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Sediment induced soil spatial variation in paddy fields of Northwest Vietnam

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ABSTRACT

The aim of this study was to assess the impact of various sedimentation pathways (flooding, irrigation and runoff) on the spatial variability of soil fertility in rice paddy terraces in tropical mountainous regions of Northwest Vietnam. Topsoil samples were taken during two subsequent rice cropping seasons and analyzed using a combination of diffuse reflectance mid infrared spectroscopy and conventional lab analysis. A mixed model was used (i) to evaluate the spatial variability among and within paddy cascades before planting in function of field position to the main irrigation channel, and (ii) to assess the impact of various sediment deposition pathways on soil nutrients and textural changes. The topsoil taken before planting contained on average 1.75 ± 0.57 g 100 g^{-1} soil organic carbon (SOC), 0.18 ± 0.06 g 100 g^{-1} total nitrogen (TN) with silt being the dominating soil fraction (0.68 ± 0.11 g g^{-1}). Moderate sediment delivery of high quality through the irrigation system resulted in a significant enrichment in lower lying paddies following a linear trend for SOC (SOC (g 100 g^{-1}) $= 1.4 + 0.02$ Distance (m), $R^2 = 0.31 - 0.62$), total nitrogen (TN (g 100 g^{-1}) $= 0.11 + 0.004$ Distance (m), $R^2 = 0.33 - 0.61$) and a significant linear decrease in the sand fraction (sand (g g^{-1}) $= 0.3 - 8\,E^{-04}$ Distance (m), $R^2 = 0.28 - 0.48$) with increasing distance from the irrigation channel along the cascade. Comparison of the samples taken before planting and after harvesting proved that the spatial variability in the topsoil was induced by sediment deposition resulting in a decrease of 0.11 g 100 g^{-1} of SOC and 0.01 g 100 g^{-1} of total N and an increase of 0.02 g g^{-1} of the sand fraction in paddies close to the irrigation channel which received less nutrient rich sediment deposition. However, besides the effect of sediment rich irrigation water, direct sediment depositions originating from the highly eroded and unfertile uplands or deposited during flooding events (typhoons) strongly decreased soil fertility in the rice fields due to their low nutrient and high sand content. In conclusion, the alterations and maintenance of soil fertility of rice fields depended on the balance of the various sediment sources, i.e. quality and quantity, and is thus, strongly related to both upland management and extreme weather events and irrigation practices. These findings are relevant in the framework of site-specific fertilizer management by taking advantage of spatial variability in soil fertility along cascades of rice paddy terraces in tropical mountainous regions.

1. Introduction

In mountainous Northern Vietnam, an important agroecosystem is a composite swidden agriculture which integrates annual food crops, such as maize, cassava and upland rice, and fallow in the uplands with permanent wet rice fields downstream of the catchment (Lam et al., 2005). The cultivated land per person in Northern Vietnam is decreasing strongly due to population pressure, so that continued deforestation and slash and burn practices on steep slopes are common in order to expand the upland area (Wezel et al., 2002). Thus fallow periods become shorter and scarcer, with dominating continuous annual cropping systems in accessible upland areas. Due to the decreasing duration of fallow periods and large nutrient losses through erosion in the upland area, the composite swidden system is not considered sustainable anymore (Dung et al., 2008). Consequently, land use intensification, especially annual monocropping systems, that have a low soil cover during their establishment phase (e.g. maize), induce severe erosion on steep slopes, with presumably negative on- and off-site impacts on soil fertility, related crop productivity and pollution of streams (Wezel et al., 2002). While small and moderate nutrient rich sediment deposition into downstream cultivated land might be beneficial, large sediment delivery could rapidly become a damaging incident, burying the original fertile soil under low quality sediments, silting up reservoirs, altering its hydrological behavior causing water scarcity or flooding risk (Lantican et al., 2003). In Northern Vietnam 0.7 mil. ha are under paddy cultivation, of these 60% are located in hilly areas, on terraces

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forming interconnected cascades, and hence are influenced by upland sediment deposits (Wezel et al., 2002; General Statistics Office of Vietnam, 2008).

Irrigation systems act as a sediment conveyor during strong rainfall events especially in intensively cultivated upland areas (Gao et al., 2007). During erosion events, nutrients are removed and, attached to eroded sediments, reallocated in the watershed (Dung et al., 2008; Pansak et al., 2008). As suspended sediment, transport and deposition depend on water discharge and particle size distribution, deposited sediments create patterns of spatial variability in soil fertility downstream of the watershed (Gao et al., 2007; Mingzhou et al., 2007). Dobermann and Oberthür (1997) acknowledged the existence of temporal and spatial variability in soil fertility of irrigated rice fields. Dobermann et al. (2003) linked spatial nutrient variability to climate and crop management influencing the detachment, transportation and deposition of sediments and nutrient balances of the fields, rather than solely to the nature of parent material and landscape features such as topography.

Factors contributing to spatial variability depend strongly on the spatial scale. At field level puddling is one of the main factors affecting the dynamic soil–water system by altering the plough pan and therefore hydraulic conductivity and anaerobic conditions (Lennartz et al., 2009). Besides the age of the rice fields and the linkage to the alteration of the plough pan (Lennartz et al., 2009), internal runoff and deposition processes play a role at toposequence level (Dercon et al., 2003; Homma et al., 2003; Dercon et al., 2006). An increase of soil fertility, crop productivity and an increase of water availability due to higher soil organic carbon and clay deposits were linked with fields situated at the lower slope positions of a terrace sequence (Homma et al., 2003; Tsubo et al., 2007; Boling et al., 2008; Rüth and Lennartz, 2008). These processes alter the soil chemistry of fields mainly at the footslope position (Tachibana et al., 2001) especially clay composition was altered and smectite genesis was induced (Prakongkep et al., 2008).

At watershed level, the redistribution of nutrients through erosion–sedimentation processes in upland — lowland areas and its impact on soil fertility in the lowland are too often neglected (Mochizuki et al., 2006; Rüth and Lennartz, 2008). Sediments could increase nitrogen use efficiency of applied fertilizer by increasing cation exchange capacity, clay content and soil organic matter (Mingzhou et al., 2007). Therefore, beside internal runoff and soil deposition processes in rice paddies, it is important to understand the impact of external sediment contributions as an additional source of nutrient deposits regarding specific fertilizer recommendations for improving resource use and crop management. King et al. (2009) demonstrated the importance of carbon and nitrogen transport by irrigation and runoff water in a furrow irrigated field. According to their study, irrigation water enriched with sediments and dissolved organic carbon resulted in a net increase in total *C* and *N* loads in irrigated fields. Sediment deposits represent reallocated carbon in the landscape and due to their large variability in irrigated fields furthermore play a significant role when discussing carbon sequestration in intensively irrigated agroecosystems (Poch et al., 2006).

The purpose of this study was to understand the impact of different sediment transportation–deposition systems related to intensive upland cultivation on the alteration of soil fertility in and among irrigated and rainfed rice paddy cascades. Three sediment transportation–deposition systems were considered: (i) irrigation water from the reservoir transported through channels, (ii) direct runoff water from upland areas, and (iii) deposition of suspended sediments and bed load from the stream during extreme flooding events. The study focused on the assessment of spatial variability in soil organic carbon, total nitrogen and particle size distribution induced along and among four cascades of paddy terraces of approximately 160 m due to differences in quality and quantity from various sediment sources. The objectives of this study were thus to assess (i) the spatial variability of soil properties at cascade and landscape level, (ii) the alteration of soil organic carbon, total nitrogen and particle size distribution linked to the type of the sediment deposition pathways (irrigation, flooding and direct runoff) and iii) the effect of distance of the field from the irrigation channel on soil fertility.

2. Material and methods

2.1. Experimental site

The present study was carried out from February until October 2007, during two rice cropping seasons in the Chieng Khoi commune (350 masl, 21°7′60″N, 105°40′0″E) situated in the Yen Chau district, Northwest Vietnam (Fig. 1a, b). The studied watershed of 2 km^2 has an average annual precipitation of 1200 mm (average 1998–2007) and is located in the tropical monsoon belt, characterized by a rainy season from April until September (Fig. 2). The area consists of steep upland hills (up to 86%) with silt-fine sandstone and limestone as parent material. According to the WRB classification (Deckers et al., 1998), Alisols and Luvisols are frequently occurring soil types in this area. At the time of evaluation, upland areas were under intensive maize (*Zea mays* L.) and cassava (*Manihot esculenta* Crantz) cultivation from March until December. On the other hand, the valley bottoms are characterized by anthraquic Anthrosols and used for paddy rice (*Oryza sativa* L.) production, in some areas already for up to 200 years.

An extended open-channel irrigation system and a lake reservoir allow two rice cropping seasons a year, one irrigated (spring crop; February/March–June/July) and another mainly rainfed (summer crop; July–October/November). In case of temporary drought periods, the reservoir is able to provide sufficient irrigation water also for the second summer crop. However, due to the topography, gravitational irrigation is often not possible for those paddies on the higher located terraces at the foot slope of the hills, where only one rice crop a year is cultivated during the wetter summer period. In the studied watershed a total of 60 ha of rice fields can be irrigated due to a combination of open-channel and river irrigation. There is a stream originating from the Karst mountains which was dammed in 1962 and is now fed by the same reservoir of the irrigation system.

2.2. Sediment transportation–deposition pathways into paddy fields

Depending on the cropping season and field position in the landscape various sediment sources contribute to the spatial variability among cascades. At the beginning of the first cropping season, sediments entering the rice fields are mainly provided through the irrigation system. The irrigation water had an average concentration of 2 mg l^{-1} organic C and 1.5 mg l^{-1} total N when no rain occurred. During low intensity, short duration rainfall events (<25 mm day^{-1}) organic C concentrations increased by a factor of 10 and total N by a factor of 1.25. During high intensity rainfall events (>25 mm day^{-1}) factors up to 45 for organic C and up to 7 for total N were recorded. However, during the rainy season additional sediments are delivered to some of the rice fields besides the irrigation system. First of all there is the direct, undiluted inflow from the cultivated area into the upper rainfed terraces due to water harvesting techniques on the steep upland slopes in order to overcome temporary drought periods. Secondly, as the irrigation reservoir is filling up in May–June due to successive rainfall events, the reservoir spillover will start to work around July increasing the water level in the river. When there are successive heavy rainfall events or even typhoons from July onwards, there is no buffer capacity left in the reservoir resulting in a large increase in water height of the stream. This can lead to flooding of adjacent fields which are under normal