, Morocco
[c] Department of Environmental Management, Vietnam National University of Agriculture, Hanoi, Vietnam

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ABSTRACT

Retracing net erosion rates linked to land use change in tropical agricultural catchments dominated by smallholder farmers is challenging, due largely to catchment heterogeneity and uncontrolled farming practices. To tackle this problem and to complement a preceding study (Brandt et al., 2016), we introduce here an advanced approach that integrates compound-specific $\delta^{13}C$ isotopes (CSSI) and fallout radionuclides (FRN), Excess lead-210 ($^{210}Pb_{ex}$) and Cesium-137 (^{137}Cs) to estimate past net erosion rates of dominant land use types in the mountainous catchment Chieng Khoi (207 ha, Northwest Vietnam). Spatially-integrated topsoil (0 to 2 cm) samples of dominant land use types (e.g., protected and secondary forests, teak, fruit orchards, maize, cassava) were collected from at least three discrete plots of each land use type within the upland area (i.e., erosion sites) of the studied catchment. In the corresponding lowland area, a representative sediment profile was localized and divided into sections of 2 to 4 cm for CSSI and FRN analysis. Samples for FRN reference data were taken from undisturbed areas in close proximity. At a soil deposition site near a lakeshore, $^{210}Pb_{ex}$ data determined the age and sediment accumulation rates of 19 sediment layers to a depth of 38 cm. Based on $^{210}Pb_{ex}$ activity, maximum sediment accumulation rates of 127 t ha^{-1} y^{-1} were calculated, corresponding to erosion rates of about 16 t ha^{-1} y^{-1} for the total catchment area. CSSI data confirmed that maize and cassava were the most important erosion sources during a period of dramatic land use change (1987 to 2004), when forests were cleared and high-yielding maize hybrids were introduced. Based on integrated FRN and CSSI data, net erosion rates of maize and cassava reached maximum rates of 4.8 t ha^{-1} y^{-1} (maize), 6.2 t ha^{-1} y^{-1} (cassava). This major finding verified the potential of integrating FRN and CSSI to accurately estimate land use type-specific net erosion rates. In conclusion, determining past sediment budgets for specific land use types provides insight into the accelerating impact of specific land use change on soil retrogression and degradation. Such knowledge is of prime importance for effective soil conservation through evidence-based land management and decision making.

1. Introduction

In mountainous areas of Southeast Asia, land use change is an acknowledged threat to ecosystem stability, putting rural livelihoods at serious risk (Valentin et al., 2008; Wezel et al., 2002). Accelerating urbanization, changing market forces, and loss of agricultural land in the lowlands has pushed farmers to migrate to upland regions. Typically, this migration has resulted in serious intensification of land use followed by soil retrogression and degradation (Yen et al., 2013). For example, in the Chieng Khoi catchment in the northwestern uplands of Vietnam, shifting cultivation has been increasingly abandoned in favor of hybrid cash crops, primarily maize (*Zea maize* L.) and cassava (*Manihot esculenta* Crantz) (Podwojewski et al., 2008; MSEC, 2003). Consequently, severe erosion on steep slopes (up to 174 t ha^{-1} yr^{-1}) occurred (Dung et al., 2008; Lam et al., 2005; Pansak et al., 2008; Tuan et al., 2014), along with accelerated sedimentation of paddy fields, local reservoirs and rivers (Dung et al., 2009; Lippe et al., 2014; Schmitter et al., 2012).

Strategies to counteract further soil degradation and the extension of agricultural land into remaining forests require solid data so that

* Corresponding author.
E-mail address: frank.rasche@uni-hohenheim.de (F. Rasche).

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evidence-based land management decisions and effective soil conservation measures can be made. In this respect, fallout radionuclides (FRN; e.g., Cesium-137 (^{137}Cs), excess lead-210 (^{210}Pb$_{ex}$) and Beryllium-7 (^{7}Be) have proven most suitable for generating soil redistribution patterns at the catchment scale (Dercon et al., 2012; Mabit et al., 2008; Zapata, 2003). Based on their different half-lives and origins, FRN make it possible to date the layers of a sediment profile and provide quantitative estimates on the amount (kg m^{-2} y^{-1}) of relocated soil (Dercon et al., 2012; Mabit et al., 2008; Walling et al., 2003). ^{137}Cs (half-life 30.17 yr) is of anthropogenic origin and is produced during nuclear fission. From 1952–1980s, ^{137}Cs was globally disseminated by atmospheric testing of thermonuclear weapons (UNSCEAR, 2000). ^{210}Pb$_{ex}$ (half-life 22.2 yr) is of geogenic origin and its atmospheric fallout is constant over time at a specific site (Appleby and Oldfield, 1978). For more detailed and up-to-date information of the specific FRN used for this study (i.e. ^{137}Cs, ^{210}Pb$_{ex}$), we refer the reader to the following two major review articles: Mabit et al. (2013) and Mabit et al. (2014).

Although FRNs estimate 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). To resolve this question, the compound specific stable isotope (CSSI) technique using lipid biomarkers has been recently introduced to trace the sources of sediments (Chikaraishi and Naraoka, 2003; Gibbs, 2008; Mead et al., 2005; Ratnayake et al., 2011). Principally, this technique uses land use cover-dependent differences in the δ^{13}C isotopic signatures of specific organic compounds (i.e., soil fatty acids (FA)). The CSSI technique has been successfully tested and validated to estimate the proportional contributions of different land use sources to sediment bodies (e.g. Alewell et al., 2016; Blake et al., 2012; Brandt et al., 2016; Hancock and Revill, 2013).

To reconstruct historical land use, Gibbs (2014) suggested a multi-isotopic investigation involving FRN and CSSI techniques. To complement a preceding study by Brandt et al. (2016), we present here an enhanced approach that integrates FRN and CSSI techniques to accurately estimate land use type-specific net erosion rates, making it possible to determine past sediment budgets for specific land use types. Thus, we hypothesized that integrating FRN-derived quantitative past sediment budgets with CSSI-calculated proportional soil contributions to the layers of a sediment profile would permit estimation of land use type-specific past net erosion rates. We further hypothesized that knowledge about past net erosion rates would provide critical insights into past soil redistribution, providing a way to evaluate the accelerating impact of specific land use change on soil degradation in heterogeneous agricultural catchments.

2. Materials and methods

2.1. Study area and sample collection

2.1.1. Study site

The Chieng Khoi catchment is located in the Chieng Khoi commune (21°7′60″N, 105°40′0″E), Son La province in Northwest Vietnam (Brandt et al., 2016). In this catchment, an irrigation lake was constructed in 1974 to regulate the supply of water to downstream paddy rice fields. 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, with a catchment area of about 207 ha. Elevation of the area around the lake ranges from 429 to 493 m above sea level (a.s.l.) with a slope of up to 86%.

Characteristic land use types of the upland area surrounding the lake were identified as potential sediment sources. These land use types included crops such as maize (*Zea mays* L.) and cassava (*Manihot esculenta* Crantz), as well as commercial forests consisting of teak (*Tectona grandis* L.) or Chukrasia (*Chukrasia tabularis* A. JUSS.). Fruit orchards, including mango (*Mangifera indica* L.), jackfruit (*Artocarpus heterophyllus* LAM.), tamarind (*Tamarindus indica* L.), and longan (*Dimocarpus longan* LOUR.), were also identified. Additionally, protected and secondary forests surrounding the lake were considered as potential sediment sources.

2.1.2. Land use history of the Chieng Khoi catchment

To quantify past sediment contributions from specific land use types, information on land cover history was obtained by interviewing local farmers of Ban Tum and Ban Me villages (Minh et al., 2011; Nguyen, personal communication). Considerable land use change started in the middle of the 20th century. Before 1973, almost the entire upland area of the catchment was covered in primary and secondary forest. Local varieties of upland rice and maize were cultivated only on small areas for shifting cultivation. During the early 1990s, deforestation intensified and the areas under cultivation increased. Cleared areas were cropped with fruit trees and increasingly with local varieties of bi- or tri-ennial cassava. Increasing land degradation and the loss of soil fertility led to the disappearance of upland rice (*Oryza sativa* L.) production after 1990. Cultivation of cotton (*Gossypium spec.*) was discontinued by the end of the 1980s, and white mulberry (*Morus alba* L.) for silkworms at the end of the 1990s (Lippe, personal communication). Near the end of the 1990s, teak, Chukrasia, and pine were introduced for reforestation and later extended to production forests. Cultivation of fruit orchards, including mango, jackfruit, tamarind, and longan, was also promoted. Since 1996, shrub- and tree-covered steep slope areas were successively replaced by high yielding hybrid maize and commercial 1-year cassava varieties. First, maize and cassava areas were intercropped with fruit trees. When demand and prices soared, intercropping was replaced by monoculture. This development was accompanied by increased use of chemical fertilizers, deep ploughing, and a transition from stick to furrow planting. After forest clearance, maize was cultivated as long as soil fertility was sufficient. When soil fertility declined on maize fields, 1-year cassava was introduced and cultivated for several years (Tuan et al., 2014). Fields are commonly left fallow when soil fertility declines below the requirement of cassava (Nguyen, personal communication).

2.1.3. Sample collection and preparation

Soil and sediment samples were collected from July to September 2010 and March to May 2012. Topsoil (0 to 2 cm) samples of individual land use types were collected from at least 3 discrete plots of each land use type within the upland area around the 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 provide a composite sample of each land use type. Collecting composite samples made it possible to integrate spatial variability and therefore obtain a representative sample for each source. The alluvial fanlike site of the sediment core was located at the upper shore of a lake cove. This location was chosen for the surrounding land use types, which were representative of the entire catchment area (Fig. 1b). The sediment core was divided into sections of 2 to 4 cm to a depth of 280 cm. The samples for CSSI and FRN analyses were taken every 2 cm. The generic feasibility test of integrating FRN and CSSI data to estimate land use type-specific net erosion rates was based on only one representative sediment profile. More profiles may have revealed in more detail the spatio-temporal variability of sediment deposition of the study area and refined information on the impact of specific land use types to past erosion processes. However, due to the need to limit the analytical expenditure for this exploratory approach, additional sediment profiles were not considered in this study. The first undisturbed reference site for ^{137}Cs and ^{210}Pb$_{ex}$ was located in proximity to the sediment profile and the second site was located in the Ban Cang area neighboring the Chieng Khoi catchment. Reference sites were investigated for ^{137}Cs and for ^{210}Pb$_{ex}$ to evaluate the reference inventory that would then be compared to the radioisotopic inventory in the sedimentation area where