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Institute of Plant Production and Agro-Ecology in the Tropics and Subtropics

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CARBON AND NITROGEN REDISTRIBUTION ACROSS THE LANDSCAPE AND ITS INFLUENCE ON PADDY RICE PRODUCTION IN NORTHWEST VIETNAM

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Cam’on ve hen gap lai!

Thank you!

Vielen Dank!

Bedankt iedereen!

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LIST OF ABBREVIATIONS

C : Carbon

CEC : Cation Exchange Capacity

CV : Coefficient of Variation

DRIFT : Diffuse Reflectance Infrared Fourier Transform (spectroscopy)

EMC : Event Mean Concentration

FAO : Food and Agriculture Organization (of the United Nations)

Fe : Iron

Inorganic C : Inorganic Carbon

K : Potassium

MIRS : Mid-InfraRed Spectroscopy

N : Nitrogen

NIRS : Near-InfraRed Spectroscopy

NMR : Northern Mountainous Region

Organic C: Organic Carbon

P : Phosphorus

P_{av} : Available phosphorus (Bray II)

PLS : Partial Least Square regression

RPD : Residual Prediction Deviation

RMSEP : Root Mean Square Error of the Prediction

SAS : Statistical Analysis Software

SOC : Soil Organic Carbon

SE Asia : Southeast Asia

Total N : Total Nitrogen

CHAPTER 1

GENERAL INTRODUCTION

1 General introduction

1.1 Background

In Northern Vietnam, traditional composite swidden agriculture combines swidden agriculture, also often referred to as shifting cultivation or slash-and-burn agriculture, in the uplands with permanent paddy rice cultivation in the lowlands (Vien, 2003). Since 1990's, rapid population growth, strong economic growth, and changing governmental land use policies have intensified agricultural production in the mountainous regions of Vietnam converting the traditional swidden cultivation on steep slopes into a more continuous monocropping system (i.e. maize and cassava) (Valentin et al., 2008; Ziegler et al., 2009). Characteristic long fallow periods within swidden agriculture have been reduced significantly or even have become absent (Vien and Thanh, 1996; Dung et al., 2008). The annual monocropping systems that now are predominant in the uplands made the soil susceptible to erosion, especially at the onset of the rainy season when land cover is known to be scarce (Vezina et al., 2006; Pansak et al., 2008). Landscape fragmentation and biodiversity loss as a result of deforestation, soil degradation due to reduced fallow periods and associated erosion and runoff have been studied intensively (Ziegler et al., 2004b; Vezina et al., 2006; Dung et al., 2008; Valentin et al., 2008; Ziegler et al., 2009; Van Do et al., 2010). Currently more attention is paid to the off-site effects such as flooding, siltation of irrigation systems and pollution of water bodies at landscape or catchment level (Lantican et al., 2003; Bruijnzeel, 2004; Gao et al., 2004; Kahl et al., 2008; López -Tarazón et al., 2009). Deposition and transportation of sediments downstream are depending on the characteristics of the landscape, water discharge and particle size distribution (Chaplot et al., 2005a; Chaplot et al., 2005b; Schiettecatte et al., 2008). Therefore, deposited sediments create patterns of spatial variability in soil fertility downstream of the watershed (Mingzhou et al., 2007). Nevertheless, the redistribution of sediment associated nutrients downstream and its impact on crop production are to date not well addressed in research. Especially in intensified paddy systems, the additional inputs of plant nutrients conveyed by irrigation systems can be important in understanding spatial variability of rice production in tropical mountainous regions (Lantican et al., 2003; Mingzhou et al., 2007). Rüth and Lennartz (2008) indicated that a part of the spatial variability in soil properties and crop performance of paddy systems in mountainous regions could be explained by erosion–sedimentation processes. Therefore, this thesis focused on quantifying the sediment associated nutrient loads redistributed through irrigation and its effect on soil spatial variation and related crop productivity in downstream situated paddy systems.

1.2 Northern Mountainous Region of Vietnam

Vietnam, located in Southeast Asia, has a total surface area of 331,150 km² of which 249,972 km² is agricultural land (General Statistics Office of Vietnam, 2008). The Northern Mountainous Region (NMR) of Vietnam occupies 95,434 km² and has a population of approximately 12 million people, including 30 ethnic minorities (e.g. H'Mong, Black and White Thai, Dao, Lo Lo) (Vien, 2003). According to Vien (2003), NMR can be divided into three altitudinal zones each with predominant farming systems and associated ethnic groups: (i) high mountainous (> 800 m a.s.l.) with swidden cultivation, (ii) low mountainous zone (200 - 300 m a.s.l.) with composite swiddening and (iii) mid-elevation mountainous zone (300 - 800 m a.s.l.) which often combines elements from farming systems found in the high and low mountainous zones.

National land tenure policies have been an important factor influencing land use change (Sikor and Truong, 2002; Sikor, 2006; Saint-Macary et al., 2010). The land law of 1988 ended the collective farming system by allocating the land to private households and was followed by several land laws in the 1990's including land reallocation and the issuing of land use certificates (Saint-Macary et al., 2010). The allocation of permanent fields to households together with the market pressure caused a strong agricultural intensification of upland fields in the 1990's (Sikor, 2006). Additionally, due to demographic pressure and resettlement policies, the cultivated land per person in Northern Vietnam decreased strongly (Wezel et al., 2002b) so that deforestation followed by slash and burn practices are not uncommon in order to expand the upland agricultural area (Dung et al., 2008). Moreover, the rapid increase in animal feed demand throughout the country pushed maize production in Northern Vietnam from 56 10^3 Mg in 1990 to 212 10^3 Mg in 2000 (Huan et al., 2002) (Figure 1-1). As a result of the current socio-economic pressure, the relatively sustainable traditional swidden cultivation in tropical mountainous areas converted into a more intensive agricultural system with annual cropping systems (e.g. maize) with short or no fallow periods (Turkelboom et al., 2008; Ziegler et al., 2009).

Furthermore, rice production in the lowland was intensified tremendously over the last decades. The exponential increase of rice production in Vietnam was initiated by several major policy reforms (i.e. the de-collectivization in the early 1980' and the rice market liberalization in 1989) and supported through the introduction of new rice varieties and chemical fertilizer (Pingali et al., 1997; Sikor, 2006) (Figure 1-1). The area of paddy rice per person in mountainous villages is on average 200 m² and the amount of fields per household depends on its number of members (Vien, 2003). Due to the limited paddy area per household, the intensification of rice production in the mountainous regions is highly depending on optimization of its current system in terms of fertilizer application, water management and nutrient dynamics.

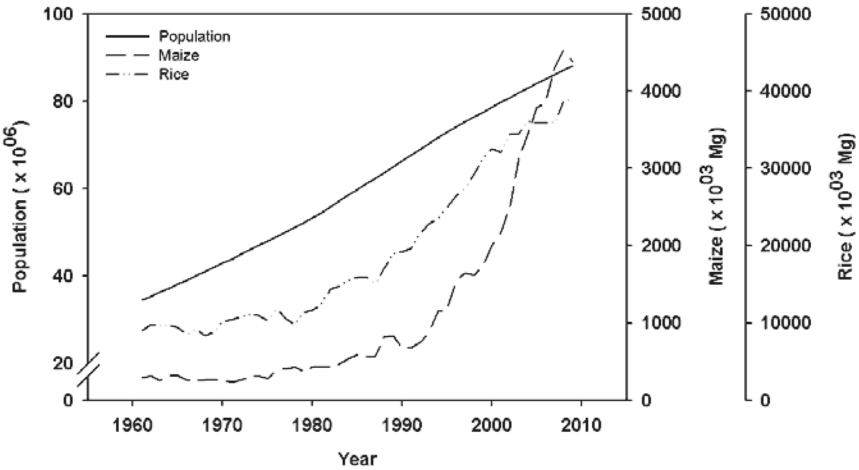

Figure 1-1: An overview of population growth, maize and rice production within Vietnam from 1961 till 2009 (source: FAO Stat, 2010).

1.2.1 Swidden cultivation

Swidden cultivation, also often referred to as shifting cultivation or slash-and-burn agriculture, has been practiced for more than centuries and is one of the most common agricultural practices in the steep upland areas throughout Southeast Asia (Fox et al., 2000; Rerkasem et al., 2009). Traditional shifting cultivation originally incorporated slash-and-burn techniques for field clearance, followed by a short cropping period, e.g. upland rice (*Oryza sativa* L.), cassava (*Manihot esculenta* L.), maize (*Zea mays* L.), and a long fallow period, i.e. six to fifteen times the cropping period, through which the soil fertility is able to recover (Tinker et al., 1996; Fox et al., 2000; Delang, 2002; Vien et al., 2006). Ziegler et al. (2009) showed that the long-term environmental impacts on hydrology are negligible because of the rapid regeneration of vegetation during fallow periods, as well as due to the limited amount and continuous relocation of cultivated fields. The conversion of traditional swidden systems into intensified annual monocropping systems, predominately maize, has a strong environmental impact regarding biodiversity, geomorphology, soil quality, carbon storage and hydrology (Bruun et al., 2009; Rerkasem et al., 2009; Ziegler et al., 2009). For example, the reduction of the fallow period has a strong influence on soil porosity, root strength and soil aggregate stability (Ziegler et al., 2009). Bruun et al. (2009) estimated a reduction of 90% in above ground C stock and 40% soil organic C loss within the topsoil when the fallow phase is reduced to four years. The effect of soil degradation due to the reduction of fallow periods on crop production is temporarily masked by the development of new varieties and the usage of chemical fertilizers (Wezel et al., 2002a; Wezel et al., 2002b).

In intensively cultivated areas with no or short fallow periods, soil erosion severely enhances land degradation, especially during the establishment phase when soil cover is low (Vezina et al., 2006; Dung et al., 2008; Valentin et al., 2008). Lal (2001) reported that 1094 million ha worldwide and 441 million ha in Asia are seriously affected by water erosion. Soil loss and runoff are highly variable and depend on climatic conditions as well as soil and land use type, years of field cultivation, topography and landscape fragmentation (Sidle et al., 2006; Ziegler et al., 2007; Valentin et al., 2008; Van De et al., 2008). Sidle et al. (2006) reported soil loss by erosion in Southeast Asia ranging between 0.4 and 460 Mg ha^{-1} yr^{-1} depending on measurement scale (i.e. plot or catchment level), slope, land use and soil conservation practices (e.g. terracing, hedgerow, ground cover). Nutrient losses due to soil loss and runoff strongly influence nutrient balances and are strongly affected by the amount of cropping cycles (i.e. 2 or 4 year cropping cycles) and land use (i.e. upland rice or cassava) succeeding the fallow phase (Dung et al., 2008). When considering the nutrient losses associated with burning, the fallow period necessary for N recovery in intensified swidden systems was estimated to range between 29 and 37 years depending on the amount of cropping cycles (Dung et al., 2008).

The sustainability of intensified cropping systems is an important issue in order to meet the increasing food demand with a continuously declining availability of arable land. Soil conservation techniques such as contour hedgerow, cover crop systems, grass strips and agroforestry are studied intensively and are often promoted in order to reduce erosion and runoff (Ziegler et al., 2006a; Pansak et al., 2008; Nyssen et al., 2009; Veum et al., 2009). However, the adoption of soil conservation measures by farmers remains low as they are often perceived as economically unattractive and labor intensive (Wezel et al., 2002b; Knowler and Bradshaw, 2007). Additionally, land tenure security and reallocation threats in the northern mountainous regions in Vietnam strongly influence adoption (Saint-Macary et al., 2010). Pansak et al. (2008) showed over a period of three years that minimum tillage and mulching reduced soil loss significantly (from 24.5 to 10.5 Mg ha^{-1}), whereas runoff only decreased moderately (from 866 to 642 m^3 ha^{-1}) in comparison when using leucaena (Leucaena Leucocephala) hedgerow systems (225 m^3 ha^{-1}). The application of minimum tillage and mulching therefore shows great potential for intensification of composite swidden agriculture as it combines the reduction of erosion without significantly minimizing water availability which is of high importance for downstream rice production systems.

1.2.2 Rice production

Rice is the main staple food in Southeast Asia and its production will continue to be challenged in meeting future food demands. Vietnam became, after Indonesia, the second largest rice producer in the SE Asia with 35 million Mg in 2007 of which 90% is produced in the Mekong and Red River delta (Pingali et al., 1997; FAO Stat, 2009). In Vietnam, 53% of the rice area is irrigated, 39% is rainfed, 5% is considered to be upland rice and 3% is flooded (Hatcho et al., 2010). Although the area of paddy rice remained relatively constant in NMR since 1995, the average paddy production increased from 2.7 Mg ha^{-1} to 4.6 Mg ha^{-1} in 2009 (General Statistics Office of Vietnam, 2010).

Worldwide, rice production is found to be very heterogeneous as it is highly depending on climatic conditions, soil fertility, variety suitability, land and water management and fertilizer application (Bouman and Tuong, 2001; Fageria et al., 2003; Kyuma, 2004; Haefele and Wopereis, 2005). The assessment of the main factors influencing spatial variation in crop performance is highly depending on the spatio-temporal scale chosen (Dobermann et al., 1997; Yanai et al., 2000; Dobermann et al., 2003; Liu et al., 2008; Haefele and Konboon, 2009; Lennartz et al., 2009). For example, land preparation can play an important role on soil-water dynamics at field level (Singh et al., 2006; Lennartz et al., 2009). When looking at rice paddy terraces, internal runoff, sediment deposition and crop management (e.g. nutrient input through fertilization) become important (Dercon et al., 2003; Tsubo et al., 2006; Boling et al., 2010). An increase of soil fertility and crop productivity are found in lower situated paddies which is related to the downward movement of nutrient rich soil particles due to land preparation and water management (Tachibana et al., 2001; Tsubo et al., 2006; Prakongkep et al., 2008; Rüth and Lennartz, 2008). At larger scales, the redistribution of nutrients due to sediment deposition throughout the landscape need to be taken into account besides climate, the nature of parent material and landscape features (e.g. topography) (Dobermann et al., 2003; Zhang and Gong, 2003; Mingzhou et al., 2007; Liu et al., 2008).

1.2.3 Nitrogen (N) and Carbon (C) cycles in paddy fields

Paddy systems are characterized by an intensive use of agricultural inputs. Soil fertility (e.g. fertilizer and crop residue use) and irrigation water management play a dominant role in the optimization of these systems. However, the alternating flooding – drying cycles, which are characteristic for paddy systems, make N and C cycles very complex as it changes the biological, chemical and physical properties. The changes in water conditions (i.e. reducing conditions) influences the transformation and migration of N (e.g. ammonia volatilization, denitrification, leaching and runoff) within the system (Bandyopadhyay and Sarkar, 2005; Ghoneim et al., 2008; Li et al., 2008; Ju et al., 2009). During drying cycles under more aerobic conditions formed nitrate will be leached during flooding or denitrified due to the prevailing anaerobic conditions (Keeney and Sahrawat, 1986). Another example is ammonia volatilization which is highly depending on pH of the irrigation water and the presence of ammonium, as an increase of both factors can result in significant NH_3 losses. Bandyopadhyay and Sarkar (2005) reported that the NH_4^+-N concentration within the irrigation water contributed for 80% to the variation of ammonia losses. Ammonium on the other hand can be fixed depending on the type of clay minerals, immobilized through microorganisms or nitrified depending on the redox conditions (Keeney and Sahrawat, 1986). The form under which N is added into the paddy system will additionally influence N mineralization-immobilization processes and therefore influence the main pathway for N losses (Nishida et al., 2007; Kaewpradit et al., 2008; Ju et al., 2009; Zhao et al., 2009). For example, ammonia volatilization is higher when swine manure is used compared to poultry because of its higher NH_4^+ and readily mineralizable N content (Nishida et al., 2007) but lower compared when only urea is used (Bandyopadhyay and Sarkar, 2005). The convergence of fertilizer application with storm events on the other hand, can significantly increase N-losses due to runoff (i.e. lateral flow) (Kim et al., 2006; Tang et al., 2008). Tang et al. (2008) showed that the years of cultivation and the toposequence position play an additional role in N losses and estimated N losses between 0.1 and 22.7 kg N ha^{-1}. First of all, paddy fields situated at the upper part of the toposequence receive more irrigation water which induces more runoff-associated N losses. Furthermore, the age of a paddy field influences the presence and compactness of the pan layer. Therefore higher N-losses through leaching are expected in younger paddy fields. As a result, in young paddy fields subsurface flow can become an important pathway for N losses besides surface flow when considering nutrient transport from terraced paddy fields (Tang et al., 2008).

Similarly to the N cycle, C decomposition and translocation depends highly on the quantity and quality of C input (e.g. residue incorporation or manure) and affects N-mineralization processes (Kimura et al., 2004; Kaewpradit et al., 2008). One of the input parameters less understood is the effect of sediment deposition through irrigation or upland runoff on nutrient cycles in paddy fields. The effect of sediments is multifunctional as it affects paddy hydrology, soil fertility and crop productivity (Homma et al., 2003; Tsubo et al., 2006; Boling et al., 2008). Sediments transportation to paddy fields can occur through surface water irrigation or runoff from upland fields carrying additional nutrients (Lantican et al., 2003; Tang et al., 2008). Therefore, it is important to understand upland-lowland linkages in order to quantify and assess the impact of sediment transport on paddy cultivation.

1.2.4 Linkage upland- lowland

Intensification of agriculture and associated land use changes in uplands not only affect on-site biodiversity, water regime, soil degradation but also downstream areas by for instance flooding, siltation of reservoirs and pollution of water bodies (Lantican et al., 2003; Ziegler et al., 2007; Kahl et al., 2008; Valentin et al., 2008; López -Tarazón et al., 2009). Assessing the effect of upland intensification on downstream areas is complex as many processes influence sediment redistribution and therefore associated nutrient dynamics (Collins and Walling, 2004). Furthermore, the landscape often encompasses linear features such as roads, footpaths and canals which are known to stimulate erosion processes and conveyance of sediments (Ziegler et al., 2000; Ziegler et al., 2004a). Therefore, it is difficult to estimate the portion of sediments that are being redistributed in the landscape or delivered to neighboring streams. Chaplot et al. (2005b) measured a decrease in sediment and soil organic carbon (SOC) yields when comparing micro-, meso- and catchment level indicating that a significant amount is redistributed in the landscape. Over the last decades, several studies were conducted on plot, toposequence and catchment level in order to understand the effect of land use changes on sediment transportation and nutrient dynamics (Coleman et al., 1990; Gao et al., 2004; Aksoy and Kavvas, 2005; Ziegler et al., 2007; Rüth and Lennartz, 2008; Schiettecatte et al., 2008; Seitzinger et al., 2010). The additional source of C and N through sediment deposition can partly explain the spatial variation of soil fertility found in the lowland (Rüth and Lennartz, 2008). In China, the transportation of sediments through irrigation along the Yellow river was shown by Mingzhou et al. (2007) to improve soil quality in terms of decreasing salinity and increasing organic matter and total N content. The redistribution of sediments within the landscape and its alterations on soil fertility, therefore, will have an influence on downstream crop production and should be taken into account when assessing the environmental impact of land use change scenarios in order to advice local policy makers in land use planning and fertilizer recommendations.

1.3 Chieng Khoi commune

The study was conducted in Chieng Khoi Commune (21°7’60”N, 105°40’0”E) one of the 13 communes situated in the Yen Chau District, Son La Province, Northwest Vietnam (Figure 1-2). Chieng Khoi is representative for the majority of communes located in the NMR where composite swidden systems were highly intensified by which the uplands were converted into permanent annual monocropping systems (Figure 1-3). The commune covers a total area of 3189 ha and consists of six Black Thai villages having a total population of 471 households (Quang et al., 2008). On average, a Black Thai household has a farm size of 1.65 ha which is often fragmented into small units ranging between 0.01 and 0.3 ha depending on location within the landscape (i.e. upland or lowland) and attributed land use class (e.g. rice, upland crop, forest). The undulating landscape has an altitudinal range between 320 and 1600 m above sea level (a.s.l.) with slopes ranging between 0.05 and 65%. Paddy rice is cultivated in the lowland while maize and cassava are, together with perennial land use types (e.g. timber and fruit tree plantations) the main cropping systems in the uplands (Figure 1-4). The majority of the soil types can be classified according to the WRB classification as Luvisols, Alisols and Stagnic Anthrosols (Clemens et al., 2010). An overview of the different soils classified by the farmers using participatory tools is shown in Figure 1-5.

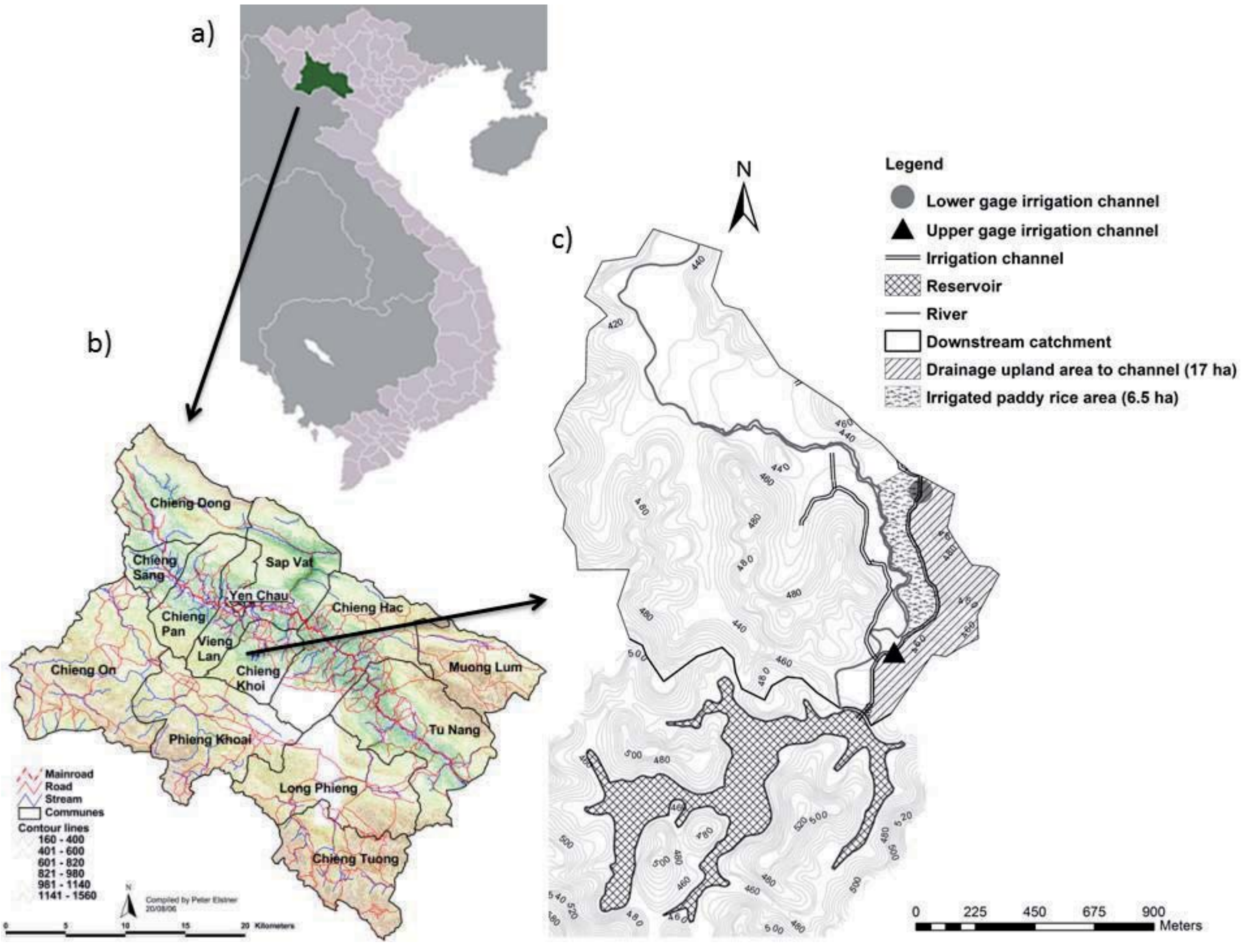

Figure 1-2: a) Location of Son La Province in Northwest Vietnam, b) Overview of communes within Yen Chau District which is situated in Son La province and c) Detailed overview of the study area with the position of water samplers (triangle and circle) and the location of the paddy rice terraces (cross) located in Chieng Khoi Commune (Graphics and maps adopted from SFB 564- The Uplands Program 2006-2009).

a)

b)

c)

d)

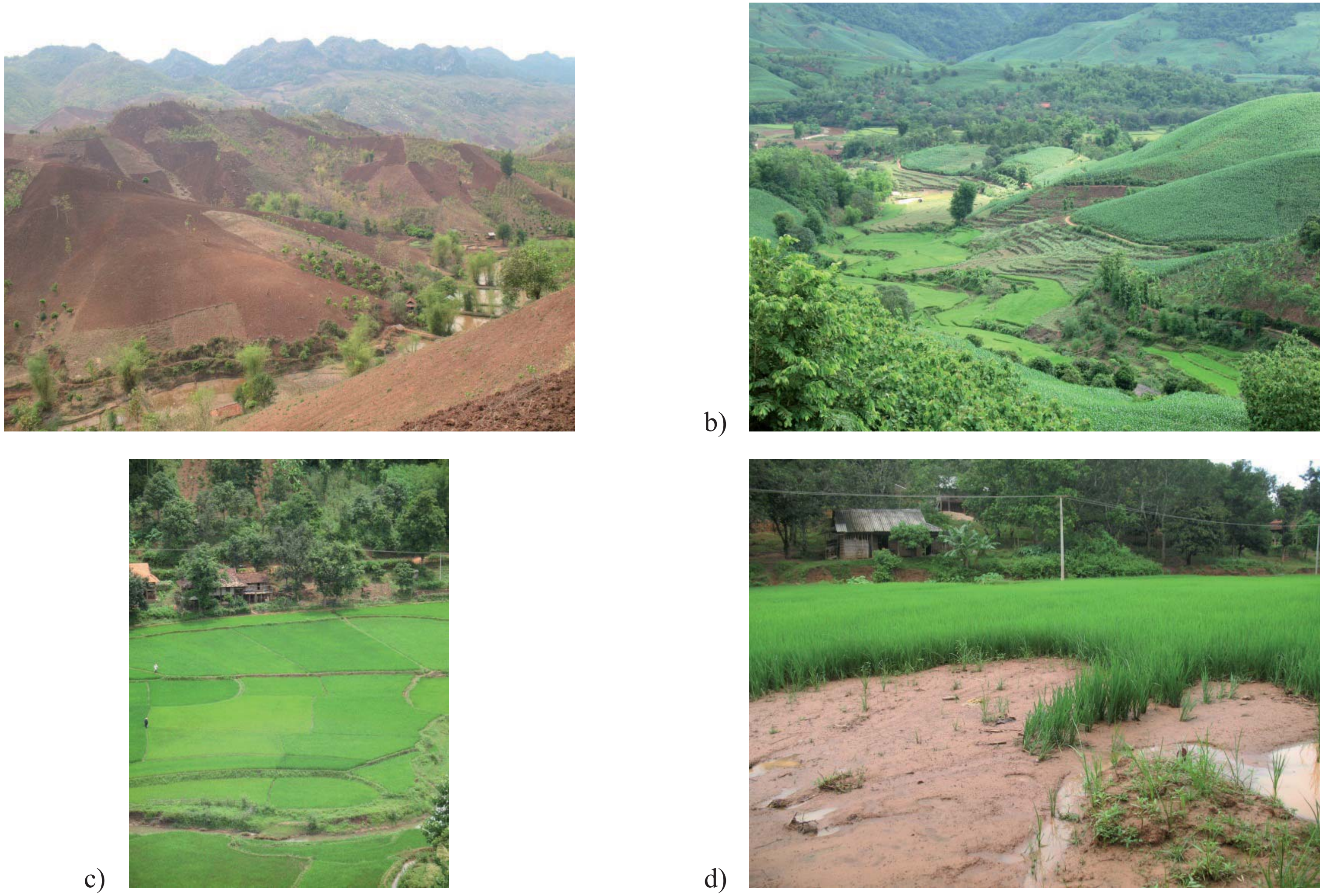

Figure 1-3: a) Ploughed upland fields in Chieng Khoi preceding the maize season, b) Maize cultivated upland fields and paddy systems in the lowland of Chieng Khoi, c) One of the monitored toposequences in Chieng Khoi, d) Sedimentation in a paddy field after a big storm event in 2007.

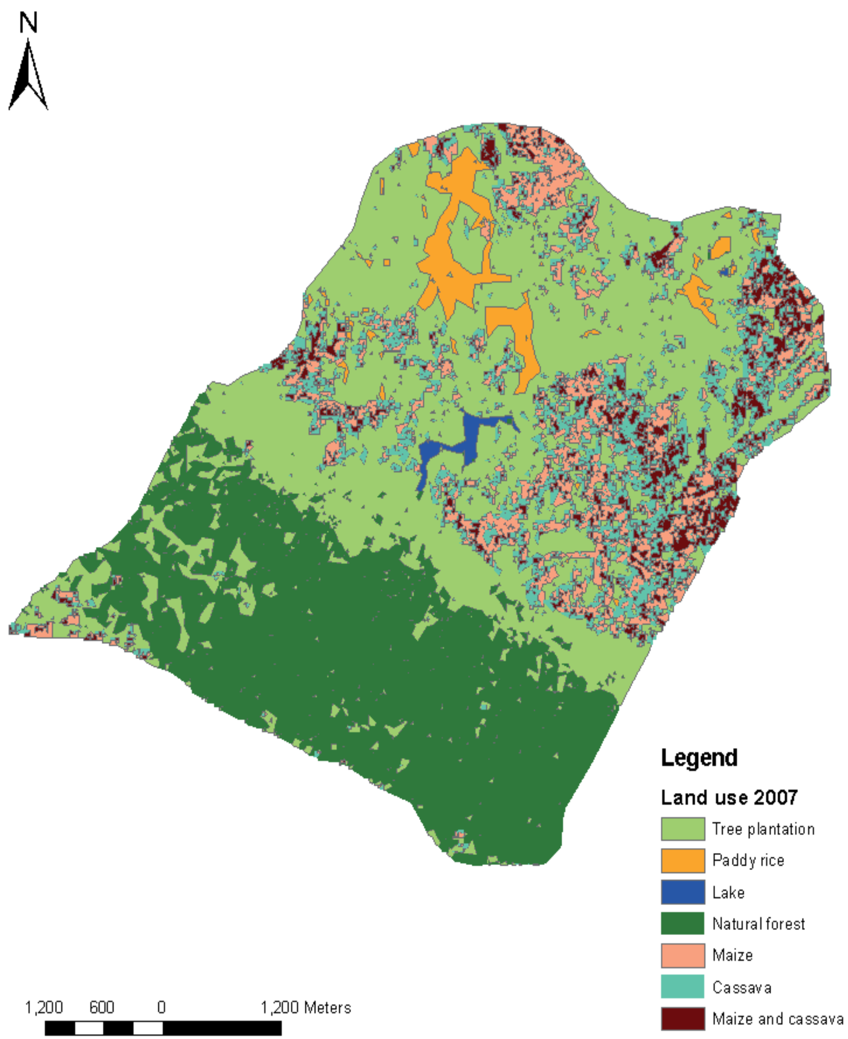

Figure 1-4: Land use classification based on LISS III 2007 satellite image (Nguyen, 2009).

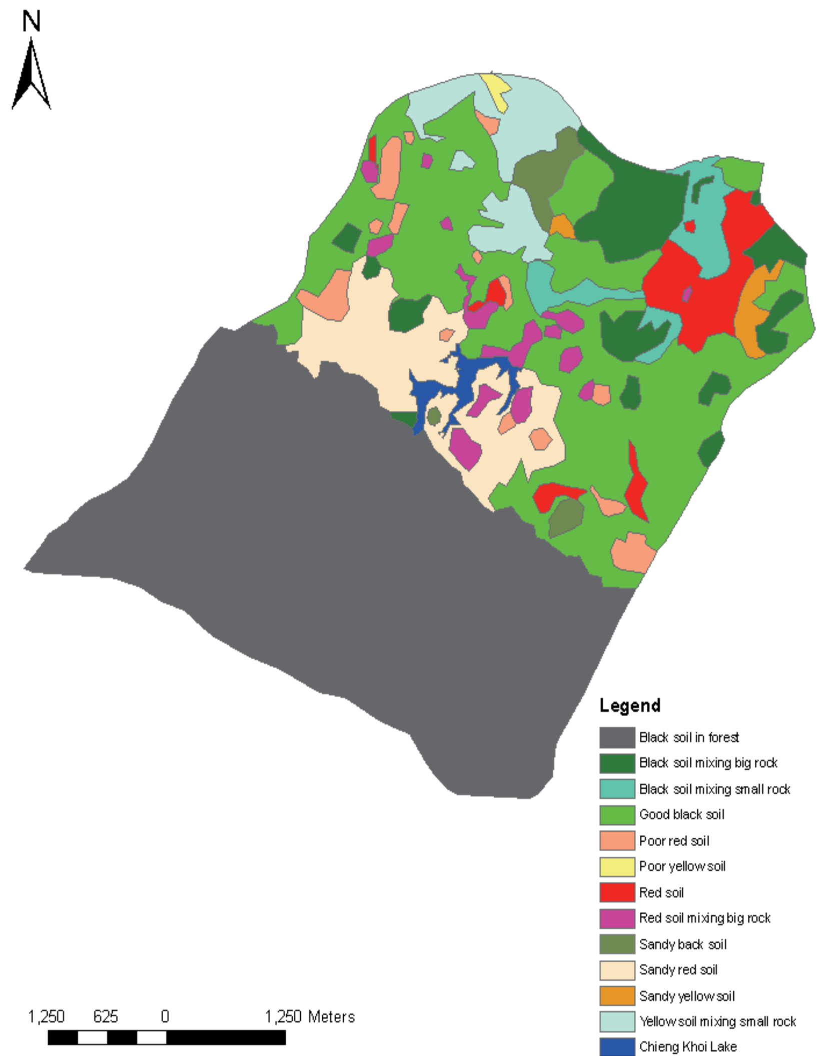

Figure 1-5: Soil type classification based on farmers knowledge (modified after Clemens et al., 2010).

1.4 Techniques to analyze upland – lowland relationships

The spatio-temporal assessment of nutrient redistribution at landscape level through irrigation and its effect on lowland rice production request a combination of various techniques (Figure 1-6). Water quality monitoring of the irrigation water was performed using automatic water samplers for sample taking. Samples were analyzed for inorganic C, organic C and total N using the combustion method (Chapter 2). The effect of sediment loaded irrigation water on soil fertility in paddy fields was performed by using detailed sampling schemes before transplanting and after harvesting of the paddy topsoil (Chapter 3). A combination of mid infrared spectroscopy and conventional wet analysis was used in order to process the large amount of soil samples taken. Stable isotope techniques (^{13}C and ^{15}N) were used in order to distinguish between the effect of sediment deposition and other factors such as nutrient and water availability on rice performance (Chapter 4). In the following sections, an overview and justification is given on the potential techniques useable in this kind of studies.

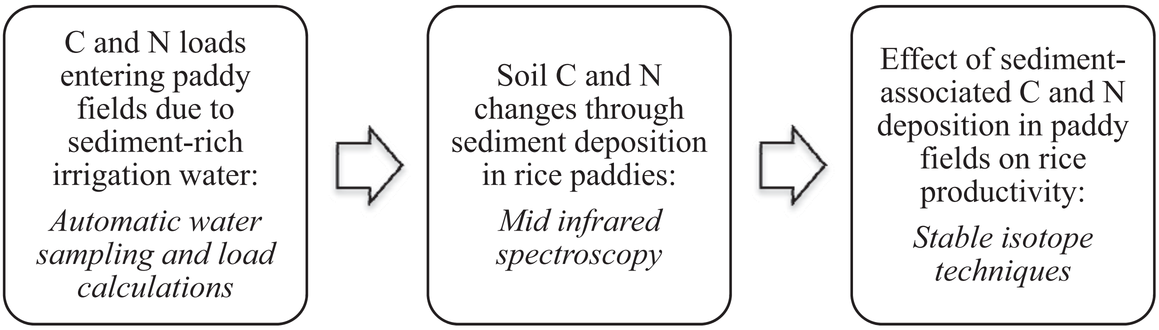

Figure 1-6: Overview of the techniques used in this study.

1.4.1 Nutrient distribution at landscape level

1.4.1.1 Water sampling and load calculations

Water quality monitoring has a high spatio-temporal character at landscape or catchment scale as it is an integration of various biochemical processes (King and Harmel, 2003; Gao, 2008). The quality of collected water samples is highly depending on the sampling technique chosen and will therefore influence, besides the calculation methods, the accuracy of load estimations (King et al., 2005; Schleppi et al., 2006; Drewry et al., 2009). The chosen sampling strategy often depends, besides the purpose of the study, on available resources and equipment (Robertson, 2003).

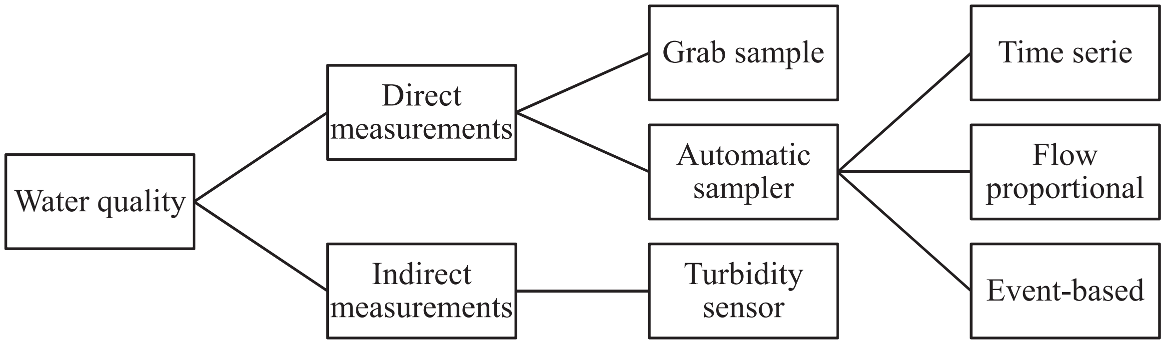

Figure 1-7: Overview of possible water sampling strategies for assessing water quality parameters.

A distinction should be made between direct and indirect measurements. Direct measurements include manual (i.e. grab sample) or automatic (i.e. automatic water sampler) sampling while indirect measurements use a proxy such as turbidity for estimating sediment transport (Gao, 2008) (Figure 1-7). Grab sampling is often referred to as taken a sample at irregular time intervals throughout the year (e.g. weekly, monthly basis) (Ziegler et al., 2006a). A more detailed sampling scheme can be used for storm event sampling where the time interval is shortened between samples in order to monitor changes in sediment concentration during rainfall events. The disadvantage of this method is that sampling is labor intensive and difficult as storm events often have a relatively short duration. Therefore, loads can be significantly underestimated (Harmel et al., 2003; Robertson, 2003). One of the alternatives is using automatic samplers where samples can be taken at fixed time (time series) or discharge intervals (flow proportional) (King and Harmel, 2003; Gao, 2008). Automatic water samplers are widely used in sedimentation and nutrient transport studies (Kronvang and Bruhn, 1996; Lopez et al., 2000; King and Harmel, 2003; Gao et al., 2004; Holz, 2010). Although time-based sampling strategies reduce the mean bias of estimated load when small time intervals are chosen, the error significantly increases over bigger time intervals or when storm events occur (King and Harmel, 2003). When sampling storm events, a better option is flow proportional sampling where a sample is taken when a defined amount of flow passes a certain point. Therefore, during high flows, a more frequent sampling will be performed which reduces errors regarding load estimations of storm events (King and Harmel, 2003). The automatic water sampler has a limited amount of bottles, thus the defined amount of flow plays an important role within the sampling procedure (Lopez et al., 2000). Event-based–flow proportional sampling can be a solution in this where sampling is initiated when a predefined threshold of water level in streams is exceeded (Harmel et al., 2003; Gao, 2008). However, when working in irrigation systems (Figure 1-8), the changes in water level is not only depending on rainfall-runoff but also on irrigation management which makes it difficult to use event based sampling.

Figure 1-8: Installation of the ultra-sensor for water level measurements coupled to the automatic water sampler in the upper part of the irrigation channel. The samples on the picture show the changes in water quality during a rainfall event in 2008.

The use of automatic samplers clearly reduces labor costs in terms of sample taking but not necessarily regarding analysis. The amount of samples can be reduced by taking composite instead of discrete samples (King and Harmel, 2003). Discrete sampling implies a one sample, one bottle strategy, whereas a composite sample can have a defined amount of samples per bottle. King and Harmel (2003) showed that there was no statistical disadvantage between composite or discrete sampling, so that the amount of samples could be clearly reduced, resulting in an economic advantage. Hence, a flow proportional-composite sampling strategy was used in

Chapter 2 for estimating the effect of storm events on irrigated C and N loads. Details regarding flow component separation and load calculations are provided in Chapter 2.

1.4.1.2 Mid infrared spectroscopy

Many conventional lab methods are available for analyzing soil chemical and physical properties, each having their advantages and disadvantages and depending on the resources available. Organic C, for example can be analyzed by using Walkley-Black, lost on ignition (Entry et al., 2002) or using the combustion method (Cobo et al., 2010), with the latter one having a much higher precision (Roelofs, 1983). Another method is diffuse reflectance spectroscopy, i.e. using visible (400-700 nm), near infrared (700-2500 nm) or mid infrared spectra (2500-25000 nm), which has been proven to be a useful tool in quantitative and/or qualitative analysis of soil samples for various applications (McCarty et al., 2002; Pirie et al., 2005; Viscarra Rossel et al., 2006; Reeves III et al., 2008; Cobo et al., 2010). Diffuse Reflectance Fourier Transform Infrared spectroscopy has several advantages compared to other infrared spectroscopy techniques due to the easiness of sample preparation and greater numbers of useful bands (Parker and Frost, 1996). The principle is based on the reflection and absorbance of the infrared light by the sample due to its present compounds (Viscarra Rossel et al., 2006). The spectrum of one soil sample can inherit simultaneously information on chemical (e.g. CEC, pH, total N, inorganic C, etc.), physical (e.g. sand, silt and clay fraction) and biological properties (Viscarra Rossel et al., 2006; Zornoza et al., 2008). As soil samples consist out of a complex variety of functional groups, multivariate statistical tools are needed such as multivariate analysis, principal component or partial least squares regression in order to identify the functional groups as they can be represented by multiple bands within the spectra (McBratney et al., 2006). There are several advantages of diffuse reflectance spectroscopy compared to conventional wet laboratory techniques used in soil analysis as they are non-destructive, rapid, less expensive, allowing fast analysis of a large number of samples (McBratney et al., 2006). Both NIR and MIR spectra are used intensively for the assessment of soil chemical properties each having their own advantages and disadvantages (McCarty et al., 2002; van Groenigen et al., 2003; Pirie et al., 2005; Madari et al., 2006; Viscarra Rossel et al., 2006; Reeves III et al., 2008; Zornoza et al., 2008; Cobo et al., 2010). The mid infrared spectrometer is more expensive and often less portable and local calibrations are needed as the chemistry of the soil matrix place an important influence (Reeves III and Smith, 2009). However, as the majority of the molecular vibrations for soil components occur within the range of 2500 and 25000 nm, MIR spectra are found to be more sensitive compared to NIR spectra (Pirie et al., 2005; Viscarra Rossel et al., 2006). McCarty et al. (2002) showed that MIR spectra contain more information for example on soil C compounds compared to NIRS. Similar results were obtained by Reeves III et al. (2006) when looking at soil C pools and even concluded that the isotopic discrimination of ^{13}C in soils could be measured after accurate calibration. In order to assess sediment induced soil spatial variability of paddy fields at cascade level in this thesis, MIR spectra of soil samples were combined with the results obtained by using conventional wet analysis (Chapter 3).

1.4.2 Nutrient and water availability in crop production systems

Water use efficiency is linked to the stomatal conductance and CO_2 assimilation by plants during photosynthesis as the biochemical pathway for CO_2 intake and H_2O release is shared. The estimation of CO_2 assimilation, stomatal conductance and transpiration are combined in many photosynthesis measurements (Millan-Almaraz et al., 2009). One of the most commonly used measurements is gas exchange chambers for understanding the carbon and water cycles in the soil-plant system (Kron et al., 2008; Yuan et al., 2009). The method consists of measuring CO_2 exchange of a plant sample in a closed or open chamber by recording the proportional changes of the gas in the chamber produced by the plant (Millan-Almaraz et al., 2009). The accuracy of the measurements is sensitive to the precise measurement of CO_2 in the air and in the chamber, and fluctuations in chamber temperature and humidity. However, when a large number of samples needs to be analyzed (e.g. landscape ecosystem studies) it can become very time intensive. The quantification of driving mechanisms behind nutrient and water induced yield losses using traditional techniques is difficult as many processes are involved (Clay et al., 2005). As there is a clear linkage between plant nutrient uptake and soil water availability, the use of stable isotopes (^{13}C and ^{15}N) as integrators for the understanding of interactions and competition between plants or within an ecosystem can be a solution (Dawson et al., 2002).

Stable isotopes such as ^{13}C, ^{15}N and ^{18}O have been used worldwide not only in order to understand the photosynthetic pathways, pathways of nutrient and water uptake by plants or water competition between plants (Farquhar et al., 1989; Bandyopadhyay and Sarkar, 2005; Impa et al., 2005; Pansak et al., 2007; Ito et al., 2009) but also to understand processes within rivers, catchments and ecosystems (Ehleringer et al., 2002; Fox and Papanicolaou, 2007; Ogrinc et al., 2008; Brunet et al., 2009). The use of ^{13}C and ^{15}N stable isotopes has been proven to be a successful technique in assessing *ex post* the effect of water limitation and N uptake on crop performance (Farquhar, 1983; Clay et al., 2001a; Dercon et al., 2006a; Fan et al., 2007; Pansak et al., 2007; Kaewpradit et al., 2009). Ribulose diphosphate carboxylase (RuBisCo) catalyses the fixation of CO_2 in plants to ribulose diphosphate and has a great affinity for $^{12}CO_2$ which is in abundance when plants are not water stressed. When water limitation occurs, the stomata of C_3 plants, such as rice, close in order to reduce water losses. Hence, the diffusion of air inside and outside the leaf decreases and the fixation of $^{13}CO_2$ by RuBisCo is increased (Clay et al., 2001b). The typical isotopic ratio of ^{13}C ($\delta^{13}C$) for C_3 plants is species dependent and ranges around -30 to -22‰ and increases (i.e. become less negative) when water limitation occurs (Farquhar et al., 1989; Impa et al., 2005). However, in C_4 plants the large effect of RuBisCo on $\delta^{13}C$ is suppressed in the semi-closed bundle sheath (Farquhar et al., 1989). Therefore, the isotopic composition will be less for C_4 in comparison with C_3 plants. When water stress occurs in C_4 plants, the $^{13}CO_2$ diffused through the stomata will concentrate in HCO_3^- and Phosphoenolpyruvate (PEP) carboxylase discriminates against $H^{13}CO_3^-$. Water limitation in C_4 will therefore cause a decrease (i.e. becomes more negative) of $\delta^{13}C$ which ranges for well watered conditions between -10 and -14‰ depending on plant species (Farquhar, 1983). Factors which influence CO_2 diffusion such as nitrogen availability, salinity and light will therefore also influence ^{13}C discrimination causing an increase or decrease of $\delta^{13}C$ depending on the photosynthetic pathway of the plant species (Farquhar et al., 1989; van Groenigen and van Kessel, 2002; Dercon et al., 2006a).

The use of the stable isotope ^{15}N assists in understanding N uptake and fertilizer use efficiency as N dynamics within the spoil-plant system is often complex, especially in paddy fields (Yoneyama et al., 1991b; Bandyopadhyay and Sarkar, 2005; Kaewpradit et al., 2009). Many studies used ^{15}N enrichment techniques in order to understand the N uptake/losses and estimate the fertilizer use efficiency within cropping systems (e.g. Bandyopadhyay and Sarkar, 2005; Goto et al., 2006; Fan et al., 2007; Ghoneim et al., 2008). The various inputs of N through irrigation, fertilizer application and residue management into the cropping system, will have an impact on the natural abundance of ^{15}N in soils and consequently in plants (Nishida et al., 2007; Ebid et al., 2008; Bernot et al., 2009). Furthermore, the wet-dry cycles, characteristic for paddy fields, will not only have an impact on the transport and transformation of N but will also influence the natural abundance of ^{15}N (Yoneyama et al., 1990; Yoneyama et al., 1991a). For example, when the period of saturation increases an enrichment of $\delta^{15}N$ within the soil was found by Billy et al. (2010). This can be linked with the increase of ammonium concentration under the anaerobic conditions and the preferred uptake of $^{14}N\text{-}NH_4^+$ by rice plants causing an enrichment of $\delta^{15}N$ in the topsoil (Yoneyama et al., 2001b). Therefore, the natural abundance of ^{15}N in paddy soils reflects the history of soil and water management (Nishida et al., 2007). In the current thesis stable isotopes, ^{13}C and ^{15}N, were analyzed in rice grains and paddy soil samples taken at harvest, in order to assess the impact of spatial variation of water and nitrogen availability on rice yields along cascades (Chapter 4).

1.5 Justification

Socio-economic changes have put tremendous pressure on agricultural land in the tropical mountainous regions of Northern Vietnam changing its rather sustainable composite swiddening system into intense annual monocropping systems (Turkelboom et al., 2008; Ziegler et al., 2009). The effect of these intensified systems in the uplands in terms of soil degradation, erosion associated nutrient transport and yield reduction have been widely addressed over the past years (Lam et al., 2005; Dung et al., 2008; Nikolic et al., 2008; Bruun et al., 2009). The erosion-induced transport and deposition of sediments within the landscape is complex as it depends on topography, the occurrence of linear elements (e.g. roads, paths) and the chosen scale (Ziegler et al., 2000; Chaplot et al., 2005b). The sediment associated nutrients can have several impacts downstream such as siltation of irrigation systems, flooding and pollution of water bodies (Lantican et al., 2003; Bruijnzeel, 2004; Gao et al., 2004; López -Tarazón et al., 2009). Sediment deposition in the lowlands depends on water discharge, topographic characteristics and particle size distribution (Gao et al., 2007; 2008). As sediments, depending on its quantity and quality, can be an additional source of nutrients, patterns of spatial variability (e.g. organic C) can be expected in the lowlands (Mingzhou et al., 2007; Schiettecatte et al., 2008). As pointed out by Mingzhou et al. (2007) sediment deposition can improve crop performance due to an increase of cation exchange capacity, clay content and soil organic matter which positively influences nitrogen use efficiency. Therefore, there is a need for quantifying sediment related carbon and nutrients redistributions within cultivated watersheds and its effect on soil fertility (Valentin et al., 2008). Especially, in Southeast Asia where valley bottoms are under intensive rice cultivation the additional source of nutrients can play an important role as paddy fields act as a sediment and nutrient trap (Yan et al., 2010). Often fertilizer recommendations for rice are not catchment specific, resulting in an over-fertilization increasing the pollution of water bodies due to excessive N and P transport (Kim et al., 2006). Furthermore, due to climate change, the occurrence of extreme storm events, such as typhoons, will increase (Cruz et al., 2007). The effect of typhoons on sediment transportation and deposition throughout the landscape needs to be addressed in order to understand the sustainability of current land uses in up- and lowlands as they are interlinked. This scientific work tries to quantify the amount of C and N originating from the upland and its redistribution through irrigation into downstream paddy toposequences in order to understand and improve spatial variability of rice performance. Furthermore, it seeks to understand the upland-lowland linkages in terms of sediment transportation and its vulnerability during extreme rainfall events.

1.6 Hypotheses

The main hypotheses addressed in this thesis are:

a) The, through erosion removed, carbon and nitrogen is redistributed by various sedimentation-deposition pathways from the intensively cultivated upland to the lowland,
b) Depending on the sediment characteristics and deposition pathway, the redistribution of C and N is creating patterns of soil spatial variation and therefore influences rice productivity in the lowland,
c) Extreme rainfall events such as typhoons will influence the quality and quantity of sediment deposition and therefore, would pose a risk to the sustainability of the system,
d) Farmers' perception on agricultural practice is influenced by extreme rainfall events which could stimulate adoption of soil conservation practices.

1.7 Goal and objectives

The goal of this study was to understand the erosion induced redistribution of carbon and nitrogen within the landscape and its impact on rice productivity in the lowland in an intensively cultivated watershed in Northern Vietnam.

The specific objectives were to:

a) Quantify the carbon and nitrogen loads irrigated to the lowland and transported out of the subwatershed during the rainfall season,
b) Assess the spatial redistribution of carbon and nitrogen within and along rice toposequences, its effect on soil fertility and rice productivity,
c) Distinguish between water and nutrient induced yield losses occurring within toposequences using stable isotope techniques,
d) Understand the driving factors behind farmers' practices and the influence of extreme events such as flooding on the adoption of mitigation strategies (e.g. soil conservation techniques).

1.8 Outline of the study

In Chapter 1 a brief overview is given of the driving factors behind land use intensification and its implications on landscape level in Northern Vietnam followed by a short discussion about the techniques used throughout the study. Chapter 2 deals with the quantification of C and N flows from upland area, through irrigation water into downstream paddy rice terraces. The effect of sediment deposition on soil spatial variation among and within terraces is discussed within Chapter 3, and the effects on rice production in Chapter 4. The last paper presented here (Chapter 5) was an interdisciplinary study addressing the impact of extreme events on farmers perception on agricultural practices in the upland and its linkage to downstream rice production. The general discussion and future recommendations related to this study can be found in Chapter 6, and the summary in Chapter 7. All references used within this work are listed in Chapter 8.

CHAPTER 2

REDISTRIBUTION OF CARBON AND NITROGEN THROUGH IRRIGATION IN INTENSIVLY CULTIVATED TROPICAL MOUNTAINOUS WATERSHEDS

2 Redistribution of carbon and nitrogen through irrigation in intensively cultivated tropical mountainous watersheds[1]

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2.1 Abstract

This study aimed at tracing and quantifying organic carbon and total nitrogen fluxes related to suspended material in irrigation water in the uplands of Northwest Vietnam. In the study area, a reservoir acts as a sink for sediments from the surrounding mountains, feeding irrigation channels to irrigate lowland paddy systems. A flow separation identified the flow components of overland flow, water release from the reservoir to the irrigation channel, direct precipitation into the channel, irrigation discharge to paddy fields and discharge leaving the sub-watershed. A mixed effects model was used to assess the C and N loads of each flow component. Irrigation water had an average baseline concentration of 29 ± 4.4 mg l^{-1} inorganic C, 4.7 ± 1.2 mg l^{-1} organic C and 3.9 ± 1.6 mg l^{-1} total N. Once soils were rewetted and overland flow was induced, organic C and total N concentrations changed rapidly due to increasing sediment loads in the irrigation water. Summarizing all monitored events, overland flow was estimated to convey about 63 kg organic C ha^{-1} and 8.5 kg N ha^{-1} from surrounding upland fields to the irrigation channel. The drainage of various non-point sources towards the irrigation channel was supported

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by the variation of the estimated organic C / total N ratios of the overland flow which fluctuated between 2 and 7. Nevertheless, the majority of the nutrient loads (up to 93-99%) were derived from the reservoir, which served as a sediment-buffer trap. Due to the overall high nutrient and sediment content of the reservoir water used for irrigation, a significant proportion of nutrients was continuously reallocated to the paddy fields in the lowland throughout the rice cropping season. The cumulative amount of organic C and total N load entering paddies with the irrigation water between May and September was estimated at 0.8 and 0.7 Mg ha^{-1}, respectively. Therefore deposition of C and N through irrigation is an important contributor in maintaining soil fertility, and a process to be taken into account in the soil fertility management in these paddy rice systems.

2.2 Keywords

C and N flows; irrigation; overland flow; paddy fields, Vietnam; water quality.

2.3 Introduction

In tropical mountainous regions of Southeast Asia, increasing population pressure and enhanced market access resulted in a rapid deforestation and land use intensification on steep slopes (Dung et al., 2008; 2005; Valentin et al., 2008; Ziegler et al., 2009). In Vietnam, from a total land area of 33 million ha, 75% are located in mountainous and hilly regions off which 50% are used for agriculture (The World Bank and The Danish Agency for International Development, 2002). One of the most common agro-ecosystems in Northern Vietnam is composite swidden agriculture (Dung et al., 2008; Lam et al., 2005; Ziegler et al., 2009) which consists out of an alternation of fallow and cash crops in the upland areas (e.g. maize and cassava) in combination with permanent paddy fields at the lower slopes and valley bottoms. Over the last decades the duration of the fallow periods has been reduced and composite swidden agriculture has been replaced by permanent annual cropping systems which resulted in accelerated land degradation through erosion and nutrient losses (Dung et al., 2008; Pansak et al., 2008; Vezina et al., 2006; Ziegler et al., 2009), and changes in catchment hydrological behavior due to landscape fragmentation (Ziegler, 2007).

Sediment and associated nutrient transport depend on soil and land use type, slope and landscape fragmentation (Valentin et al., 2008; Van De et al., 2008; Ziegler et al., 2007), and can cause negative on-site (e.g. soil fertility reduction and crop productivity decline) and off-site (e.g. stream pollution and reservoir siltation) impacts at catchment level (Berka et al., 2001; Havens et al., 2001; Lu and Higgitt, 2001; Pansak et al., 2008; Wezel et al., 2002). Van Oost et al. (2007) estimated that globally 1 Pg yr^{-1} of organic carbon (C) is lost by erosion from agricultural land and found ranges of organic C losses between 30 and 300 kg ha^{-1} $year^{-1}$ depending on land use, cultivation practices and watershed characteristics. Lal (2003) reported considerably higher rates of organic C redistributed worldwide by water erosion ranging between 4 and 6 Pg yr^{-1} of which 2.8 - 4.2 Pg yr^{-1} was transferred to lowland areas.

Climate change studies have pointed out that extreme rainfall events and an increase in drought periods will continue to occur (Bates et al., 2008; Cruz et al., 2007). Water demand for agricultural and non-agricultural use will continue to increase although water availability will be challenged in the future (Xiong et al., 2010). Cruz et al. (2007) stated that due to water scarcity, rice yields will drop at the end of the 21st Century by 3.8% in Asia. As rice is the main staple food in Southeast Asia, seasonal water shortage will call for expansion and improvement of irrigation systems as well as water management in order to meet the increasing food demand (Hatcho et al., 2010; Kirby and Mainuddin, 2009; Turral et al., 2010). Besides surface water induced erosion and sedimentation patterns in the landscape, the presence of irrigation systems can contribute additionally to the redistribution of nutrients within irrigated lowlands. The contribution of irrigation water in terms of nutrient and sediment deposition is highly influenced by irrigation channel gradient (Mingzhou et al., 2007) and irrigation scheme (King et al., 2009; Poch et al., 2006). In Sacramento Valley (USA), furrow irrigation in an intensively cultivated watershed resulted in a net input of 2 Mg sediment ha^{-1} yr^{-1} (Poch et al., 2006) and 0.03 total C Mg ha^{-1} yr^{-1} from which the majority was delivered during rainfall events. Furthermore the study showed a net loss of 0.005 total N Mg ha^{-1} yr^{-1} due to runoff created during irrigation after fertilization (King et al., 2009). In an intensively cultivated watershed in China, Tang et al. (2008) reported an averaged input of 0.02 Mg total N ha^{-1} yr^{-1} in paddy fields from irrigation water. While small and moderate nutrient-rich sediment deposition on downstream located farmland such as paddy fields might be beneficial, large nutrient-poor sediment delivery could decrease the original soil fertility (Cassel et al., 2000; Mingzhou et al., 2007; Schmitter et al., 2010).

The purpose of this study was to assess the redistribution of C and N through irrigation water in intensively cultivated mountainous regions of Northwest Vietnam and to evaluate the contribution of rainfall induced runoff from upland areas on additional irrigated C and N loads. The specific aims were (i) to separate the measured discharge in the irrigation channels into the different flow components and their role in redistributing C and N loads (e.g. overland flow, direct rainfall, inlet, outlet and irrigation discharge), (ii) to evaluate the role of an irrigation system with regards to sink and sources of C and N into the lowland, and (iii) to estimate the vulnerability of irrigated lowlands during the rainy season with regards to nutrient fluxes.

2.4 Materials and methods

2.4.1 Experimental site

The assessment of carbon and nitrogen loads in the irrigation water was carried out from May till September 2008, during the rainfall season in the Chieng Khoi commune, Yen Chau district, Son La province, Northwest Vietnam. As the area is located in the tropical monsoon belt, the rainy season starts in April and can last till September-October. Especially at the end of the rainy season, the occurrence of typhoons is not uncommon where daily rainfall amounts can rise to 200 mm.

In the south of the Chieng Khoi catchment, a stream originating from Karst mountains was dammed in 1962, resulting in a lake with a capacity of 1 x 10^6 m^3, which currently serves as an irrigation reservoir (Figure 2-1). The contributing area of intensively cultivated uplands to the reservoir is approximately 490 ha. The maximum water level of the reservoir is 12.25 m and the fluctuations strongly depend on rainfall and irrigation requirements. Construction of open-channel irrigation systems made intensification of rice production in the area possible by providing enough water for surface irrigation in the dry season to allow a spring (February/March – June/July) besides a summer rice season (July – October/November). The reservoir is feeding a main irrigation channel which splits after 200 m in two irrigation channels supplying irrigation water to 60 ha of paddy rice. The streambed of the open-channel irrigation system under study was made out of concrete. Additionally, the spill-over of the reservoir feeds the dammed stream during July- September when the reservoir fills up completely. Outside of this period, runoff, interflow and baseflow mainly originating from the irrigated rice fields are the only contributing processes influencing the river discharge.

The present study focused on a subwatershed within the Chieng Khoi catchment which consisted out of 17.1 ha of upland area draining towards the irrigation channel and 6.5 ha of irrigated paddy area fed by the channel. The irrigation water used in this area is supplied by one of the two irrigation channels originating from the reservoir (Figure 2-1).

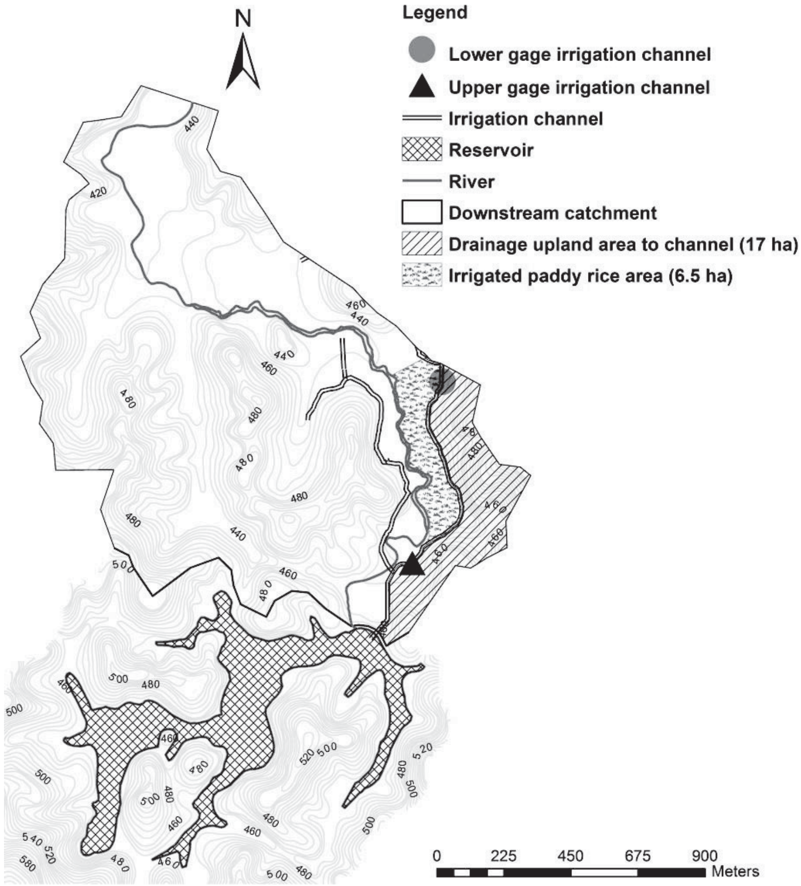

Figure 2-1: Overview of the position of both automatic water samplers (upper gage and lower gage, black triangle and grey circle, respectively) along one of the irrigation channels within the Chieng Khoi watershed (Son La Province). The marked area above the irrigation channel delineates the upland drainage area towards the channel while the area between the irrigation channel and the river marks the paddy area that is irrigated between both measurement stations.

In the subwatershed, the upland area is characterized by steep upland hills (i.e. slopes up to 86%) which are intensively cropped with maize (*Zea mays L.*) and cassava (*Manihot esculenta* Crantz) from March until December. The parent material is often silt-fine sandstone and limestone and the two major occurring soil types in the upland area are Alisols and Luvisols (Deckers et al., 1998). In the lowland, the soils are classified as anthraquic Anthrosols on which paddy rice (*Oryza sativa* L.) is the major cultivated crop, in some areas for up to 200 years.

2.4.2 Total organic carbon and total nitrogen fluxes in irrigation water

Rainfall was monitored every two minutes and summarized every 10 minutes by a weather station (Campbell Scientific) which included a tipping bucket rain gauge with a precision of 0.1 mm. In 2008, the total rainfall amounted to 1054 mm of which 720 mm fell within the measured period (May till September 2008). As the irrigation channel was of concrete, the baseflow and interflow of the upland area could be neglected as extra input sources as well as percolation losses from the bed with regards to outflow components. Within the channel, two automatic water samplers were installed: (i) at the inlet of the concrete irrigation channel (upper gage) after the split of the main irrigation channel and (ii) at 1.1 km downstream from the inlet, leaving the delineated studied subwatershed (lower gage) (Figure 2-1). This set up assisted in differentiating the amount and quality of the water coming from the reservoir (upper gage) and the water from the surrounding uplands along the irrigation channel. In total, 25 events covering various average rainfall intensities ranging between 0.1 and 11 mm h^{-1} and different rainfall amounts, fluctuating between 0.1 and 30 mm were sampled at both sampling stations. During each rainfall event, sampling was carried out flow proportionally at both measurement stations (Figure 2-1) using automatic water samplers (Maxx Mess- und Probennahmetechnik GmbH, Germany) which were connected with ultrasonic sensors (Nivus GmbH, Germany) for water level measurements. Water levels were automatically converted to discharge using a calibrated stage-discharge curve. Five flow proportional samples each of 50 ml were combined into one flask creating a composite flow proportional sample. The amount of composite samples taken during rainfall events depended on rainfall duration and discharge in the channel (Table 2-1). Each monitored event started with a baseline sample before rainfall started and ended when the baseline was reached after a rainfall event. Furthermore, baseline samples were taken in a bi-weekly interval throughout the measurement period May to September 2008. In total, 419 composite samples were taken, frozen to avoid C and N losses, and analyzed for total N, inorganic and organic C by combustion using a LiquitocII C and N analyzer (Elementar Analysensysteme GmbH, Germany). Inorganic C was measured at 32°C after acidification with HCl while total organic C and total N was measured by combustion until 800°C.

2.4.3 Data analysis

The data analysis was designed to carry out a flow component separation (overland flow, direct rainfall, inlet, outlet and irrigation discharge). This allowed (i) characterizing and classifying rainfall events based on the different flow components and their effect on mean inorganic and organic C and total N concentrations for each event (i.e. event mean concentration, EMC), (ii) calculating the loads of total N, inorganic and organic C associated to these components, and (iii) evaluating the nutrient loads irrigated to the paddy fields and leaving the watershed at the outlet.

2.4.3.1 Event definition

Cross correlation analysis was used to quantify the temporal lag between peaks in rainfall time series and discharge time series at the outlet. According to Biron et al. (1999) stationary event time series were established out of the original precipitation and flow time series through least-squares regression with time as predictor variable by adding the model residuals to the mean values of the respective time series. The calculated lag times were interpreted as reaction time of the hydrologic system under study. Rainfall events were consecutively defined to last from start to finish of periods of continuous precipitation and appending the calculated lag times to the end of these periods. Periods of continuous precipitation were defined as not being intermitted by periods of no precipitation longer than 30 minutes.

2.4.3.2 Flow component calculation

As the irrigation channel monitored in this study was constructed out of concrete, baseflow and interflow were excluded from the calculation of the flow components. With this precondition the hydrological system can be described as follows:

$$Q_{pp} + Q_{in} + Q_{of} = Q_{irr} + Q_{out} \qquad \text{Eq. 2-1}$$

where Q_{pp} (m^3) is the direct precipitation into the stream channel, Q_{in} (m^3) the gaged outflow from the reservoir (upper gage), Q_{of} (m^3) the overland flow discharging into the stream channel from adjacent slopes between the two gages, Q_{irr} (m^3) the amount of water used for irrigation of the paddy fields situated between the upper and lower gage and Q_{out} (m^3) the measured outflow at the lower gage. Q_{pp} (m^3) was calculated multiplying the channel surface area by precipitation. For all further analyses Q_{in} was shifted two time steps forward (10 minutes per time step) according to an observed overall lag time of 20 minutes between Q_{in} and Q_{out}. During dry periods, i.e. in absence of Q_{pp} and Q_{of}, Q_{irr} was calculated at time step *i* by subtracting outflow at the lower gage from outflow from the reservoir:

$$Q_{irr,i} = Q_{in,i} + Q_{out,i} \quad \text{Eq. 2-2}$$

During rainfall events, where equation 1 has two unknowns (i. e. Q_{irr}, Q_{of}), $Q_{irr,i}$ was assumed to be the product of pre-event irrigation rates and the relative change in reservoir release (Q_{irr}) due to irrigation management since the onset of the event:

$$Q_{irr,i} = \left(Q_{in,pre} - Q_{out,pre}\right) \times \left(1 + \left(Q_{in,i} - Q_{in,pre}\right) Q_{in,pre}{}^{-1}\right) \quad \text{Eq. 2-3}$$

with subscript *pre* denoting the last time step preceding the event. The partitioning of inputs from Q_{in} into contributions to Q_{out} and Q_{irr} was kept constant during the event and Q_{of} subsequently calculated recalling Eq. 2-1.

2.4.3.3 Event characteristics

For exploratory data analysis and the subsequent mixed effects model, all events were characterized by hydrological and hydrochemical parameters. The former comprised average precipitation intensity, cumulative precipitation amount and duration, cumulative flow component discharges and preceding rainfall conditions (i.e. time to the preceding event and cumulative rainfall of the preceding rainfall event). The latter included total N, inorganic and organic C minimum and maximum concentrations of the two gages, flow component loads and event mean concentrations (*EMC*), which allowed cross event intercomparison, calculated according to:

$$EMC = \sum\left(Q_j \times C_j\right) / \sum Q_j \quad \text{Eq. 2-4}$$

with Q_j the discharge (m³) for a composite sample i during an event and C_j the corresponding concentration (mg l^{-1}) of a water parameter (e.g. inorganic C, organic C and or total N).

Within each event, for each composite sample, the load for all water parameters was calculated for each measurement station according to:

$$L_j = C_j \times Q_j / 1000 \qquad \text{Eq. 2-5}$$

where L represents the total N, inorganic C or organic C load (kg) for a composite sample j. These calculations were done for both water sampling stations. The use of subscript i in Eq. 2-2 and Eq. 2-3 denotes the equidistant discharge measurements (10 min.) and the time period for the composite sample respectively while j varies in accordance with flow proportional sampling.

The load for the irrigation component was estimated with the assumption that the concentration of irrigation water equals the concentration of outflow, implying that all input sources mix fully at the uppermost point of the stream segment between the two gages. This approach was based on the observation that loads from overland flow in the lower part of the stream segment contributed much less to irrigation water due to absence of favouring landscape features (e.g. roads). Overall, the initial assumption holds, if the irrigation load is interpreted as maximum possible load. With the same degree of uncertainty, the load of overland flow was calculated by subtracting the loads of rain and reservoir outflow from the sum of the loads of irrigation discharge and lower gage outflow. Event loads for each flow component where calculated by summing up all composite sample loads within the event.

Using the average baseline concentration of organic C and total N in the irrigation water measured before each rainfall event, the contribution of a rainfall event to the overall load at the point of interest (e.g. upper gage, lower gage and irrigation water) can be calculated according to:

$$L_{irr,R_0} = C_{irr,R_0} \times Q_{irr} / 1000 \qquad \text{Eq. 2-6}$$

$$D_L = L_{irr} - L_{irr,R_0} \qquad \text{Eq. 2-7}$$

L_{irr,R_0} represents the cumulative baseline load (kg) irrigated during an event assuming baseline (pre-event) concentrations C_{irr,R_0} (mg l^{-1}) and event cumulated Q_{irr} (m^3). D_L, the difference between L_{irr} (Eq. 2-5) and L_{irr,R_0} reveals the irrigation load (kg) , which can be attributed to flow processes connected to the rainfall event, which can also be expressed as an event load factor (%), when normalized by L_{irr}.

2.4.3.4 Mixed effects model

A general description of the different flow components and associated variation of total N, inorganic and organic C concentrations and loads for all 25 events was obtained by using the procedure Univariate in SAS v9.2 (Liu et al., 2004). The Spearman rank correlations between the discharge of the different flow components, water level at the reservoir and the total N, inorganic and organic C loads were calculated by running the procedure CORR in SAS. The results were used to exclude correlated variables when developing the mixed effect model.

In order to extrapolate the contribution of the 25 sampled events on the irrigation water diverted to the paddy fields between upper and lower gage and the load leaving the lower gage, over the entire monitored season (May till September), a mixed effects model was built for total N, inorganic and organic C using the procedure MIXED in SAS v9.2. Previous studies have pointed out the linkage between load estimation and discharge components in natural rivers using multiple linear regression or generalized linear models (Cox et al., 2008; Haggard et al., 2003; Stenback et al., 2011). Filling time of a composite sample influences the load calculation due to the effect of cumulative discharge fluctuations as the samples are taken flow proportionally. Therefore the MIXED procedure was chosen in this study where filling time for each composite sample was taken as a random effect. Within the model, reservoir level, average rainfall intensity, cumulative irrigation discharge to the paddy fields, overland flow discharge and discharge at the lower gage, were taken as fixed effects. As samples were taken flow proportionally, there is a time dependency between the samples of one event. Therefore, all samples taken within the event were treated as a repetition. The calculated loads for each water parameter and discharge data were log transformed in order to obtain homogeneity of variance and normal distribution of the residuals. The model used was:

$$\ln(y) = \mu(x_1, x_2, x_3, x_4, x_5) + e = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + e \qquad \text{Eq. 2-8}$$

where y is the total N, inorganic or organic C load (kg event^{-1}) of the irrigation water or passing through the lower gage, respectively; α is the intercept; $\beta_1, \beta_2, \beta_3, \beta_4$ and β_5 the regression coefficients; x_1 the average rainfall intensity (mm h^{-1}) during bottle filling; x_2 the log transformation of the cumulative discharge irrigated to the paddy fields between the upper and lower gage (m³); x_3 the log transformed cumulative overland flow; x_4 the log transformation of cumulative discharge passing through the lower gage and x_5 the water level in the reservoir during the event (m). When evaluating the covariates at their means across the samples and assuming log normality of *y,* the influence of rainfall on load contribution could be assessed by comparing the predictions with the prediction when the average rainfall intensity ($\bar{x}_1$) and overland flow ($\bar{x}_3$) equaled zero. Therefore the percent change can be estimated using:

$$R = \hat{y}_{x_1 = \bar{x}_1 and\ x_3 = \bar{x}_3} / \hat{y}_{x_1 = 0\ and\ x_3 = 0} = e^{(\beta_1 \bar{x}_1 + \beta_3 \bar{x}_3)} \qquad \text{Eq. 2-9}$$

Therefore,

$$C_R = (R - 1) \times 100 \qquad \text{Eq. 2-10}$$

with R the ratio between the prediction of the model Thus, all three covariates would be evaluated at their means across the sample using the average of each covariate ($\bar{x}_1$, $\bar{x}_2$, $\bar{x}_3$, $\bar{x}_4$ and $\bar{x}_5$) with ($\bar{x}_1$ and $\bar{x}_3$ > 0) and without (x_1 and x_3= 0) rainfall for the same time period, α the intercept, β_1, β_2, β_3, β_4 and β_5 the regression coefficients and C_R the contribution of rainfall.

The confidence interval of 95% for the covariate parameter estimate ($\bar{x}_1$ and $\bar{x}_3$) was computed using the CL (confidence limit) statement in the mixed procedure. The calculation of C_R and respective confidence interval computation was using the average of each covariate over the 25 rainfall events in order to analyze the impact of the 25 events on the loads irrigated towards the paddy fields and the loads passing through the lower gage. The functions from the mixed effects model were used for estimating the loads for the entire period May till September using the overall dataset containing rainfall, discharge and lake level.

2.5 Results

2.5.1 Hydrological characterization of the subwatershed

Depending on the reservoir management, the discharge passing the upper gage varied between 0.01 and 0.34 m³ s^{-1}, while the irrigation discharge to the paddy fields and at the lower gage fluctuated between 0 and 0.26 m³ s^{-1}, and 0 and 0.30 m³ s^{-1}, respectively. For the measured events, rainfall ranged between 0.2 and 30.7 mm with average intensities varying from 0.3 to 11.6 mm h^{-1} (Table 2-1) and maximum intensities between 0.6 and 74 mm h^{-1} (data not shown).

Table 2-1: Event mean concentration (EMC) (mg l^{-1}) for organic C and total N, total rainfall (mm), average rainfall intensity (mm h-1), rainfall duration (min), rainfall amount of the event preceding the measured event (pre-rainfall, mm), time between the rainfall event studied and the previous rainfall event (time pre-rainfall, h) and total amount released from the reservoir into the irrigation channel (discharge reservoir, m³) for all measured events at the two measurement stations (upper and lower gage).

Event (No.)	Date (dd/mm)	No.[a]	R[b] (mm)	Average RI[b] (mm h^{-1})	Duration R[b] (min)	Discharge reservoir (m³)	Time pre-R[b] (h)	Pre-R[b] (mm)	EMC organic C (mg l^{-1})		EMC Total N (mg l^{-1})	
									Upper[c]	Lower[c]	Upper[c]	Lower[c]
1	04/05	7/5	1.2	0.5	160	1016	70.5	3.7	5.1	6.2	2.1	2.5
2	05/05	10/12	20.7	11.6	110	3313	17.0	1.2	3.7	115.7	2.1	15.5
3	06/05	5/5	0.7	1.1	40	966	28.8	17.4	4.3	7.4	2.1	2.4
4	07/05	10/16	0.9	0.5	120	2679	20.0	0.7	3.6	5.1	2.2	2.6
5	09/05	10/12	12.0	10.3	70	1832	18.5	0.3	3.7	33.9	1.7	5.9
6	30/05	9/11	12.2	2.2	340	2749	92.0	0.2	4.2	9.3	1.8	2.9
7	31/05	5/6	0.2	0.3	40	1152	3.0	12.2	2.7	3.4	1.4	1.2
8	05/06	3/4	3.2	9.6	20	1119	8.2	6.4	4.1	6.6	1.8	2.3
9	05/06	5/7	18.8	5.6	200	1713	2.5	3.2	12.7	64.6	3.7	12.3
10	08/06	3/4	0.8	1.6	30	864	17.5	2.4	4.0	4.5	1.8	1.9
11	08/06	3/12	0.7	0.7	60	780	6.3	0.8	4.6	5.1	2.1	2.0
12	11/06	7/12	22.3	7.9	170	2173	42.5	0.6	29.3	117.7	4.4	17.5
13	11/06	5/6	0.2	0.3	40	965	2.5	22.3	4.9	8.4	1.6	3.2
14	12/06	4/6	1.1	0.7	100	623	7.3	0.2	4.9	3.8	3.0	1.9
15	12/06	3/5	0.4	0.8	30	488	1.2	1.1	2.5	4.7	2.0	2.5
16	14/06	12/16	30.7	8.0	230	3680	6.3	3.2	17.5	68.6	4.6	10.3
17	15/06	5/5	1.3	0.8	100	1167	9.3	0.2	4.8	6.5	3.0	3.4
18	18/06	3/4	0.2	0.6	20	267	7.7	0.8	3.7	7.2	4.2	4.6
19	25/06	5/9	12.5	5.1	180	1657	37.2	4.0	3.6	14.0	5.3	6.3
20	27/06	3/6	1.8	3.6	30	244	36.3	0.5	3.3	4.6	4.8	5.1
21	27/06	3/5	0.7	0.5	90	303	1.0	1.8	3.3	4.4	4.7	4.6
22	03/07	9/6	1.7	1.8	120	2932	13.8	2.1	3.2	3.9	4.8	4.6
23	07/07	6/7	12.0	5.5	130	1478	15.5	28.1	5.9	34.4	5.1	8.8
24	30/08	4/4	23.1	8.2	170	9593	30.3	2.1	4.5	6.5	5.1	5.8
25	03/09	5/5	10.4	3.5	360	15311	80.5	23.1	4.7	4.4	5.1	5.2

[a] Number of samples taken per event at the upper gage and lower gage, respectively.
[b] R and RI referring to rainfall and rainfall intensity, respectively.
[c] Upper and lower referring to the upper and lower measurement stations along the irrigation channel, respectively.

Depending on the rainfall duration and intensity of the 25 rainfall events, the contribution of overland flow to total discharge in the irrigation channel varied between 0 and 46% with an average of 12% (Figure 2-2). The contribution of direct rainfall captured by the surface of the irrigation channel was found to be negligible (Figure 2-2). Events 3, 4, 7, 8, 11, 13, 15, 17, 18, 20 and 21 showed negligible overland flow discharge compared to the other events.

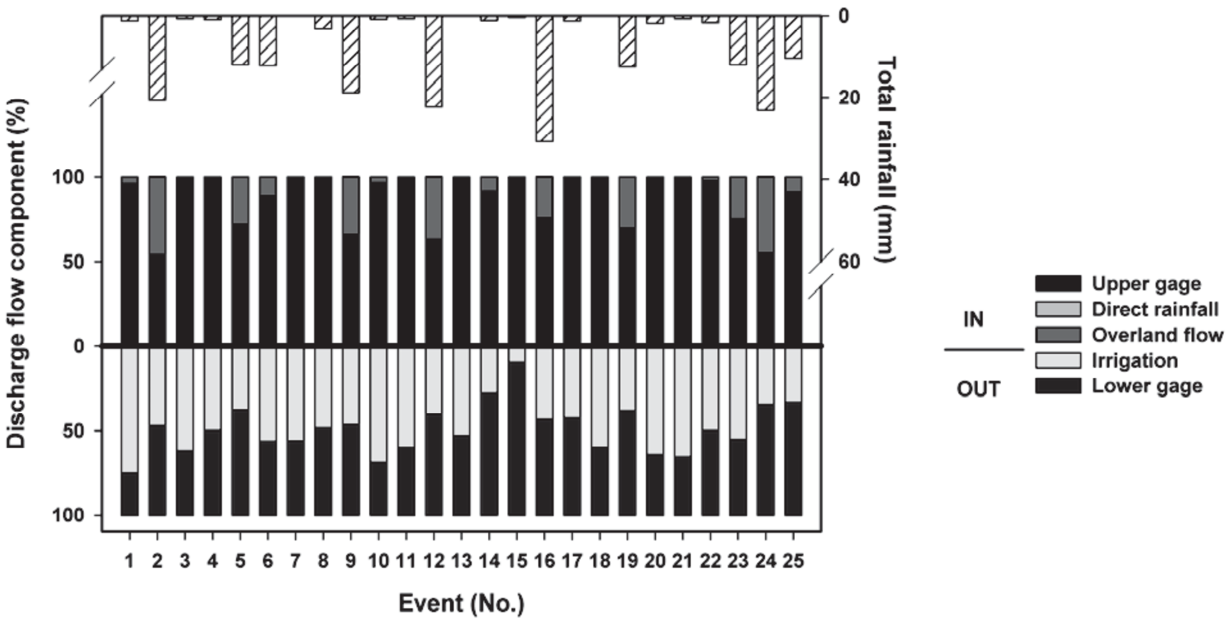

Figure 2-2: Overview of the different flow components (%) entering (i.e direct rainfall, upper gage, overland flow) and leaving the irrigation channel (i.e. irrigation between upper and lower gage, non-irrigated discharge passing through the lower gage) during a rainfall event. Vertical bars at the top represent the total rainfall (mm) for each event.

2.5.2 Hydrochemical characterization of reservoir and irrigation water along the channel

Throughout the entire measurement period and in absence of rainfall, the average baseline concentrations found in the reservoir were 29.0 ± 4.4 mg l^{-1}, 4.7 ± 1.2 mg l^{-1} and 3.8 ± 1.6 mg l^{-1} for inorganic C, organic C and total N. Rainfall had an average concentration of 4.0 ± 1.6 mg l^{-1} inorganic C, 2.6 ± 0.1 mg l^{-1} organic C, and 1.1 ± 0.1 mg l^{-1} total N. A quick response was observed of increased inorganic and organic C and total N concentrations at the lower gage depending on rainfall intensity (organic C shown in Figure 2-3).

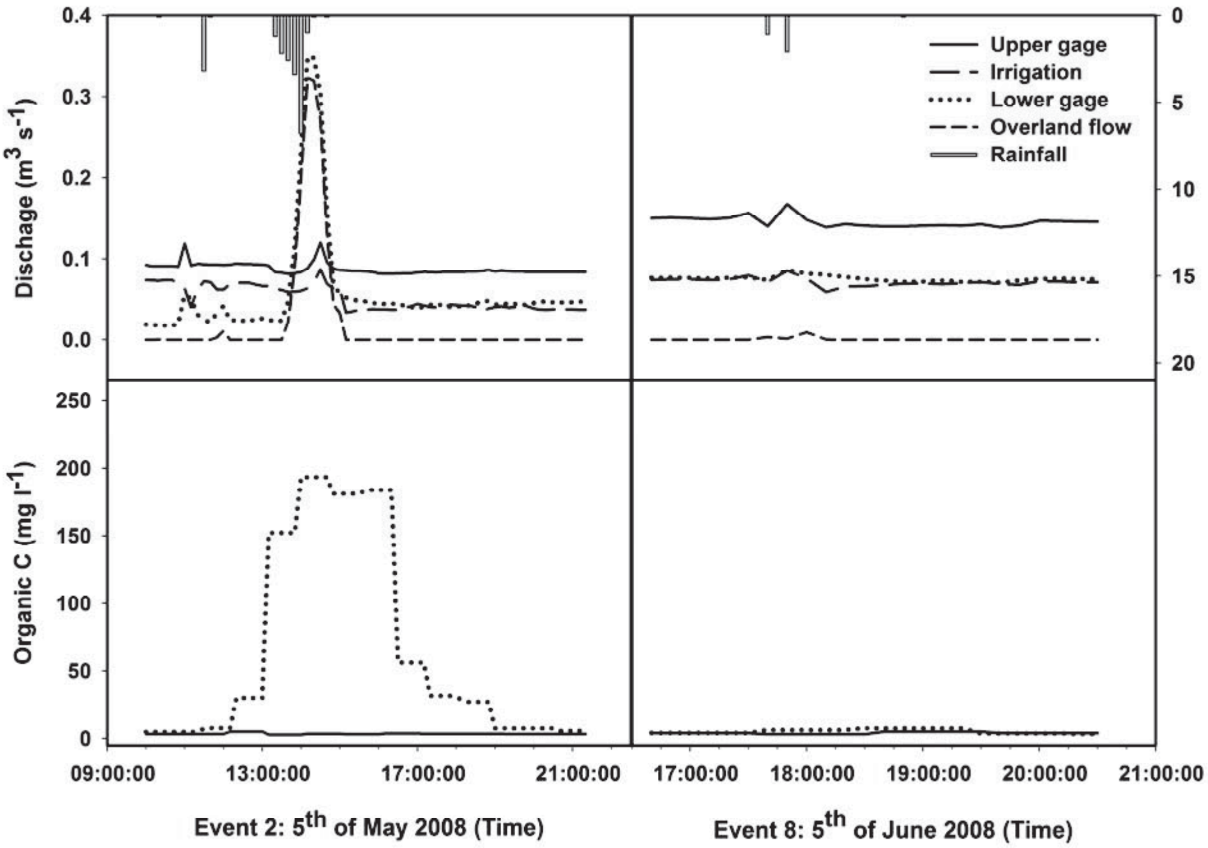

Figure 2-3: Changes in flow components (m^3 s^{-1}) (top) and corresponding organic C concentrations (mg l^{-1}) (bottom) for a high (Event 2) and low (Event 8) intensity rainfall event.

During rainfall events the quality of the water at the upper gage (inlet), coming from the reservoir, fluctuated between 14.9 to 52.2 mg l^{-1} inorganic C, 1.6 to 118.8 mg l^{-1} organic C, and 1.2 to 23.0 mg l^{-1} total N (Figure 2-4). At the lower gage (outlet) the water quality ranged between 12.0 and 84.4 mg l^{-1} inorganic C, 2.1 and 311.4 mg l^{-1} organic C, and between 1.1 and 52.6 mg l^{-1} total N. Fluctuation of inorganic C between the various samples taken within one rainfall event was found to be limited for both gages as well as between gages. Additionally, organic C and total N concentrations among the different samples, taken within a rainfall event, showed a limited fluctuation at the upper gage compared to the lower gage (Figure 2-4). For organic C, the event mean concentration (EMC) at the inlet (upper gage) ranged between 2.5 (Event 15) and 29.3 mg l^{-1} (Event 12), while for total N values between 1.6 (Event 13) and 5.3 mg l^{-1} (Event 19) were obtained (Table 2-1). At the lower gage, EMC ranged between 3.4 (Event 7) and 117.7 mg l^{-1} (Event 12) organic C, and between 1.2 (Event 7) and 17.5 mg l^{-1} (Event 12) total N. In general EMC concentrations at the upper gage were found to be lower than EMC measured at the lower gage within the same event.

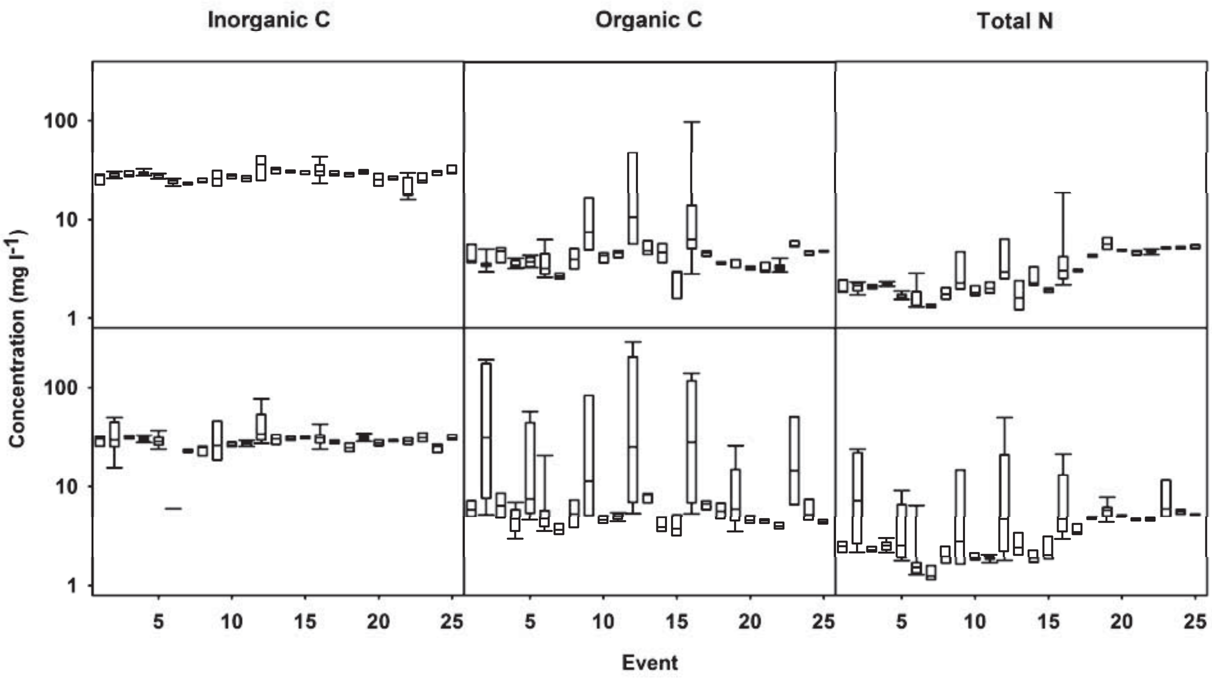

Figure 2-4: Box plots of inorganic C, organic C and total N concentrations (mg l^{-1}) for all 25 events monitored at the upper gage (top) and lower gage (bottom) with crossbars, boxes and whiskers giving the median, quartile range and range respectively.

2.5.3 Flow components and their contribution to organic C and total N loads

The calculated loads strongly depended on the duration of the rainfall event and the amount of water released from the reservoir and therefore passing through the upper gage. The events with the highest average rainfall intensity also showed the highest load in organic C and total N in the overland flow (e.g. Events 2, 5, 12 and 16) with the exception of Event 8 (Table 2-1 and Figure 2-5). Estimated overland flow loads for organic C, derived from the load balance, varied between 0 and 386 kg and for total N between 0 and 48 kg per event (data not shown). When summing up the estimated overland flow loads, for the 25 rainfall events, coming from the surrounding 17 ha of upland area which drained towards the irrigation channel between the upper and lower gage a total of 188 kg of inorganic C, 1074 kg of organic C and 145 kg of total N was found.

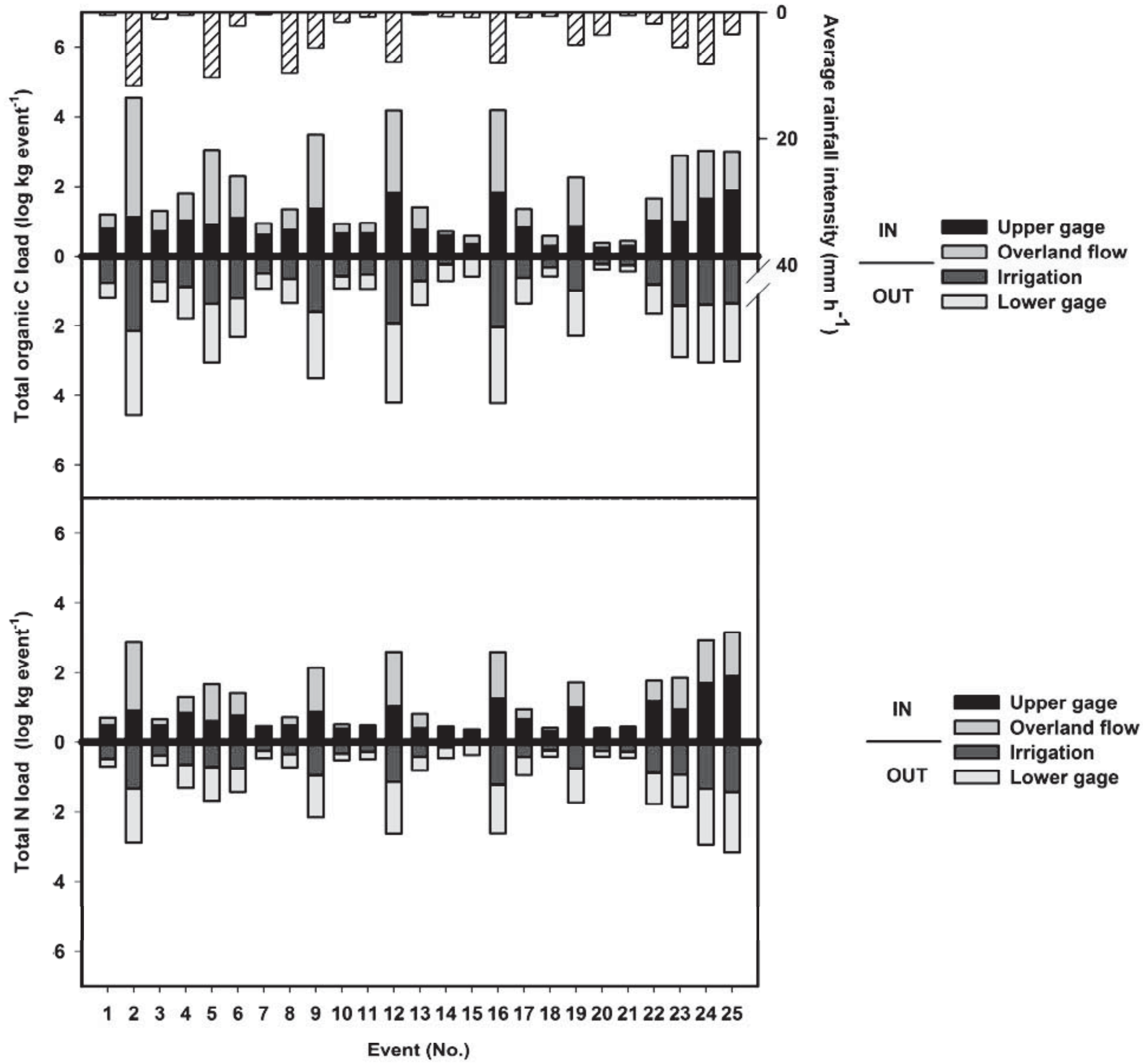

Figure 2-5: Separation of the total load in organic C (top) and total N (bottom) (kg event^{-1}) for each event into the contribution of the different in- and outflow components. The data are $\log_{10}$ transformed. Vertical bars at the top represent the average rainfall intensity (mm h^{-1}) for each event. Loads from direct rainfall were negligible and hence not presented.

Based on the calculated organic C and total N load of the overland flow component for each event, the average organic C / total N ratio was calculated. On average, the water released from the reservoir had an organic C / total N ratio of 2 with a slight decreasing trend along the season. The range of the ratio in the overland flow varied strongly among the 25 events especially for the rainfall events with higher rainfall intensity (Events 2, 5, 9, 12, 16 and 23) where values up to 6.8 were found (Event 16). A significant linear relationship was found (R^2 = 0.82, $p<0.001$) between the organic C / total N ratio of the overland flow and the amount of rainfall (Figure 2-6).

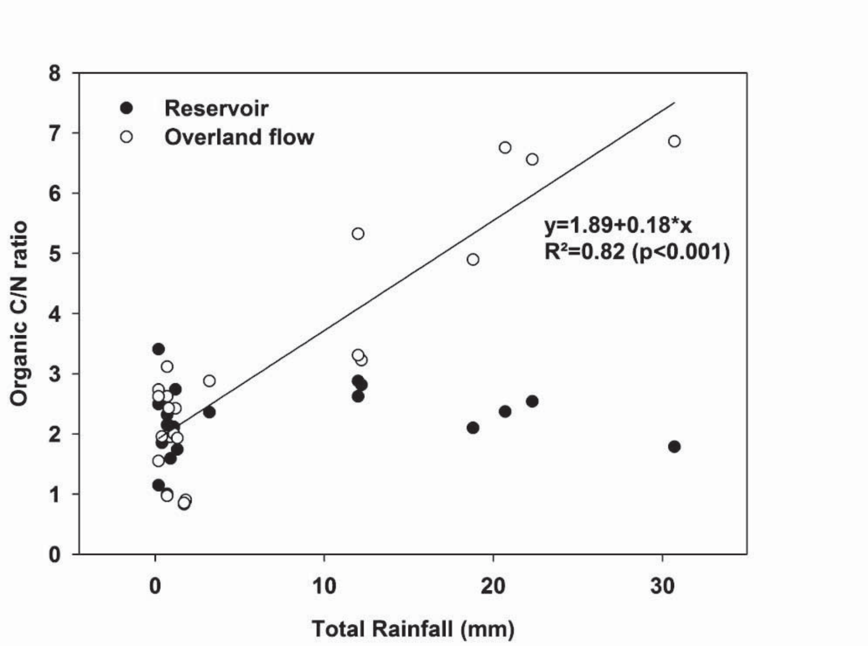

Figure 2-6: Relationship between the estimated organic C / total N ratio of the overland flow and the amount of rainfall (mm) compared to the organic C /total N ratio of the reservoir.

Rainfall characteristics and overland flow were strongly correlated among each other (r = 0.82 – 0.99, p <0.001) (Table 2). Irrigated inorganic carbon was found to be weakly correlated with the discharge at the upper gage (r = 0.26, $p<0.001$) and irrigated total N loads were stronger correlated to the lake level (r = 0.43, $p<0.001$).

Table 2-2: Spearman correlation coefficients (r) between julian day (day), rainfall characteristics (average intensity (mm h^{-1}), rainfall amount (mm) and rainfall duration (min)), volume of each flow component (m^3) (overland flow, irrigation, direct precipitation, upper and lower gage), water level in the lake (lake level) (m) and loads irrigated (inorganic C, organic C and total N) (kg $sample^{-1}$).

Parameter	No.[a]	Julian day	Average Rainfall intensity	Rainfall amount	Rainfall duration	Overland flow	Irrigation	Direct precipitation	Upper gage	Lower gage	Lake level	Load inorganic C irrigated	Load Organic C irrigated
Julian day	419	1.00											
Average rainfall intensity	419	0.02	1.00										
Rainfall amount	419	0.02	0.99^{b}	1.00									
Rainfall duration	419	0.02	0.97^{b}	0.98^{b}	1.00								
Overland flow	410	-0.02	0.84^{b}	0.85^{b}	0.82^{b}	1.00							
Irrigation	410	0.17^{c}	-0.10	-0.09	-0.06	-0.06	1.00						
Direct precipitation	410	0.00	0.96^{b}	0.97^{b}	0.95^{b}	0.87^{b}	-0.06	1.00					
Upper gage	334	-0.01	-0.11	-0.11	-0.09	-0.10	0.32^{b}	-0.12^{d}	1.00				
Lower gage	410	0.25^{b}	0.03	0.03	0.03	0.08	0.69^{b}	0.04	0.38^{b}	1.00			
Lake level	419	0.68^{b}	0.01	0.02	0.03	-0.01	0.19^{b}	0.00	-0.08	0.10	1.00		
Load inorganic C	414	0.23^{b}	-0.08	-0.06	-0.04	-0.03	0.92^{b}	-0.04	0.26^{b}	0.65^{b}	0.17^{c}	1.00	
Load organic C	414	0.23^{b}	0.24^{b}	0.24^{b}	0.21^{b}	0.31^{b}	0.65^{b}	0.25^{b}	0.18^{b}	0.60^{b}	0.20^{b}	0.73^{b}	1.00
Load total N	414	0.46^{b}	0.10^{d}	0.11d	0.10^{d}	0.17^{c}	0.71^{b}	0.12^{d}	0.16^{c}	0.59^{b}	0.43^{b}	0.81^{b}	0.87^{b}

[a] number of observations

[b,c,d] Correlation is significant at the p<0.001, 0.01 level and <0.05 level (2-tailed), respectively.

The additional load irrigated to the paddy fields during rainfall events (D_{load}) calculated using Eq. 7 (Figure 2-7) showed that from all 25 monitored events, Events 2, 9, 12 and 16 contributed most to additional irrigated organic C and/or total N loads to the paddy fields. The highest values were found for Event 2 which showed an increase of 18 kg inorganic C, 130 kg organic C and 16 kg total N. During the rainfall events between 9 and 74% of organic C and total N loads found in the channel (an overall average of 47%) were transported through irrigation water into the paddy fields. At the lower gage between 26 and 91% of organic C and total N loads (an average of 53%) left the subwatershed monitored in this study (data not shown).

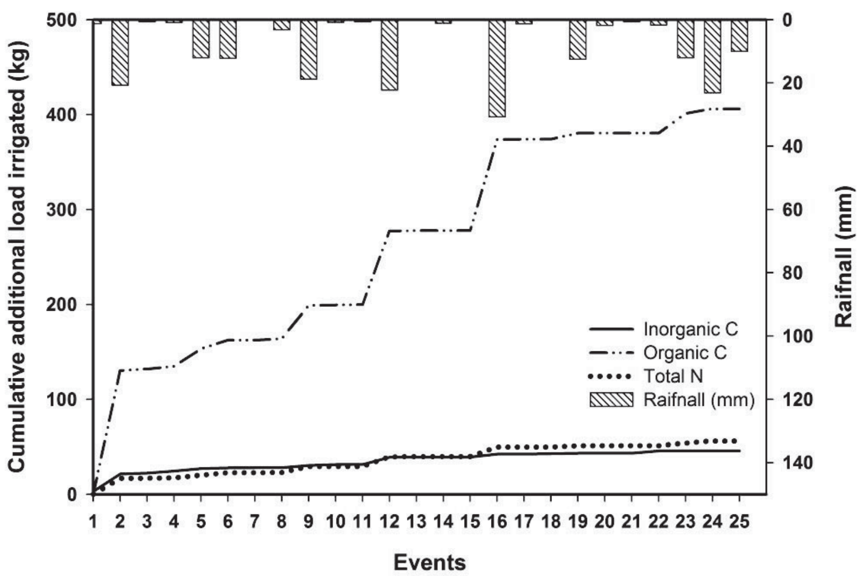

Figure 2-7: Cumulative additional (to baseline) load (kg) of inorganic and organic C and total N irrigated to the paddy fields during the 25 rainfall events.

The mixed effects model for the calculation of the irrigated loads for all three water parameters showed a significant response to irrigation discharge into paddy fields between upper and lower gage and rainfall intensity (Table 2-3). Overland flow had additionally an impact on organic C and total N loads while the level of the lake was only of significant influence for total N. Similar results were shown by the mixed effects model on the loads passing through the lower gage of the studied subwatershed. For the irrigated as well as for the loads passing through the lower gage, good predictions were found for each water quality parameter (Figure 2-8).

Table 2-3: Mixed effects model including flow components (irrigation, overland and lower gage volume), rainfall characteristics and lake level for estimating inorganic C, organic C and total N loads (ln kg event^{-1}) irrigated to the paddy fields between the upper and lower gage (Irrigation) and leaving the subwatershed (lower gage).

Model	Irrigation				Lower gage			
	Parameter estimate	df[a]	F-value	Pr>F	Parameter estimate	df[a]	F-value	Pr>F
Load inorganic C (kg event^{-1})[b]								
Model intercept	-3.460				-3.477			
Rainfall intensity (mm h^{-1})	0.008	159.0	17.5	<0.0001	0.008	159.0	17.12	<0.0001
Irrigation volume (m^3)[c]	0.906	15.7	821.9	<0.0001	-0.108	13.4	11.79	0.0043
Lower gage volume (m^3)[c]	0.071	93.8	5.7	0.0190	1.09	93.3	1308.74	<0.0001
Load organic C (kg event^{-1})[b]								
Model intercept	-4.662				-4.685			
Rainfall intensity (mm h^{-1})	0.022	150.0	28.9	<0.0001	0.022	150.0	28.9	<0.0001
Irrigation volume (m^3)[c]	0.566	32.8	28.3	<0.0001	.-0.448	28.7	17.9	0.0002
Overland flow volume (m^3)[c]	0.151	170.0	33.2	<0.0001	0.150	169.0	32.7	<0.0001
Lower gage volume (m^3)[c]	0.335	164.0	9.4	0.0026	1.350	164.0	152.6	<0.0001
Load total N (kg event^{-1})[b]								
Model intercept	-6.190				-6.218			
Rainfall intensity (mm h^{-1})	0.017	144.0	23.5	<0.0001	0.017	144.0	23.35	<0.0001
Irrigation volume (m^3)[c]	0.656	171.0	71.6	<0.0001	-0.354	171.0	20.80	<0.0001
Overland flow volume (m^3)[c]	0.077	171.0	13.6	0.0003	0.077	177.0	13.29	0.0003
Lower gage volume (m^3)[c]	0.250	134.0	9.6	0.0024	1.267	134.0	244.91	<0.0001
Lake level (m)	0.129	40.9	24.6	<0.0001	0.128	40.9	24.38	<0.0001

[a] df = degrees of freedom

[b] Transformation according to ln(x)

[c] Transformation according to ln(x+1)

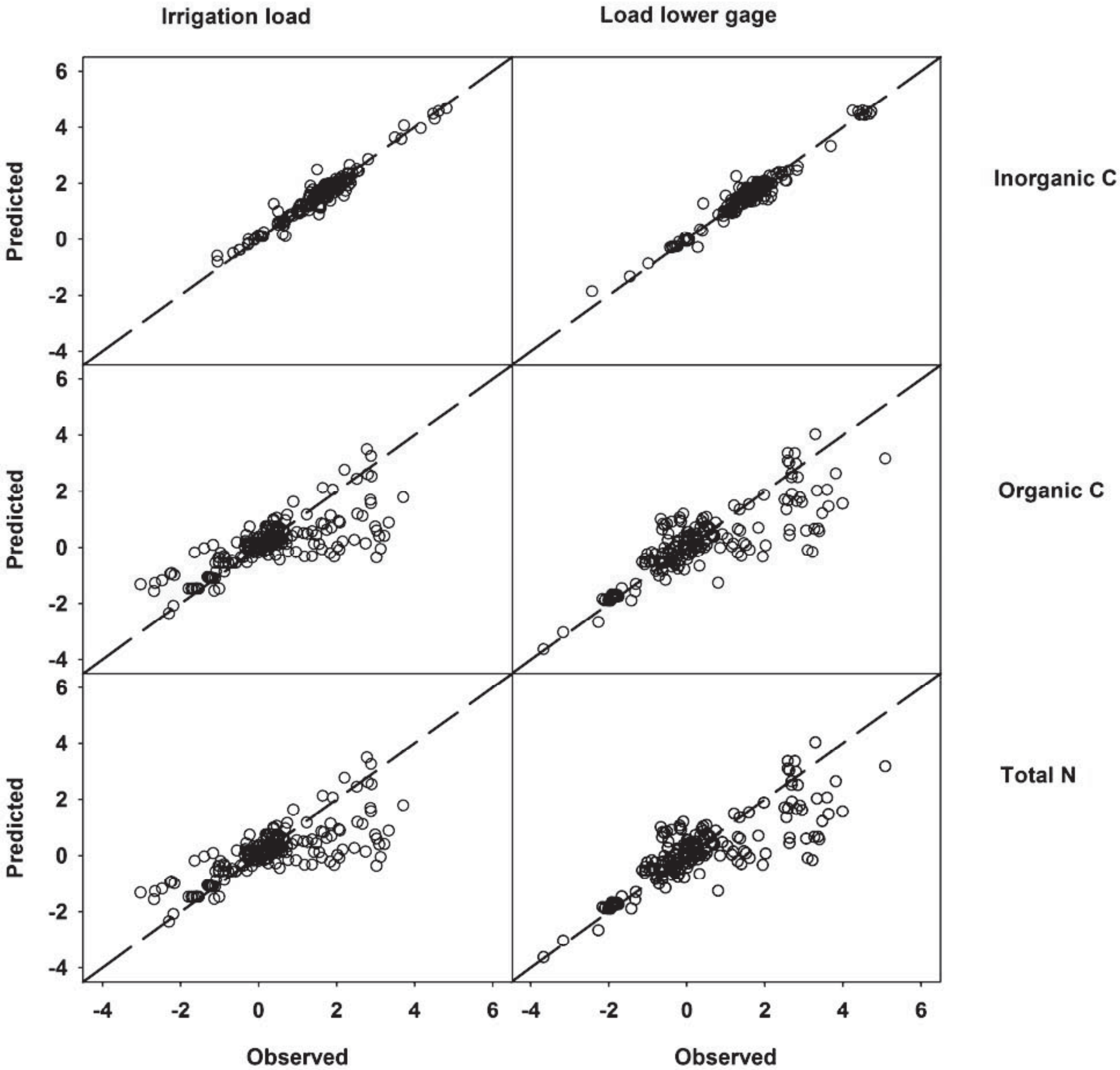

Figure 2-8: Predicted *vs*. Observed loads of inorganic C, organic C and total N (ln kg event^{-1}) irrigated to the paddy fields (left) and passing through the lower gage (right) for all composite samples taken within the 25 rainfall events.

However, a small trend was noticeable for higher loads pointing towards difficulty of the model in predicting high loads of organic C and total N. Considering all 25 events, the estimated contribution of runoff processes induced by rainfall on total load was minor compared to the overall loads irrigated during dry weather periods (Table 2-4). For inorganic C, the contribution of rainfall on total loads was estimated to be 0.04% (irrigated to the paddy fields) and 0.04% (lower gage), for organic C 6.7% (irrigated to the paddy fields) and 6.6% (lower gage), and for total N 1.8% (irrigated to the paddy fields) and 1.8% (lower gage). Estimating the loads over the entire period May till September 2008 resulted in an estimated irrigated load of 25.4 Mg inorganic C, 5.5 Mg organic C and 4.6 Mg total N (Table 2-4).

Table 2-4: The contribution of rainfall events to the increase of inorganic C, organic C and total N loads (%) irrigated to the paddy fields (irrigation) and at the outlet of the subwatershed (lower gage) for the 25 events and the total estimated loads (Mg) irrigated and passing through the lower gage in the overall period (May- September).

	Contribution of rainfall events (%)		Estimated total loads May – Sep.[a]	
	Irrigation[b]	Lower gage[b]	Irrigation (Mg)[c]	Lower gage (Mg)
Load inorganic C	0.04 (0.02-0.05)	0.04 (0.02-0.05)	25.4 (3.9)	23.8
Load organic C	6.7 (4.4-9.1)	6.6 (4.3 -9.1)	5.5 (0.8)	5.7
Load total N	1.8 (0.9-2.8)	1.8 (0.8-2.8)	4.6 (0.7)	4.7

[a]Loads are estimated applying the functions obtained by the mixed effects model (Table 2-3) on the entire dataset May till September.
[b]The confidence interval (95%) of the contribution is given in parentheses.
[c]The estimated irrigated load per ha of paddy in parenthesis (Mg ha^{-1})

2.6 Discussion

2.6.1 Effect of a surface water reservoir on C and N redistribution

The results of the mixed effects model showed that the majority of nutrients redistributed via the irrigation channel to the lowland were mainly coming from the reservoir. Only for rainfall events with maximum rainfall intensities higher than 15 mm h^{-1}, significant additional organic C and total N loads were irrigated compared to the baseline loads. Thus, the rainfall-induced overland flow draining towards the irrigation channel seemed to have a minor impact compared to the loads released from the reservoir (Table 4). These results suggest that the surface water reservoir acted as a major sink for inorganic and organic C, and for N transported from the surrounding 490 ha during erosive rainfall events to the reservoir. The contribution of rainfall events to the irrigated nutrient loads will thus strongly depend on the management of crop fields surrounding the reservoir thereby affecting the water quality and quantity of the reservoir. Therefore, the reservoir played a dominant role in overall nutrient loads in irrigation water as it contributed >99, 93 and 98% of the irrigated inorganic C, organic C and total N loads. This also points towards the importance of irrigation management as it will influence the fraction and timing of these nutrients distributed to the lowland during irrigation practices throughout the year.

The baseline concentration of organic C in the irrigation water, found in this study, corresponded with concentrations found by King et al. (2009) and Poch et al. (2006) who reported dissolved organic C values ranging from 2 to 5 mg l^{-1} and dissolved organic N values of 2 mg l^{-1} in a with surface water irrigated sunflower field in Sacramento Valley (California, USA). Similar values for total N (1.2 mg l^{-1}) were found in the irrigation water studied in China by Tang et al. (2008). In contrast, inorganic C was found to be much higher in this study compared to the results of King et al. (2009) who found that inorganic C was negligible due to the absence of carbonate-rich soils. The high values of inorganic C found in the irrigation water in our study were due to the fact that the reservoir of the studied watershed was surrounded by Karst mountains.

During rainfall events good model predictions were found for the irrigated loads as well as the loads passing through the lower gage (Figure 8). The derived model parameters showed high similarities with other multiple linear regression or generalized linear based models used for load estimations (Cox et al., 2008; Haggard et al., 2003; Stenback et al., 2011). However, in this study, the incorporation of lake level used for nitrogen load estimations was an important addition in the model as the reservoir played a significant role in the redistribution of N. Furthermore, when using composite sampling, the model showed that using the filling time as a random effect improved predictions significantly. The established models were found to be somewhat less accurate for high loads of organic C and total N in the irrigation water as well as those in the water passing through the lower gage. In general, load estimations are highly depending on monitoring period, sampling strategy and the load estimation method used (Johnes, 2007; Stenback et al., 2011). Overland flow discharge, as well as irrigated discharge, was estimated using Eq. 2-3. As overland flow was absent in the model for the prediction of inorganic C, it might suggest that the error in predicting overland flow could have had an influence on the performance of the model towards organic C and total N load estimations. An additional factor which could have played a role is the influence of the filling time in combination with the available dataset which constituted out of a larger number of small compared to high intensity rainfalls. Regarding the estimations of the irrigated nutrient loads, the assumption of maximum concentrations (in Eq. 2-5) could contribute towards an overestimation of the simulated predicted loads. However, as the trend was visible within the predicted *vs.* observed loads passing through the lower gage, it is believed that this error contribution was minor. The assumption of maximum concentrations used in the irrigated loads calculations will play a more important role when quantifying the overall irrigated load compared to the individual model predictions.

2.6.2 Contribution of overland flow on the redistribution of C and N

Although the majority of the irrigated loads, within the overall measurement period originated from the reservoir, strong rainfall events did significantly contribute additional quantities of organic C and total N to the irrigation water due to draining overland flow (Figure 2-7). An estimation of the total overland flow from the 25 events can be made when using the drainage are of 17 ha, showing that the total organic C transported, via overland flow, into the investigated irrigation channel segment was approximately 63 kg ha^{-1}. Overland flow accumulation is highly dependent on rainfall characteristics, soil type, topology, land use fragmentation, and the size of the draining catchment (López-Tarazón et al., 2010; Pansak et al., 2010; Römkens et al., 2002; Valentin et al., 2008; Ziegler et al., 2004b). The effects of drainage area and soil type on different non-point sediment sources draining as overland flow to the irrigation water were demonstrated by the changes in organic C / total N ratio among the various events. Overall, the estimated organic C / total N ratios of the overland flow were found to be higher than the organic C / total N ratio of the water in the reservoir. Low ratios as observed in the reservoir (±2) are likely to depend mainly on *in situ* production of C and N during decomposition in the reservoir as aquatic plants are much poorer in C as compared to terrestrial plants (Beusen et al., 2005), leading also to accumulation of mineral N, such as NH_4^+. An increase of the organic C / total N ratio up to 7 was found for the overland flow during higher rainfall intensity events (Events 2, 5, 9, 12 and 16) which denoted towards the drainage of non-point sediment sources from upland areas into the irrigation channel. This suggests that particularly the contribution of organic C during erosion events increases (probably particulate organic matter), leading to higher organic C / total N ratios. Similarly, Beusen et al. (2005) found that organic C / N ratios in rivers were lower for less turbid waters (often lower than 8) and higher in more turbid waters (>10) pointing to the drainage of soil erosion and terrestrial vegetation pools. However, the total amount of overland flow and the associated nutrient transport from the upland area feeding the reservoir in this study area will be higher than the estimated portion of nutrients draining to the irrigation channel due to the larger contributing area (490 ha *vs.* 17 ha). Although linear segments in the landscape (e.g. unpaved roads), due to their lower hydraulic conductivity, significantly contribute to convey runoff (Valentin et al., 2008; Ziegler et al., 2004a), a significant amount of sediments and accompanying nutrients will be deposited before reaching the irrigation channel or reservoir.

Comparison of the Event Mean Concentration (EMC) between upper and lower gage for organic C and total N showed a clear response to rainfall intensity confirming that rainfall induced overland flow can convey significant amounts of C and N from intensively cultivated upland fields into the irrigation water. Although the effect of overland flow on EMC of organic C and total N was highly influenced by rainfall characteristics, the relative increase in EMC between the upper and lower gages was found in some cases to be additionally depending on the amount of irrigation water released from the reservoir (e.g. Events 2 *vs*. 24). The amount of irrigation water released from the reservoir was higher during Event 2 compared to Event 24, which caused dilution of organic C and N loads deposited by overland flow although the rainfall condition was comparable. Therefore caution is needed when assessing the impact of overland flow on redistribution of nutrient loads as irrigation management (i.e. release of water from the reservoir) plays an additional role in irrigated watersheds besides the known effect of climate, drainage area, topography, soil and land use characteristics.

2.6.3 Contribution of irrigation water to C and N transport to paddy fields

Taking into account the irrigated paddy area, the amount of inorganic C load entering paddies with the irrigation water between May and September was estimated at 3.9 Mg ha^{-1}, while the irrigated organic C load only amounted up to 0.8 Mg ha^{-1} and the total N load up to 0.7 Mg ha^{-1}. These values are higher than the ones reported by King et al. (2009) and Poch et al. (2006) who found 0.03 Mg ha^{-1} yr^{-1} and 0.02 Mg ha^{-1} yr^{-1} of organic C, respectively and 0.07 Mg ha^{-1} yr^{-1} of total N. Their lower values partly could be due to the fact that their furrow irrigated fields were not continuously irrigated throughout the cropping season and the values estimated in their study reflected the total contribution of only four irrigation events. Secondly, as in this study maximum concentrations for overland flow were used when estimating the irrigated loads, the resulting load values have to be considered as the maximum limit that one could expect to be irrigated. Nevertheless, as less than 10% of the loads were derived from the overland flow draining towards the channel it will have had only a minor impact on the overall load estimation. As often two rice crops are established per year within the subwatershed and rainfall events were found to play a minor role in overall estimated nutrient budgets within this specific watershed for 2008, the total N, inorganic and organic C load irrigated in the watershed will be approximately double of the amounts found in this study. When looking at sediment deposition in rice paddies, a clear enrichment of organic C and total N was found along irrigated rice cascades creating a spatial pattern with a positive effect on rice productivity (Yan et al., 2010; Chapter 3 and 4). However, as runoff from paddy fields were not within the framework of this study, the question remains whether the entire irrigated C and N loads found in this study are deposited within the paddy fields and can be seen as a net gain or are partly lost by other pathways such as runoff, leaching or gaseous losses. Additionally, as irrigation management - and associated wetting and drying cycles causes an increase of dissolved organic carbon content due to the stimulation of soil microbial activity (King et al., 2009), labile C can be reallocated with the runoff water from paddy fields (Ruark et al., 2010), or CO_2 and CH_4 production can be enhanced (Kimura et al., 2004). Indeed, results of Dung et al. (2009) indicated that a proportion of nutrients entering paddy fields with the irrigation water might be lost into the downstream river system.

Often fertilizer recommendations are made for larger areas covering district or commune level rather than catchment level. This study showed that the associated nutrient redistribution through irrigation in intensively cultivated mountainous areas needs to be taken into account as it could influence the indigenous nutrient supply of irrigated rice paddy fields and therefore would contribute to the need of site specific fertilizer recommendation (Dobermann et al., 2003; King et al., 2009).

2.7 Conclusion

The present study indicated that significant amounts of total N, inorganic and organic C were reallocated to the lowland by irrigation water which was mainly influenced by the water quality of the reservoir and the overland flow draining directly to the reservoir. Although, the additional contribution of overland flow along the channel on irrigated C and N loads was temporally significant during intensive rainfall events it did not act as a major source of nutrients for paddy fields. Thus, over the entire measurement period the reservoir contributed between >99%, 93% and 98% of the irrigated inorganic C, organic C and total N loads to the lowland. As overland flow is highly depending on rainfall intensity, probable higher extreme rainfall periods in the future due to climate change, could induce even higher C and N flows draining into the reservoir. However, the continuous soil degradation of intensively cultivated upland slopes in tropical mountainous areas raises the question whether the quality and quantity of organic C and total N contributions will decrease in the long term and become less favorable for the lowlands. Whether the water nutrient contents will decrease or not in the future, this study shows that the redistribution of C and N through irrigation water is highly influenced by management practices and about half of the total nutrient load entered the paddy fields. This should be taken into consideration when optimizing rice productivity in the lowland and developing site specific fertilizer recommendations. Further research, however, is needed to estimate the final deposition of C and N within the lowlands as the amount of C and N transported from the rice fields by runoff especially during land preparation and heavy rainfall events or lost through volatilization was beyond the scope of this study.

CHAPTER 3

SEDIMENT INDUCED SOIL SPATIAL VARIATION IN PADDY FIELDS OF NORTHWEST VIETNAM

3 Sediment induced soil spatial variation in paddy fields of Northwest Vietnam[2]

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3.1 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 analysed 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 100g^{-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 100g^{-1}) = 1.4 + 0.02 Distance (m), $R^2 = 0.31\text{-}0.62$), total nitrogen (TN (g 100g^{-1}) = 0.11 + 0.004 Distance (m), $R^2 = 0.33\text{-}0.61$) and a significant

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linear decrease in the sand fraction (sand (g g^{-1}) = 0.3 – 8 E^{-04} Distance (m), $R^2 = 0.28\text{-}0.48$) 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 100g^{-1} of SOC and 0.01 g 100g^{-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 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.

3.2 Key words

Irrigation; particle size distribution; sediments; soil fertility; spatial variability; total nitrogen; total organic carbon; Vietnam.

3.3 Introduction

In mountainous Northern Vietnam, an important agroecosystem is 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., 2002b). 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., 2002b). 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 million ha are under paddy cultivation, of these 60% are located in hilly areas, on terraces forming interconnected cascades, and hence are influenced by upland sediment deposits (Wezel et al., 2002b; 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., 2006b). 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.

3.4 Material and methods

3.4.1 Experimental site

The present study was carried out from February until October 2007, during two rice cropping seasons in the Chieng Khoi commune (350 m a.s.l., 21°7'60"N, 105°40'0"E) situated in the Yen Chau district, Northwest Vietnam (Figure 3-1 a).

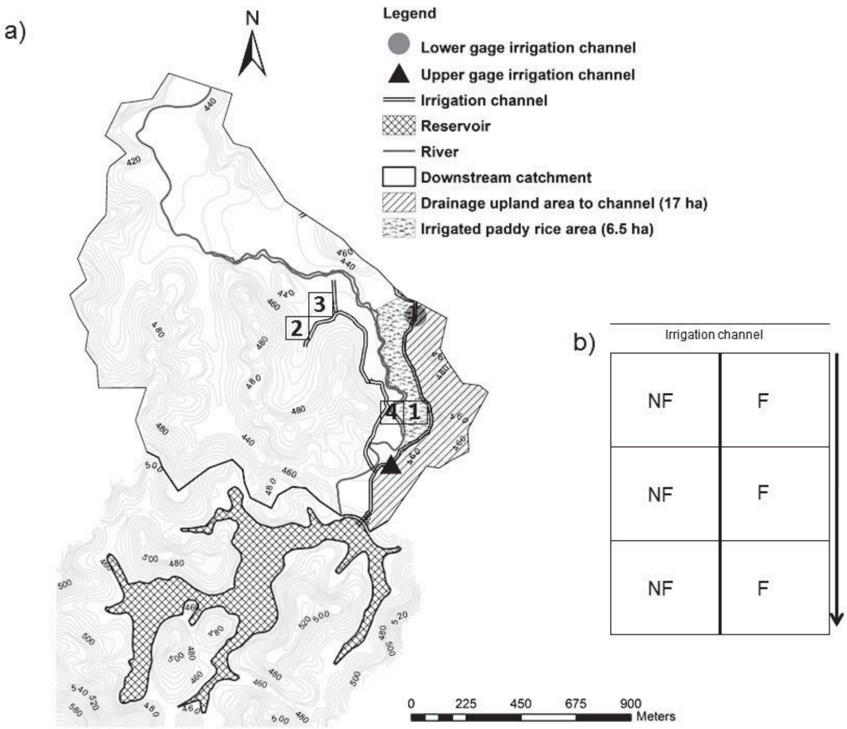

Figure 3-1: a) Overview of the Chieng Khoi catchment with the location of the cascades (squares) of paddy terraces along the irrigation channel b) Schematic representation of one cascade with the arrow giving the flow direction and distance from the irrigation channel, NF referring to non-fertilized and F to fertilized fields within the cascade.

The studied watershed of 2 km² 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 (Figure 3-2). 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.

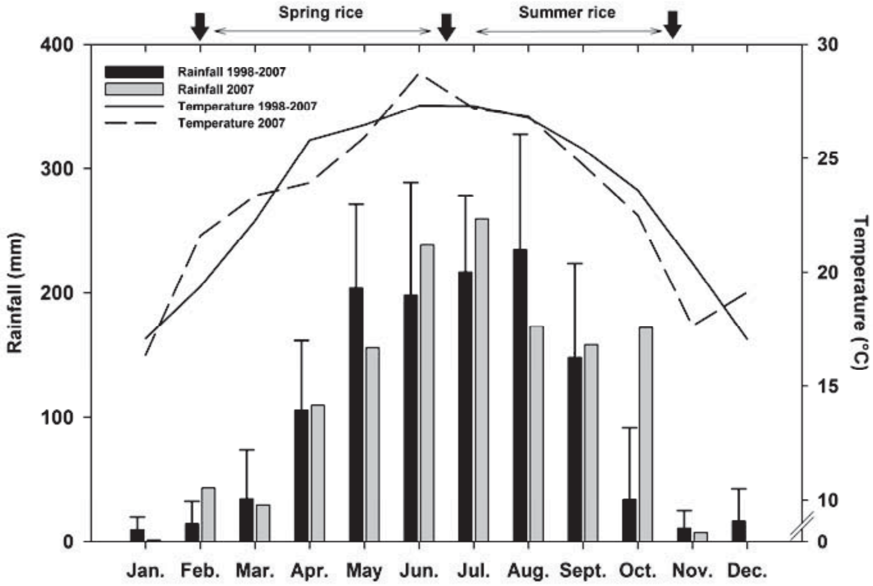

Figure 3-2: Rainfall and temperature distribution in Yen Chau for 1998-2007 and for 2007. Standard deviation for the rainfall from 1998-2007 is given by error bars. The arrows on top of the graph indicate the three soil sampling times (before planting of the first rice crop, harvest of the first rice crop and harvest of the second rice crop).

An extended open-channel irrigation system and a lake reservoir allow two rice cropping seasons per 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 located on the higher 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.

3.4.2 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 (< 25mm 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 conditions 4 to 5 m higher than the water level. The latter happened in October 2007 when the typhoon "Lekima" passed through, before the summer crop could be harvested.

3.4.3 Experimental design

In order to analyze the impact of the effect of the various sediment pathways on soil fertility in rice paddies, several cascades of rice paddy terraces were selected during participatory workshops. The selected cascades were found to represent the overall paddy area in terms of farmers practice (fertilizer application, weeding, transplanting, seed variety and land preparation), overall soil fertility and water availability. Four irrigated paddy cascades with a total of 1.6 ha (series of paddy terraces), located in two villages (Ban Me and Ban Put), with varying lengths (67-170 m) were monitored in the watershed during the spring crop out of which two were also monitored during the summer crop season (Figure 3-1 b).

Table 3-1: Properties of each monitored cascade of paddy terraces with distance being the cumulative distance from the inlet of each field towards the overall cascade length (m) and area the individual field size before division into fertilized and non-fertilized subfields. Length of the cascade entails the whole length of the cascade (till the end of the last field). Data were recorded during 2007 in the Chieng Khoi commune, Son La province, Northwest Vietnam.

	Cascade 1 (BP, concrete channel)[a] Length cascade: 112 m			Cascade 2 (BM, earth channel)[a] Length cascade: 170 m			Cascade 3 (BM, earth channel)[a] Length cascade: 96 m			Cascade 4 (BP, earth channel)[a] Length cascade: 67 m		
	Sediment source	Distance (m)	Area (m^2)	Sediment source	Distance (m)[b]	Area (m^2)	Sediment source	Distance (m)	Area (m^2)	Sediment source	Distance (m)	Area (m^2)
Field 1	Irrigation	0	200	Upland runoff	0	656	Irrigation	0	397	Irrigation	0	230
Field 2	Irrigation	7	1409	Upland runoff	18	560	Irrigation	16	582	Irrigation	4	853
Field 3	Irrigation	49	400	Upland runoff	32	251	Irrigation	25	1460	Irrigation	28	1055
Field 4	Irrigation	64	883	Upland runoff	34	848	Irrigation	50	1227	Irrigation/ flooding	43	355
Field 5	Irrigation	88	491	Upland runoff	55	281	-	-	-	Irrigation/ flooding	60	100
Field 6	Irrigation/ flooding	98	200	Irrigation	62	685	-	-	-	-	-	-
Field 7	Irrigation/ flooding	103	362	Irrigation	82	643	-	-	-	-	-	-
Field 8	-	-	-	Irrigation	97	800	-	-	-	-	-	-
Field 9	-	-	-	Irrigation	114	694	-	-	-	-	-	-

[a] BP, BM refers to Ban Put and Ban Me village, respectively
[b] For Cascade 2 the first 5 fields are rainfed

During the summer crop a rainfed cascade situated on top of Cascade 2 was additionally monitored increasing the total cascade length. Selection of the position of the rice cascades in the landscape was based on the flow pattern of irrigation water, overall cascade length and sediment sources; (i) direct upland runoff (0 m to 55 m for Cascade 2) (Table 3-1), (ii) sediment rich irrigation water (all fields in all cascades), and (iii) suspended sediments and bed load during extreme flooding events (after 98 m for Cascade 1 and after 40 m for Cascade 4) (Table 3-1). Cascade 2, 3 and 4 were irrigated through an earth channel whereas Cascade 1 received water from a concrete channel (Table 3-1). All cascades followed a split plot design, with irrigation direction as the main factor and fertilizer application as subfactor (Figure 3-1 c). The main factor treatment was that every field in the cascades, except for the first field which was receiving water from the irrigation channel, received irrigation water through a single inlet from the upper field and drained via a single outlet to the next one. In case of the rainfed paddies no irrigation water was applied and every field received, besides rainfall, runoff water from the field situated on top. All fields were divided into two equal areas (in case of narrow fields a neighbouring field was selected) resulting in two strips per cascade where the two subfactor treatments were: (i) no fertilizer application (NF) and (ii) fertilizer (F) via split application according to local recommendations resulting in an amendment of 213 kg N ha^{-1}, 150 kg P ha^{-1} and 93 kg K ha^{-1}. The aim of the subfactor treatment was to distinguish between the inherent spatial variability in soil fertility induced by sediment deposits (NF strip) and soil fertility induced by farmers' fertilization practice (F strip). All fields were planted with the same local sticky rice variety (*Oryza sativa* L.) Nep 87 in both seasons. Before transplanting, fields were ploughed and puddled by buffalo to a depth of 20 - 30 cm depth. In each season hand weeding was done twice.

3.4.4 Soil properties along the cascades

In order to monitor changes induced by past and recent sediment inputs, topsoil samples (0-5cm) were taken after field preparation (before transplanting of rice) and after each harvest. Topsoil samples taken before transplanting represented the tillage profile whereas the samples taken after each harvest indicated possible changes in nutrients and texture due to recent sediment deposits. Sampling was carried out at different distances from the irrigation inlet across the field, perpendicular to the flow direction, dividing every field into four to eight bands depending on the field length. Independently of the field length, the first two meters from the upper and lower border along the flow direction were always sampled. In each band, five to seven samples were bulked together to obtain a representative sample. In total six to eight bulked samples were taken in each field, per sampling time, depending on overall field length.

Exploratory soil information on the cascades was gathered by analyzing 32 samples taken before transplanting. The samples were analyzed for pH(KCl) (1:1), Fe^{2+} and Fe^{3+} (Cadarinop and Ocnina method) (Dung et al., 2001). Extraction for analyzing Fe^{2+} concentration was done using sulfuric acid and sodium ethanoate while the total extractable Fe content was obtained by adding additionally hydroxin amin. The Fe containing solution was analyzed with a spectrophotometer at 510 nm. Furthermore, 115 samples taken before planting were analysed for CEC and K (ammonium acetate method), total nitrogen (combustion method, Elementaranalysator EL, Elementar GmbH, Germany) and particle size distribution (laser diffraction, Beckman Coulter LS 200 Series). Carbonates were quantified on the same 115 samples after acidification using the Scheibler method (Tatzber et al., 2007) and soil organic carbon (SOC) was determined, after acidification (HCl) in order to eliminate the carbonates, using the combustion method (Elementaranalysator EL, Elementar GmbH, Germany).

Mid-infrared Spectroscopy (MIRS), after proper calibration, has proven to be a useful tool in processing large amounts of soil samples and providing reliable results on most soil properties (van Groenigen et al., 2003; McBratney et al., 2006). Therefore, to complement the conventional wet analysis on a subset of soil samples, Mid Infrared Spectroscopy (MIRS) was used to estimate SOC, total N, inorganic C, silt and sand fractions of the remaining set of soil samples taken throughout the cropping season by Partial Least Squares (PLS) regression analysis in OPUS v 6.5™ (van Groenigen et al., 2003). All soil samples were ball-milled and Diffuse Reflectance Fourier Transformed DRIFT-MIRS analysis was performed on four replicates for each sample with 16 scans per sample at a resolution of 4 cm^{-1} within the range of 4000 to 600 cm^{-1} by using a Tensor 27 (Bruker GmbH, Germany). The PLS models were calibrated and validated through the 50% test calibration option in the QUANT2 module of OPUS using the wet analysis results of 115 topsoil samples. The performance parameters of the obtained PLS models are given in Table 3-2. According to Pirie et al. (2005) a model is able to predict well in case the residual prediction deviation (RPD) is higher than 3 which was achieved.

After successful calibration and validation of the models, SOC, inorganic C, total N and particle size distribution of all 727 samples were predicted separately for each parameter and sampling period. The clay fraction was calculated from the silt and sand fraction.

Table 3-2: Overview of the MIRS models established after calibration and validation of the Mid Infrared Spectra using conventional wet analysis for each soil parameter.

Parameter (Unit)	Optimization	Rank	R^2	RMSEP	RPD	Bias
Inorganic C (g $100g^{-1}$)	No preprocessing	5	95.7	0.170	4.87	0.0002
SOC (g $100g^{-1}$)	First derivative and multiple scattering correction	6	91.4	0.204	3.49	0.0010
Total N (g $100g^{-1}$)	First derivative and multiple scattering correction	5	91.6	0.018	3.47	0.0006
Silt (g g^{-1})	First derivative and multiple scattering correction	8	90.3	0.051	3.22	0.0015
Sand (g g^{-1})	First derivative and multiple scattering correction	6	89.6	0.061	3.11	0.0013

Rank = number of vectors used in the partial least square regression, R^2 = coefficient of determination, RMSEP = root mean square error of prediction, RPD = residual prediction deviation, and Bias = systematic error.

Additionally X-Ray diffraction (50mA, 33kV) was performed on topsoil samples using a Bruker D500 in order to analyze the type of the clay minerals. Results were derived using the software Diffrac AT v3.3 (1993, Socabim, France). In order to reduce the amount of samples and to qualitatively determine the clay mineral composition only Cascades 1 and 2 were analysed as they covered the three investigated sediment pathways (irrigation: Cascade 1 and 2, undiluted runoff: Cascade 2 and flooding: Cascade 1). In total 20 topsoil samples, taken before planting from the middle position of each field situated in Cascades 1 and 2 were analysed.

3.4.5 Statistical analysis on spatial variability

A first indication of variability in soil properties (pH, CEC, K, Fe^{2+}, Fe^{3+}, SOC, inorganic C, total N and texture) within and between cascades was obtained through descriptive statistics using the Univariate procedure in SAS v8 (Cody and Smith, 2006) for the dataset obtained before planting. Variability was considered low when the coefficient of variation (CV) < 10%

and high when > 90% (Wei et al., 2008). To assess the enrichment of soil fertility in the cascade with increasing distance from the irrigation channel, regression analysis was performed for each sampling time. In order to compare the different cascades relative SOC was calculated:

$$SOC_{rj} = SOC_{ij}/I_{SOC_j}$$

Eq. 3-1

where SOC_{rj} is the relative SOC content in cascade j, SOC_{ij} is the SOC content (g $100g^{-1}$) at distance i (m) from the irrigation channel and I_{SOC_j}, the intercept of the regression function between the distance of cascade j and the SOC content of cascade j.

In order to assess the factors influencing the historical spatial variability within and between cascades a mixed model was built on the data set of the soil samples taken before transplanting. The Proc Mixed procedure of the SAS software was applied to the entire dataset before planting using the predicted values obtained from the validated MIRS models in order to analyze the historical variance of SOC, inorganic C, total N and texture in the landscape and the influence of the distance from the irrigation channel. The mixed model consisted out of village, cascade, irrigation (as rainfed paddies are not irrigated), fertilizer application (NF or F), distance from the irrigation channel (distance) and field (influenced by farmers practice) as fixed effects. The effect of village was added to assess possible differences of farmers' practices in the past and landscape position effects. Furthermore, in a second mixed model, the impact of sediment on soil fertility within and among cascades was assessed by implementing the sampling time as a fixed effect. In the second model the three datasets predicted by using the validated MIRS models from the topsoil taken before planting and after each harvest were combined. For each soil parameter, variance consistency and normal distribution of the residuals was checked. In case the variance of the residuals was consistent and normally distributed no transformation was needed. Inorganic carbon needed to be transformed by taking the square root.

3.5 Results

3.5.1 Exploratory analysis of soil properties

The irrigated Cascades 1, 2, 3 and 4 contained on average 0.88 ± 0.69 g $100g^{-1}$, 0.09 ± 0.09 g $100g^{-1}$, 1.66 ± 1.26 g $100g^{-1}$ and 0.62 ± 0.40 g $100g^{-1}$ inorganic C, respectively. SOC amounted on average to 1.72 ± 0.50 g $100g^{-1}$, 1.98 ± 0.35, 2.38 ± 0.63 g $100g^{-1}$ and 1.38 ± 0.31 g $100g^{-1}$ whereas total N was 0.22 ± 0.06 g $100g^{-1}$, 0.17 ± 0.03 g $100g^{-1}$, 0.2 ± 0.07 g $100g^{-1}$ and 0.19 ± 0.04 g $100g^{-1}$ in the irrigated Cascades 1,2,3 and 4, correspondingly. The irrigated cascades on average contained 0.69 ± 0.10 g g^{-1}, 0.74 ± 0.04 g g^{-1}, 0.74 ± 0.03 g g^{-1} and 0.53 ± 0.07 g g^{-1} silt whereas the sand fraction resembled on average 0.16 ± 0.13 g g^{-1}, 0.11 ± 0.04 g g^{-1}, 0.10 ± 0.04 g g^{-1} and 0.37 ± 0.09 g g^{-1} for Cascades 1, 2, 3 and 4, respectively (data not shown). On average the irrigated and rainfed cascades contained 0.64 ± 0.85 g $100g^{-1}$ inorganic C, 1.75 ± 0.57 g $100g^{-1}$ SOC, 0.18 ± 0.06 g $100g^{-1}$ total N and 0.19 ± 0.13 g g^{-1} sand with silt being the dominant textural soil fraction at 0.68 ± 0.11 g g^{-1} (Table 3-3).

Table 3-3: Summary of variability in soil fertility of the topsoil samples of the four cascades of rice paddy terraces (including flooded fields and rainfed paddies), using conventional lab analysis.

	N [a]	Max	Min	Mean	Median	SD [a]	CV (%) [a]
pH(KCl)	32	7.90	5.00	7.15	7.60	0.94	13 (1-7)
K^+ (mg kg^{-1})	115	188.3	32.3	96.2	92.1	38.2	40 (9-27)
CEC (cmol kg^{-1})	115	16.43	3.91	9.53	9.85	2.23	23 (7-26)
Fe^{2+}/Fe^{3+} (mg kg^{-1})	32/32	18.0/34.9	0.30/1.0	6.0/23.4	4.6/26.2	4.5/9.6	74/41 (31/16-86/75)
SOC (g $100g^{-1}$)	115	3.46	0.84	1.75	1.69	0.57	33 (15-29)
Inorganic C (g $100g^{-1}$)	115	3.30	0.00	0.64	0.29	0.85	134 (65-138)
Total N (g $100g^{-1}$)	115	0.33	0.09	0.18	0.18	0.06	31 (15-38)
Clay (g g^{-1})	115	0.20	0.07	0.13	0.14	0.03	24 (5-25)
Silt (g g^{-1})	115	0.83	0.40	0.68	0.71	0.11	16 (5-15)
Sand (g g^{-1})	115	0.52	0.01	0.19	0.14	0.13	68 (24-81)

[a] N number of observations, SD standard deviation, CV coefficient of variation. CV values based on the dataset at landscape level and its range among the different cascades (in parenthesis).

The upper rainfed fields of Cascade 2 (0-60 m) had a negligible inorganic C content (average 0.06 ± 0.02 g $100g^{-1}$), lower pH, CEC, Fe^{2+}, SOC (average 1.80 ± 0.19 g $100g^{-1}$), total N (0.12 ± 0.02 g $100g^{-1}$), clay and higher K^+, Fe^{3+} concentrations as compared to the irrigated fields of Cascade 2 (60-170 m) (data not shown in Table 3-3). Comparable with the irrigated rice fields, the silt fraction was the dominated soil fraction amounting to 0.71 ± 0.07 g g^{-1} whereas the sand fraction resembled 0.0.19 ± 0.07 g g^{-1} on average (data not shown).

Moderate to high variability in soil properties was found among the irrigated cascades using the results obtained from the conventional lab analysis before planting. The coefficient of variation (CV) varied from 15-29 % for SOC, 65-138%for inorganic C and 24-81% for sand between the various fields along the cascades (Table 3-3). Similar ranges of variability in soil parameters within rice fields were found by Rüth and Lennartz (2008) and Wei et al. (2008).

3.5.2 Spatial variability of soil fertility at cascade level before transplanting

In Cascades 2 and 3 inorganic C, SOC, total N and finer soil particles (clay and silt) increased linearly towards the end of the cascade whereas sand declined with increasing distance from the irrigation channel (Figure 3-3 and 3-4). The linear trend towards the end of the cascade was stronger for Cascade 2 as compared to Cascade 3. Statistical analysis using the mixed model before transplanting showed a significant effect of the distance in the cascade to the irrigation channel, especially for SOC ($p<0.001$) and total N ($p<0.001$) (Table 3-4). The regression functions of distance effect on soil properties, obtained for Cascades 2 and 3, were linear and significant for all measured soil properties (Table 3-5). Analysis of the topsoil taken before planting using X-ray revealed kaolin domination in the smaller clay fraction and a higher quartz content in the upper rainfed fields and their content decreased towards the lower fields in Cascade 2 (data not shown). Besides kaolin, higher quantities of feldspars and lower Fe^{2+} and higher Fe^{3+} and K concentrations were found on the upper rainfed fields compared to the irrigated fields in Cascade 2. However, Cascades 1 and 4 located in Ban Put did not exhibit such a linear trend regarding the spatial distribution of soil fertility but had a rather quadratic response with increasing distance from the irrigation channel for all (Table 3-5). Hence, Cascade 1 showed a decrease of inorganic C, SOC, total N, clay and silt and an increase of the sand fraction after 60-70 m from the irrigation channel and after 40-50 m for Cascade 4 (Figure 3-3 and 3-4).

Table 3-4: Temporal and spatial variability in soil fertility in the topsoil of paddy soils at cascade and landscape level.

	Soil parameters (Pr> F)[b]					
	SOC	Inorganic C[b]	Total N	Sand	Silt	Clay
Mixed model before planting[a] (df)						
Vill (1)	0.384	0.020	0.425	0.677	0.105	0.020
Casc (vill) (2)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Irr (vill x casc) (1)	0.982	0.003	0.166	0.4845	0.553	0.130
Fert (irr x vill x casc) (5)	<0.001	<0.001	<0.001	<0.001	<0.001	0.013
Field (fert x irr x vill x casc) (37)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Distance (vill x casc) (4)	<0.001	0.004	<0.001	<0.001	0.033	0.003
Mixed model over time[a] (df)						
Vill (sampl) (5)	0.062	<0.001	0.211	0.011	0.245	0.036
Casc (village x sampl) (2)	<0.001	<0.001	<0.001	<0.001	0.002	<0.001
Irr (vill x casc x sampl) (2)	0.714	0.058	0.407	0.827	0.242	<0.001
Fert (irr x vill x casc x sampl) (10)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Distance (vill x casc x sampl) (8)	<0.001	<0.001	<0.001	<0.001	0.003	0.003
Sampl (vill xcasc x irr x fert x field) (87)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

[a]Vill = village, Casc = cascade, Irr = irrigation or rainfed, Fert = fertilizer application, Field= field within the cascade, Sampl = sampling time (before planting, after first harvest, after second harvest), df = degree of freedom between brackets and Pr the probability.

[b]Root square was taken for inorganic carbon

Table 3-5: Regression between soil organic carbon (SOC, g $100g^{-1}$), total N (%) and sand (g g^{-1}) content of paddy soils and the distance along the cascade at different sampling times in function of distance to the irrigation channel (D).

Cascade	Sampling	Equation	R^2adj /R^2 [a]
1	Before planting	$SOC = 1.72 + 0.02\,D – 2.00\,E^{-04}\,D^2$	0.45***
		$Total\ N = 0.13 + 2.00\,E^{-03}\,D - 1.69\,E^{-05}\,D^2$	0.36 ***
		$Sand = 0.21 - 4.80\,E^{-03}\,D + 4.29\,E^{-05}\,D^2$	0.31 ***
	After harvesting second crop	$SOC = 1.77 + 3.37\,E^{-03}\,D – 3.00\,E^{-04}\,D^2$	0.44 ***
		$Total\ N = 0.14 + 1.80\,E^{-03}\,D - 1.72\,E^{-05}\,D^2$	0.27 ***
		$Sand = 0.27 - 6.10\,E^{-03}\,D + 6.68\,E^{-05}\,D^2$	0.47 ***
2	Before planting	$SOC = 1.12 + 6.30\,E^{-03}\,D$	0.62 ***
		$Total\ N = 0.09 + 6.00\,E^{-04}\,D$	0.61 ***
		$Sand = 0.22 – 9.00\,E^{-04}\,D$	0.28 ***
	After harvesting second crop	$SOC = 1.01 + 6.70\,E^{-03}\,D$	0.58 ***
		$Total\ N = 0.08 + 6.00\,E^{-04}\,D$	0.54 ***
		$Sand = 0.24 - 7.00\,E^{-04}\,D$	0.14 **
3	Before planting	$SOC = 1.68 + 0.03\,D$	0.31 ***
		$Total\ N = 0.13 + 3.15\,E^{-03}\,D$	0.33 ***
		$Sand = 0.37 - 5.35\,E^{-03}\,D$	0.48 ***
4	Before planting	$SOC = 1.72 + 0.02\,D - 1.70\,E^{-04}\,D^2$	0.46 ***
		$Total\ N = 0.13 + 2.23\,E^{-03}\,D - 1.80\,E^{-05}\,D^2$	0.50 ***
		$Sand = 0.18 - 5.12\,E^{-03}\,D + 4.96\,E^{-05}\,D^2$	0.42***

[a] With confidence interval $\alpha = 0.5$, ***, ** and * indicate significance $p \leq 0.001$, 0.01 and 0.05 levels, respectively.

Similar to Cascade 2, the X-ray results for Cascade 1 revealed higher quartz peaks in the fields having a higher sand content and kaolin dominated the clay fraction (data not shown). Soil properties (i.e. inorganic C, SOC, total N and texture) in the NF and F strips showed the same trend in the relationship regarding their position in each cascade but were not fully identical (Figures 3-3 and 3-4, Table 3-5).

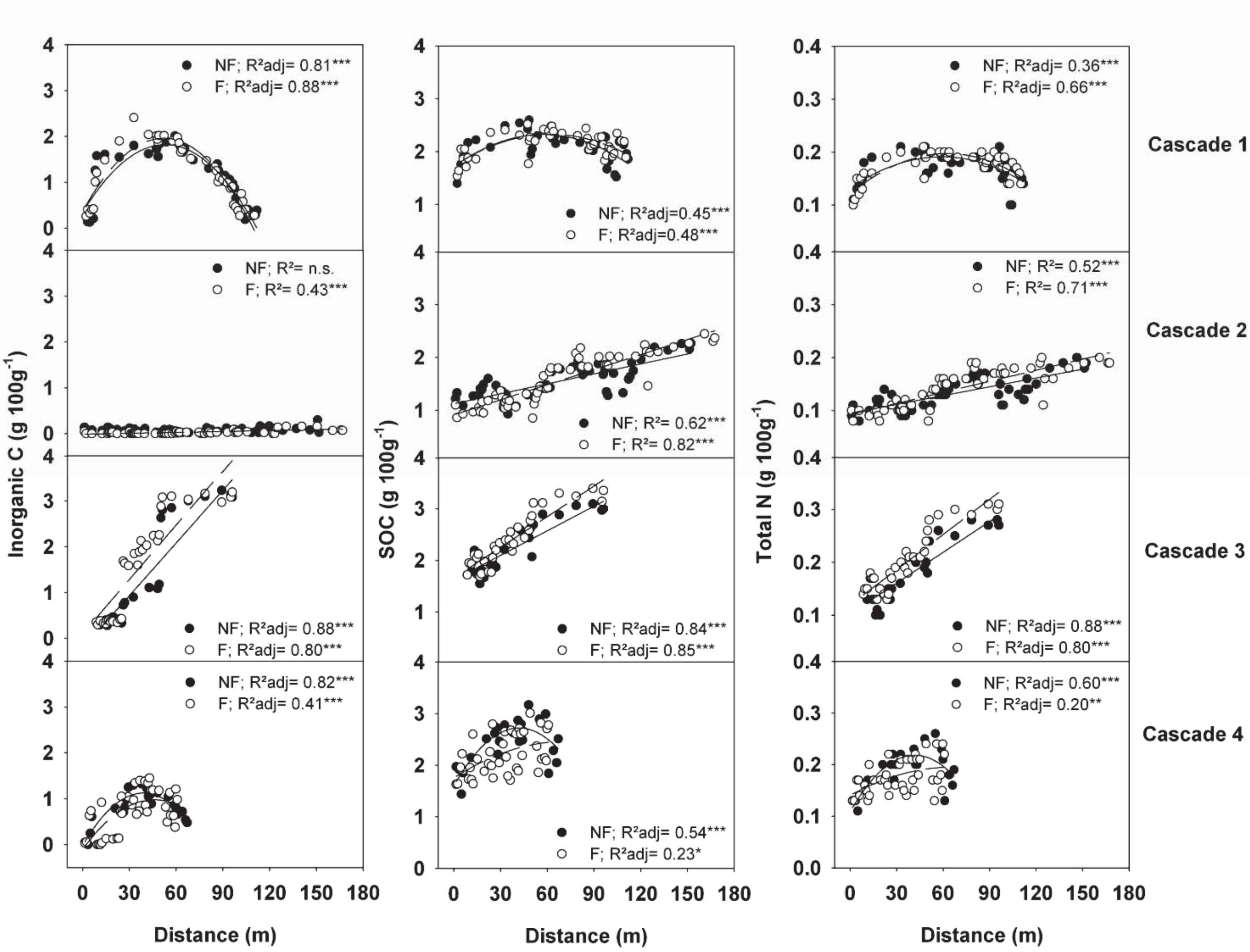

Figure 3-3: Relationships between inorganic C, soil organic carbon (SOC) and total N content of the topsoil before transplanting for non-fertilized (NF) and fertilized (F) strips in paddy fields and the distance from the inlet of the irrigation channel (Distance) for all cascades. ***, **and * indicate significance at $p \leq 0.001$, 0.01 and 0.05 levels, respectively.

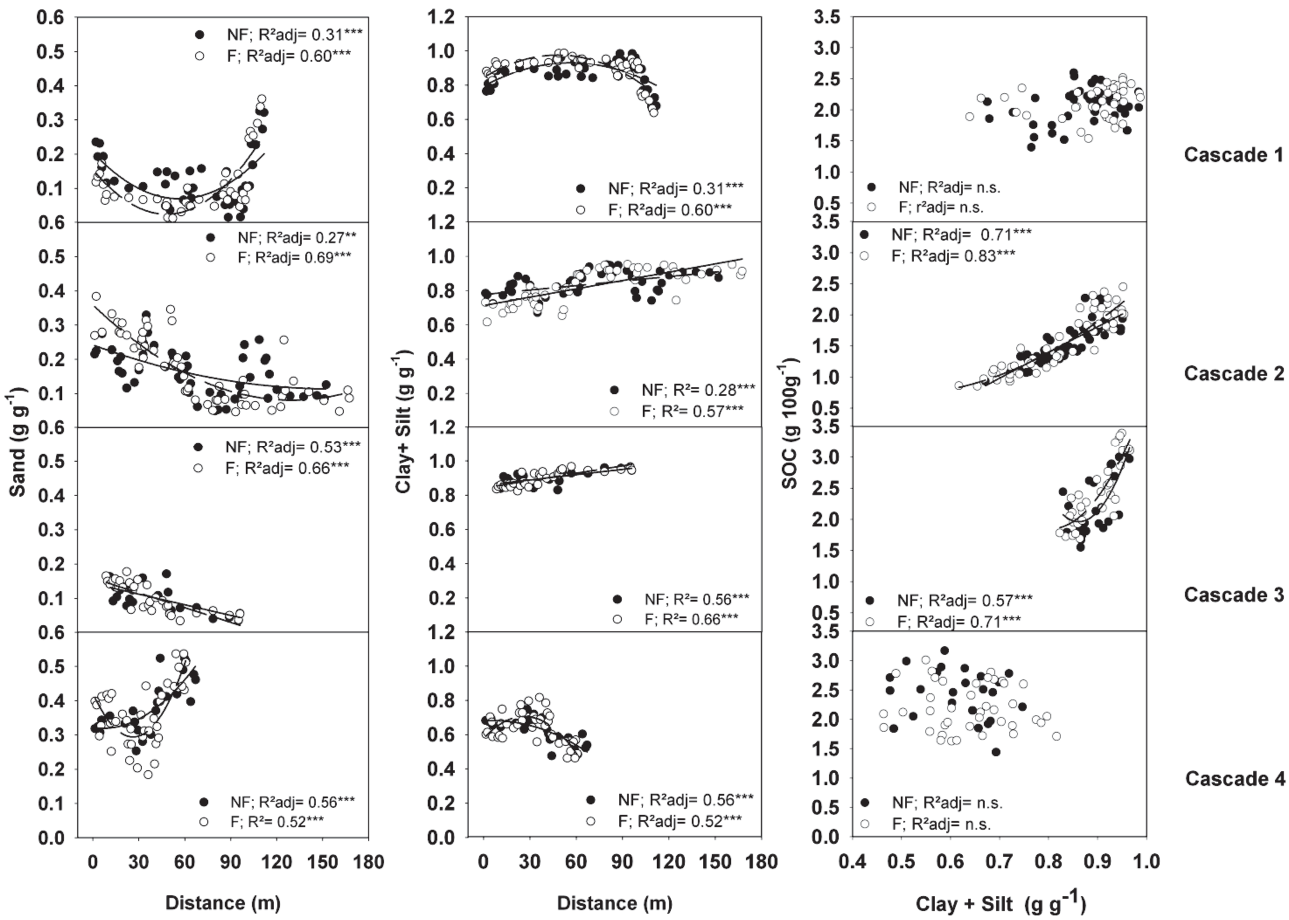

Figure 3-4: Relationship between sand, finer (clay + silt) soil fractions of the topsoil before transplanting and distance from the inlet of the irrigation channel (Distance) for non-fertilized (NF) and fertilized (F) strips in paddy fields; as well as soil organic carbon (SOC) content in function of the finer (clay + silt) soil fraction for non-fertilized (NF) and fertilized (F) strips for all cascades. ***, ** and * indicate significance at $p \leq 0.001$, 0.01 and 0.05 levels, respectively.

3.5.3 Spatial variability induced by sediment deposits

In order to assess soil fertility changes by fresh sediment deposits due to irrigation practices, soil parameters were again measured after rice harvest for Cascades 1 and 2. They showed a similar trend compared to the results obtained before transplanting (Table 3-5, Figure 3-5). However, a slightly higher intercept was obtained for the sand fraction (+0.02 g g^{-1}) for Cascade 2 and a lower intercept for SOC (-0.11 g $100g^{-1}$) and total N contents (-0.01 g $100g^{-1}$). For Cascade 1 a slightly higher intercept was obtained for sand (+0.06 g g^{-1}), SOC (+0.05 g $100g^{-1}$) and Total N (+0.01 g $100g^{-1}$) after harvesting (Table 3-5). The increase in sand fraction over two cropping seasons was more pronounced for Cascade 1 (0.06 g g^{-1}) then for Cascade 2 (0.02 g g^{-1}).

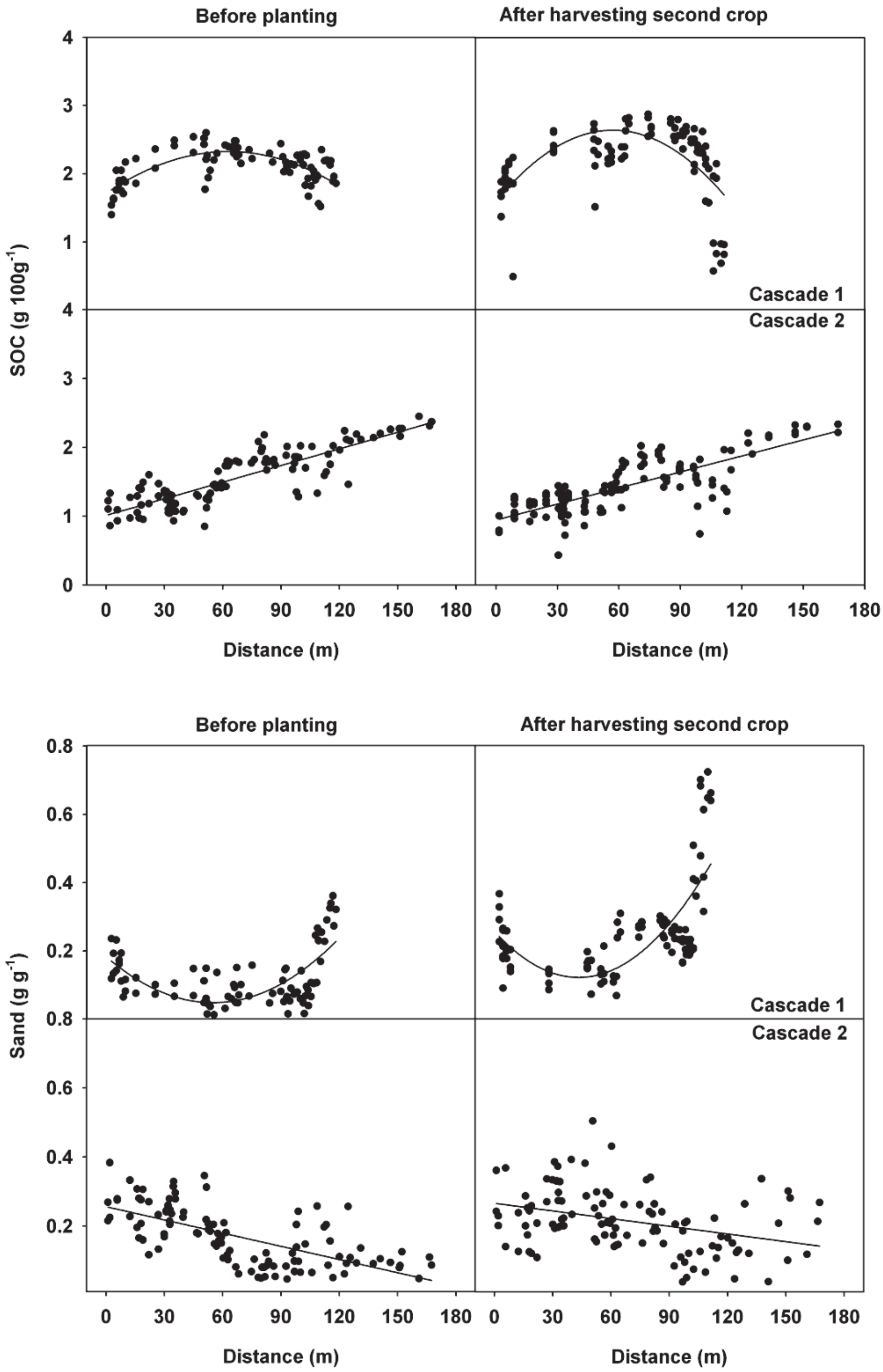

Figure 3-5: Comparison of soil organic carbon (SOC) content and sand fraction along the cascades (Distance) before rice planting and after harvesting the second rice crop for Cascades 1 and 2.

After harvesting of the second season the SOC, at the lower fields of Cascade 1 dropped drastically compared to levels found before planting whereas the sand fraction increased

(Figure 3-5). In addition, a slightly steeper slope was found for SOC and total N in the case of a linear regression and the opposite was found for the sand fraction (Cascade 2, Table 3-5). These results were confirmed by the mixed model before planting and after harvesting on both cascades, confirming a significant impact of sampling time in each field on all parameters ($p<0.001$) and a clear effect of distance from the irrigation channel during each sampling time in every cascade ($p<0.001$) (Table 3-4).

3.5.4 Spatial variability at landscape level

In general, inorganic carbon and clay contents were higher in Ban Me (Cascades 2 and 3) compared to Ban Put (Cascades 1 and 4). The mixed model before planting and after harvesting pointed to a significant difference between the villages for inorganic C ($p<0.001$) and clay ($p=0.036$) content and between the cascades within the village for all measured parameters ($p<0.001$) (Table 3-4). The relative SOC content of the first field fluctuated between 0.8 and 1.4 over the cascades (Figure 3-6).

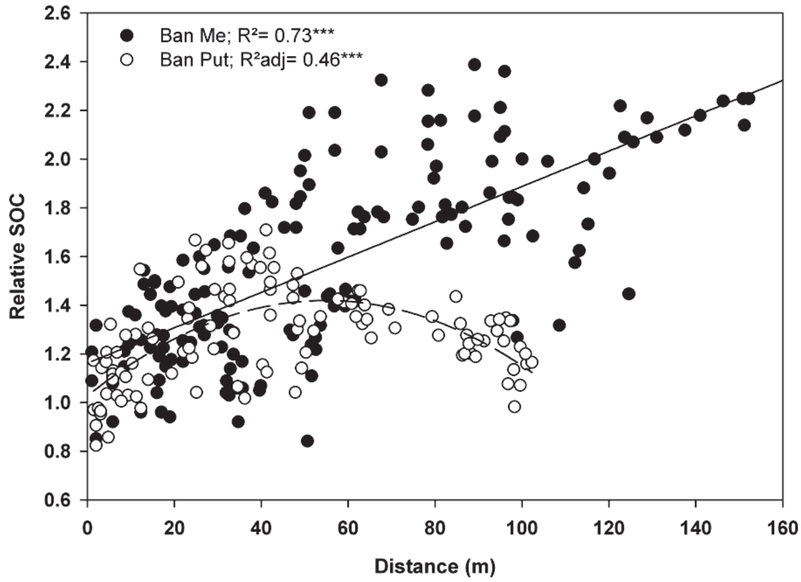

Figure 3-6: Relationship between relative soil organic carbon (SOC) content distance from the irrigation channel (Distance) for both villages, i.e. Cascades 2 and 3 in Ban Me (affected mainly by sediment inputs via irrigation water) and Cascades 1 and 4 in Ban Put (additionally affected by flooding of more distant fields).

In Ban Me there was a rather strong linear increase towards the end reaching relative SOC contents up to 2.4, whereas Ban Put entailed similar relative SOC contents in the lower paddies as found in the upmost paddies (Figure 3-6). A significant correlation between the finer soil fraction and SOC was found with correlation coefficients ranging from 0.57 to 0.83 ($p<0.001$) for the cascades in Ban Me whereas no significant correlations were found for the cascades in Ban Put.

3.6 Discussion

The results showed that the four paddy cascades can be divided into two groups; (i) non flooded cascades where the increase in soil fertility was related to an increase of distance from the irrigation channel resulting in a linear fertility-distance relationship influenced by irrigation water (Cascades 2 and 3) and undiluted runoff (Cascade 2), and (ii) cascades where the lower fields were flooded showing a quadratic fertility-distance trend (Cascade 1 and 4) (Figures 3-3, 3-4 and 3-5, Table 3-5). This indicated that different sediment sources contributed to an enrichment or depletion of soil fertility explaining spatial variability patterns on landscape level. In addition, results suggested a downward movement and deposition of nutrient rich material towards the end of a cascade where the intercept and the slope of the nutrient by distance relationship was compared between before planting and after harvesting (Figure 3-5, Table 3-5). Opposite results have been found for sand compared to SOC and total N as it is the heavier soil fraction and hence sand has a rather short travel distance. Similar results of nutrient enrichments were found by Dercon et al. (2003) on slow forming terraces in the Andes and by Homma et al. (2003) and Tsubo et al. (2007) on rainfed rice terraces and linked to a downward movement of finer nutrient rich soil material. The downward movement of sediment particles is further influenced by farmers practice such as puddling and transplanting (Somura et al., 2009) which resuspends fine material in paddies adding in its downward translocation.

3.6.1 Sediment induced spatial variability through irrigation at cascade level

Kyuma (2004) attributed the variability in inherent soil fertility and base status in irrigated rice fields mainly to the influence of parent material. In contrast, Dobermann et al. (2003) associated similar variations in soil fertility characteristics in irrigated rice fields in various Asian countries to differences in crop management, soils and climate rather than solely to the nature of parent material and landscape features such as topography. As the parent material and climate in our study were similar throughout the catchment, the origin of spatial variability in irrigated paddy terraces was most likely induced by different farmers' practices, such as crop management (Lennartz et al., 2009) and source of irrigation water. When spatial variability could be explained by farmers' crop management, e.g. organic and inorganic fertilizer use, a rather random variability instead of a linear trend would be expected in Cascades 2 and 3. Historical land use management practices could partly explain variations of soil organic carbon and nitrogen content (e.g. organic fertilizer application) (Yanai et al., 2000), whereas irrigation practices and unequal distribution of sediments can explain the small differences in texture and inorganic carbon (Lantican et al., 2003) between the fertilized and non-fertilized strips before planting. However, as crop management was not altered during our study, the majority of spatial variability observed most likely can be attributed to the continuous inflow, transportation and deposition of sediments during irrigation. Poch et al. (2006) and King et al. (2009) also pointed to a significant contribution of irrigation water on a net surplus of sediments as observed in our study. They particularly linked the enrichment of soil organic carbon through sediment deposition in lower fields to the reallocation of dissolved organic carbon in the runoff water. This is supported by the observed presence of high organic carbon contents in the irrigation water during rainfall events and the eventual linear increase of SOC towards the end of a cascade found in this study. Fluctuations of these organic carbon concentrations in irrigation channels depend on sediment quality and quantity. The drainage of erosion prone areas into the irrigation channel is affected by the duration and intensity of each rainfall event and the current soil cover which is determined by its agricultural practice (Ziegler et al., 2004b).

3.6.2 Sediment induced spatial variability in soil fertility depending on sediment origin

The linear trend of soil fertility towards the end of the cascade can be even stronger enforced in case of direct undiluted runoff water from the upland area as found in case of the upper rainfed rice fields (Cascade 2) or altered in case of sediment deposition during flooding events on lower terraces in the cascade (Cascades 1 and 4) (Figure 3-5).

The rainfed paddies in Cascade 2, receiving undiluted runoff water showed a higher sand fraction and lower SOC and total N content as compared to the upper field of the irrigated Cascades 1, 3 and 4. The higher feldspar peaks in the X-ray results in the rainfed paddies can be linked to the higher potassium concentrations found in these paddies, suggesting that these were most likely potassium feldspars, which points to recent sediment deposition (Thanachit et al., 2006; Prakongkep et al., 2008).

Furthermore, flooding events in relation to sediment deposits altered the linear trend of soil fertility changes along a cascade. Cascades 1 and 4, which were next to the river and affected by flooding during typhoons, showed, therefore a rather quadratic trend where similar SOC and total N concentrations were found in the lower flooded rice fields compared to the first irrigated fields in the cascades. This was due to additional unfertile sediment depositions, high in sand content through flooding events occurring during heavy rainfall events. These findings were supported by the X-ray results showing higher quartz concentrations in the lower fields of the flooded cascades due to an increase of sand deposition.

In case of the non-flooded cascades, the increase of SOC was related to an increase of the clay and silt fraction (Cascades 2 and 3, Figure 3-4). This points to transportation of organic rich sediment material by the irrigation channel (Poch et al., 2006) and lower sediment quality transported by the stream. Sediment quality of the river varies from the one transported by the irrigation channel as it entails a coarser fraction, low in organic carbon, derived mainly out of Hortonian overlandflow from the uplands reaching the reservoir and immediately flowing over the weir into the river. In contrast, the irrigation water leaving the reservoir had a longer settling time before flowing through the system. Therefore, the water contains the lighter suspended fraction and additionally dilutes surrounding runoff originating from less erosion prone areas such as bamboo forests neighboring the channel.

3.7 Conclusion

Whereas soil erosion and sedimentation is worldwide considered to be harmful, it can improve soil fertility of lowlands depending on the quantity and quality of the sediments. Sediment loaded irrigation water enriches soil fertility by depositing fine sediments rich in organic carbon, especially on those fields located at the bottom position of the paddy cascades. The direct deposition of sediments of low quality in paddy fields, however, derived from erosion of intensively cultivated and degraded upland fields and flooding events and rather declines soil fertility of paddies in the long run. This also points to the increasing risk of these ecosystems to the expected climate change impact with a higher frequency of typhoons. Therefore, the maintenance of soil fertility of rice fields depends on the balance of sediment inputs of different sources. These findings are also useful in the framework of site-specific fertilizer management to exploit spatial variability in soil fertility along cascades of paddy terraces, leading to a better fertilizer recommendation and a resource saving land management in the area. Finally, an improved understanding of the driving factors behind spatial variability in soil fertility could be an entry point for improving currently used land use models. These models in return can be used to obtain an enhanced insight of lowland-upland biophysical linkages.

CHAPTER 4

LINKING SPATIO-TEMPORAL VARIATION OF CROP PERFORMANCE WIDTH SEDIMENT DEPOSITION ALONG PADDY RICE TERRACES

4 Linking spatio-temporal variation of crop response with sediment deposition along paddy rice terraces[3]

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4.1 Abstract

In tropical mountainous regions of South East Asia, intensive cultivation of annual crops on steep slopes makes the area prone to erosion resulting in decreasing soil fertility. Sediment deposition in the valleys, however, can enhance soil fertility, depending on the quality of the sediments, and influence crop productivity. The aim of the study was to assess (i) the spatio-temporal variation in grain yield along two rice terrace cascades in the uplands of northern Vietnam, (ii) possible linkage of sediment deposition with the observed variation in grain yield, and (iii) whether spatial variation in soil water or nitrogen availability influenced the obtained yields masking the effect of inherent soil fertility by using carbon isotope (^{13}C) discrimination and ^{15}N natural abundance techniques. In order to evaluate the impact of seasonal conditions, fertilizer use and sediment quality on rice performance, ^{15}N and ^{13}C stable isotope compositions of rice leaves and grains taken after harvest were examined and combined with soil fertility information and rice performance using multivariate statistics. The observed grain yields for the non-fertilized fields, averaged over both cascades, accounted for 4.0 ± 1.4 Mg ha^{-1} and 6.6 ± 2.5

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Mg ha^{-1} in the spring and summer crop, respectively; while for the fertilized fields, grain yields of 6.5 ± 2.1 Mg ha^{-1} and 6.9 ± 2.1 Mg ha^{-1} were obtained. In general, the spatial variation of rice grain yield was strongly and significantly linked to sediment induced soil fertility and textural changes, such as soil organic carbon (*r* 0.34/0.77 for Cascade 1 and 2, respectively) and sand fraction (*r* -0.88/-0.34). However, the observed seasonal alteration in topsoil quality, due to sediment deposition over two cropping cycles, was not sufficient to fully account for spatial variability in rice productivity. Spatial variability in soil water availability, assessed through ^{13}C discrimination, was mainly present in the spring crop and was linearly related to the distance from the irrigation channel, and overshadowed in Cascade 2 the expected yield trends based on sediment deposition. Although $\delta^{15}N$ signatures in plants indicated sufficient N uptake, grain yields were not found to be always significantly influenced by fertilizer application. These results showed the importance of integrating sediment enrichment in paddy fields within soil fertility analysis. Furthermore, where the effect of inherent soil fertility on rice productivity is masked by soil water or nitrogen availability, the use of ^{13}C and ^{15}N stable isotopes and its integration with conventional techniques showed potential to enhance the understanding of the influence of erosion – sedimentation and nutrient fluxes on crop productivity, at toposequence level.

4.2 Keywords

Paddy rice; productivity; sedimentation; soil fertility; ^{13}C discrimination and ^{15}N natural abundance.

4.3 Introduction

Rice (Oryza sativa L.) is the main staple food in Southeast Asia and its production will continue to be challenged in meeting future food demands. As rice production is influenced by climate, soil, crop characteristics and management practices (e.g. fertilizer use and water management) yields are highly variable (Dobermann et al., 2003; Kyuma, 2004). Especially in tropical mountainous areas, the downward movement and deposition of sediments derived from erosion of intensively cultivated fields on the steep slopes play a key role when addressing productivity in lowland rice fields. Soil fertility parameters, such as soil organic carbon (SOC) content, and related rice yield tend to increase with descending position of paddies in the landscape (Homma et al., 2003; Tsubo et al., 2006; Rüth and Lennartz, 2008; Haefele and Konboon, 2009; Chapter 3).

A direct linkage between soil fertility and crop productivity, however, is not always evident. Boling et al. (2008) and Ye et al., (2008) pointed towards the need of a broader dataset encompassing water availability and toposequence position besides soil and crop management factors. This is supported by Ruth and Lennartz (2008) who suggested that crop and soil management affects downward movement of finer soil particles and therefore alters the hydrological characteristics. The effect of toposequence position on water availability and therefore grain yield in rainfed rice was also pointed out by Tsubo et al. (2006) and Haefele and Konboon (2009). According to Kyuma (2004), in traditional management systems the minimum water requirement for one rice season ranges between 1000-1500 mm in Southeast Asia. Hence, as water can often be a limiting factor in rice production when irrigation water is limited, the link between soil fertility and crop productivity can be overshadowed by temporal growth limiting conditions, like water shortage, which is often spatially variable along paddy cascades.

Recent research suggested that ^{13}C discrimination can be a useful tool in assessing *ex post* water limitations during crop development affecting rice grain yields (Yin and Raven, 1998; Clay et al., 2001b; Impa et al., 2005). The typical isotopic ratio of ^{13}C ($\delta^{13}C$) for C_3 plants is species dependent and ranges around -27‰ (Farquhar et al., 1989; Impa et al., 2005). When water limitation occurs, the stomata of C_3 plants such as rice close in order to reduce water losses, hence the fixation of intercellular $^{13}CO_2$ is increased resulting in an increase of $\delta^{13}C$ (i.e. less negative $\delta^{13}C$ values) (Clay et al., 2001b). However, besides water limitations, any factor that influences CO_2 diffusion and therefore photosynthesis such as nitrogen (N) limitation has an impact on ^{13}C discrimination (Farquhar et al., 1989; Yin and Raven, 1998; Dercon et al., 2006a; Pansak et al., 2007). When assessing N use efficiency of C_3 plants, results showed that when both water and N limitation occurred, the positive effect of N-fertilizer decreased when water stress increased (Clay et al., 2001b). Therefore, variations in $\delta^{13}C$ can assist as well in assessing the role of N limitations in rice crop performance.

The use of the stable isotope ^{15}N has proven to be a useful tool in understanding N uptake and fertilizer use efficiency (Bandyopadhyay and Sarkar, 2005; Kaewpradit et al., 2009). The N cycle in paddy systems, however, is often complex due to the various inputs (rainfall, residue incorporation, organic and inorganic fertilizer application and quality of the irrigation water), losses (e.g. volatilization and runoff) and redox reactions (nitrification and denitrification) which all have an impact on the isotopic ^{15}N discrimination in a paddy (Yoneyama et al., 1990; Yoneyama et al., 2001a; Nishida et al., 2007; Ebid et al., 2008; Bernot et al., 2009). Furthermore, results of Nishida et al. (2007) indicated a decrease of the isotopic ^{15}N signature ($\delta^{15}N$) in paddy soils when no fertilizer or residues were applied and attributed it to the natural input of N due to irrigation water (dissolved and particulate N). The complexity of the N cycle in paddy rice fields increases due to the frequent alternation of wetting and drying cycles which depends on the water management and the hydrological characteristics of the paddy soil (Yoneyama et al., 1991b). The assessment of $\delta^{15}N$ and $\delta^{13}C$ stable isotopes in combination with information on soil fertility and crop management might therefore facilitate the understanding of spatial variation of rice performance along paddy terraces.

The purpose of this study was to assess the impact of sediment deposits in paddy rice terraces on rice productivity. As there is a soil fertility gradient along rice terraces (Chapter 3) the aim of the study was to evaluate (i) the spatio-temporal variation in grain yield along rice terraces, (ii) a possible linkage of sediment deposits with the observed variation in grain yield and (iii) to use stable isotopes (^{13}C and ^{15}N) to determine whether spatial variation in water or N availability influenced the obtained yields and hence masked the effect of inherent sediment induced spatial variation of soil fertility.

4.4 Materials and methods

4.4.1 Experimental site

In 2007 two rice cropping seasons were monitored in the Chieng Khoi commune which is situated in the Yen Chau district, Northwest Vietnam (Figure 4-1, a). The area consists of steep upland hills (up to a slope gradient of 86%) with fine silt-sandstone and limestone as parent material. The most frequent occurring soil types, according to the WRB classification were Alisols and Luvisols (Deckers et al., 1998). From March till December the steep uplands slopes are mainly under maize (Zea mays L.) and cassava (Manihot esculenta Crantz) cultivation. The valleys are used for rainfed or irrigated rice production, partly already for up to 200 years.

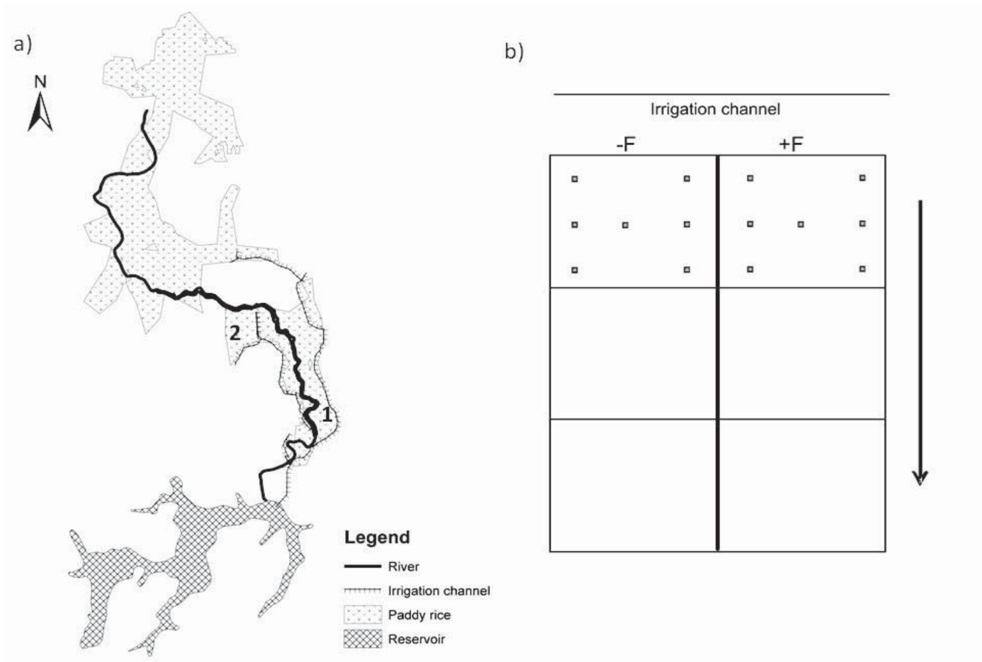

Figure 4-1: a) Overview of the Chieng Khoi area with the location of the two cascades (squares) and b) Schematic representation of a cascade with the arrow giving the flow direction of the irrigation water, -F refers to non-fertilized and +F to fertilized fields; the squares representing the seven plots of 1 m² within each field .

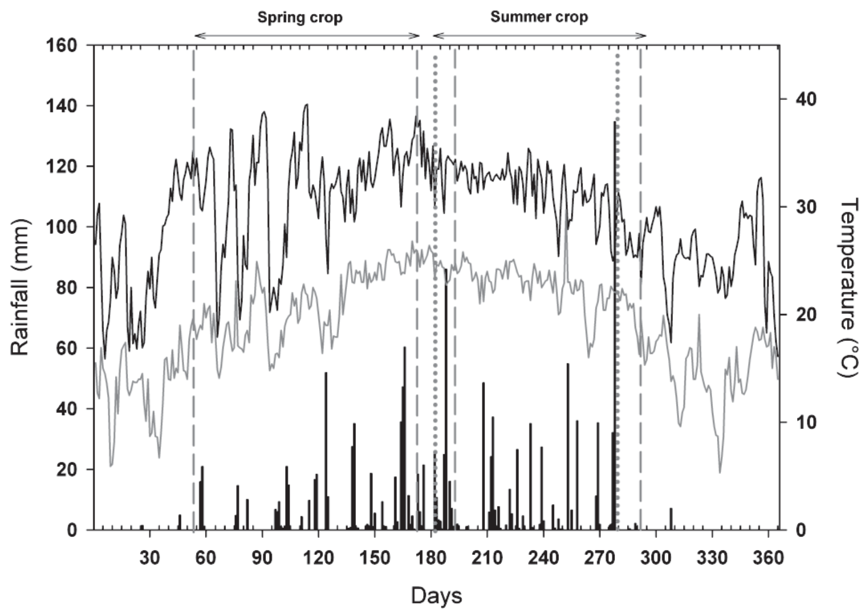

Figure 4-2: Daily rainfall distribution (vertical bars), maximum (black line) and minimum (gray line) temperatures for 2007 (in Julian days) at the experimental site of Chieng Khoi with day 1 reflecting the 1st of January 2007. Dashed lines indicate the planting and harvesting of the spring and summer crop for the two-crop paddies while the period for the summer crop for the one-crop paddies is given by the dotted line.

The studied watershed is located in the tropical monsoon belt receiving an average annual precipitation of 1200 mm of which 45% and 55% fell during the spring and summer season, respectively (Figure 4-2). However, the majority of the rain in the spring season falls at the end (May-June). A reservoir and an open channel irrigation system allow for two rice cropping seasons a year [e.g., spring (February – June/July) and summer crop (July – October)].

4.4.2 Experimental design

Two rice cascades with varying lengths (112-170 m), containing each seven to nine successive paddy fields, covering a total of 0.9 ha (series of paddy terraces) were selected to assess spatial variation of rice productivity at cascade level and the impact of sediment induced alterations in soil fertility on rice productivity (Table 4-1). Both toposequences of paddy rice terraces were monitored during two successive cropping seasons: (i) a relative dry season (spring crop), where fields were intensively irrigated depending on water availability and (ii) a rainy season (summer crop) which was mainly rainfed but irrigated in case of water shortages. In Cascade 2, the upper situated rainfed paddies (0 to 55 m) could only be cultivated during the summer crop (referred to as one-crop paddies), as no irrigation was possible due to the topographic location of these fields. Except for these first five fields (0-55 m), all fields in both cascades had two rice cropping seasons a year (referred to as two-crop paddies). The main criteria for the selected cascades were flow pattern of the irrigation water, total cascade length and the differences in sediment delivery pathways: (i) irrigation water (Cascades 1 and 2), (ii) undiluted runoff from the surrounding upland area conveyed to the paddy field by a runoff channel (0 to 55 m for Cascade 2) and (iii) occurrence of suspended sediments and bed load from the river due to flooding (after 98 m for Cascade 1). The uppermost field of cascades received water either directly from the irrigation channel or through a runoff channel in case of rainfed fields. All other fields of the investigated cascades received water through a single inlet from the above lying field and drained via a single outlet to the lower situated field. Fertilizer application was the sub-factor dividing each field in each cascade into a fertilized (+F) and non-fertilized (-F) part.

Table 4-1: Properties of two sequences of paddy terraces (Cascades 1 and 2) and the obtained averaged yield per hill in the Chieng Khoi commune, Son La province, Northwest Vietnam. Distance being the cumulative distance from the inlet of each field towards the irrigation channel (m) and area of the individual field before division into fertilized (+F) and non-fertilized (-F) subfields. Length of the cascade entails the whole length of the cascade (until the end of the last field).

	Cascade 1 (concrete channel) Cascade length: 112 m						Cascade 2 (earth channel) Cascade length: 170 m					
Field	Rice cycles ($year^{-1}$)	Sediment source	Distance (m)	Area (m^2)	Yield ($g\ hill^{-1}$) Spring crop -F/+F	Yield ($g\ hill^{-1}$) Summer crop -F/+F	Rice cycles ($year^{-1}$)	Sediment source	Distance (m)	Area (m^2)	Yield ($g\ hill^{-1}$) Spring crop -F/+F	Yield ($g\ hill^{-1}$) Summer crop -F/+F
1	2	Irrigation	0	200	5.2/6.7	6.2/6.4	1	Upland runoff	0	656		12.7/10.5
2	2	Irrigation	7	1409		7.1/7.3	1	Upland runoff	18	560		12.3/11.9
3	2	Irrigation	49	400	7.9/9.2	6.1/8.7	1	Upland runoff	32	251		8.8/10.9
4	2	Irrigation	64	883		5.4/7.1	1	Upland runoff	34	848		12.1/11.6
5	2	Irrigation	88	491	6.8/8.2	7.3/6.6	1	Upland runoff	55	281		6.4/6.7
6	2	Irrigation/flooding	98	200		9.7/8.6	2	Irrigation	62	685	5.5/9.4	6.0/8.1
7	2	Irrigation/flooding	103	362	3.9/6.5	5.0/3.9	2	Irrigation	82	643		5.3/7.0
8		-	-	-			2	Irrigation	97	800	4.3/8.2	6.8/7.8
9		-	-	-			2	Irrigation	114	694	4.3/13.8	7.8/10.8

To avoid the diffusion of dissolved fertilizer, 1 m wide bunds were made between the fertilized and non-fertilized subplots. Each fertilized field received the same type and amount of inorganic fertilizer according to the local recommendation via split application.This resulted in a total application of 213 kg N ha^{-1}, 150 kg P ha^{-1} and 93 kg K ha^{-1} per rice cycle. The first dressing, at transplanting, entailed 56% N, 100% P and 34% K of the total amount of fertilizer applied in the form of NPK and Urea. Second and third dressings contained 22% N and 33% K of the total amount of fertilizer in the form of Urea and Kali which was applied at maximum tillering and at flowering. The fertilizer application treatment (+F) assisted in assessing the effects of farmers' practice and fertilizer use efficiency while the non-fertilizer treatment (-F) indicated the inherent soil fertility effect on the variability of rice grain yield.

4.4.3 Soil fertility along the cascades

In order to assess the impact of sedimentation and the effect of different sediment delivery systems (irrigation, runoff and flooding) on crop performance, topsoil samples (0 to 5cm) were taken before transplanting and after harvesting following the flow direction of the cascades and analyzed for soil organic carbon (SOC), total N and texture. Thus seven topsoil samples were taken in each field next to the sampling positions of the crop performance measurements of rice (Figure 4-1 b). Total N and SOC were determined after acidification (HCl) in order to eliminate any present carbonates, using the combustion method (Elementaranalysator EL, Elementar GmbH, Germany), while particle size distribution was measured using the laser diffraction method (Beckman Coulter LS 200 Series). Additionally nitrate and ammonia content of the topsoil samples taken after the first harvest were measured immediately after sampling using the modified indophenol method (2M KCl extraction) for ammonia (Sparks, 1996) and Cataldo method for nitrate (0.01M KCl extraction) (Cataldo et al., 1975).

4.4.4 Crop performance along the cascades

All fields for each cascade and each season were planted with the same sticky rice variety Nep 87. In order to assess crop performance, seven plots of 1 m², following the descending flow direction of the irrigation water, were marked in each fertilized (+ F) and non-fertilized (- F) field (Figure 4-1 b), and their distance from the irrigation channel was measured. In the spring crop, the trend in rice productivity was monitored based on yields of every second field, whereas all fields of the summer crop were evaluated to prove trends observed along the toposequences in the previous rice season. Transplanting was done on all fields within three successive days for each cascade and within five days between cascades.

Same time lag was used when assessing grain yield and total biomass within and between cascades. Manual weeding was carried out when necessary. At harvest, total above ground biomass and grain yields were determined on four randomly selected hills in each of seven 1 m² plots of each field resulting in a total sample set of 28 samples per field. Average yields (kg m^{-2}) per field were obtained by averaging all harvested hills among the seven plots of 1 m².

4.4.5 The use of stable isotopes in understanding crop response

A full understanding of the fertilizer effect in the fertilized strips was obtained by calculating the internal (IE_N), agronomic (AE_N) and recovery (RE_N) N efficiencies in both seasons for all cascades by using the following equations:

$$IE_N\ (\text{kg kg}^{-1}) = (grain\ yield / total\ N\ uptake) \times 100 \qquad \text{Eq. 4-1}$$

$$AE_N\ (\text{kg kg}^{-1}) = \left(grain\ yield_{+F} - grain\ yield_{-F} / N_{applied}\right) \times 100 \qquad \text{Eq. 4-2}$$

$$RE_N\ (\%) = \left(N\ uptake_{+F} - N\ uptake_{-F} / N_{applied}\right) \times 100 \qquad \text{Eq. 4-3}$$

where $N\ uptake_{+F}$ and $N\ uptake_{-F}$ are the total N content of the biomass in the fertilized (+F) and unfertilized plots (-F) (kg ha^{-1}), *grain yield* is expressed as kg ha^{-1}, and $N_{applied}$ is the total N applied in kg ha^{-1}.

In order to assess the toposequential effect on water and N limitation and their impact on grain yield, ^{13}C and ^{15}N natural abundances were measured from a subset of the harvested material taken in the spring and summer season for both cascades. The subset consisted of rice grains and leaves from the middle position of each fertilized and non-fertilized field. To assess the spatial variability within the field, additional points were measured in case the grain yields were considerably higher or lower compared to the averaged grain yields within each field. In total, a set of 34 samples for the first season and 47 samples for the second season (including the one-crop paddies) were analyzed. Furthermore topsoil samples taken at the points of the selected grain and leaf samples in the summer season season were also analyzed for ^{15}N in order to assess the overall natural abundance of the isotopic ratio, as the soil was, besides rainfall and irrigation/runoff water, the only N source for the non-fertilized fields. All samples, ground to 1 mm using a knife-mill, were afterwards ball milled and analyzed for N concentration, ^{15}N, C concentration and ^{13}C using an Euro EA Elemental Analyzer (Euro Vector) coupled to a Finnigan Delta IRMS (Thermofinnigan). The discrimination of ^{13}C ($\delta^{13}C$) and ^{15}N ($\delta^{15}N$) was calculated for each sample by comparing the isotopic ratio of the sample with CO_2 and air reference gases standardized for Pee Dee Belimnite ($\delta^{13}C$) and atmospheric N_2 air ($\delta^{15}N$):

$$\boldsymbol{\delta^{13}C\ or\ \delta^{15}N = \left[\left(R_{sample}/R_{standard}\right) - 1\right] \times 1000} \qquad \text{Eq. 4-4}$$

where $R_{standard}$ is the $^{13}C/^{12}C$ or $^{15}N/^{14}N$ ratio of the standard and R_{sample} is the $^{13}C/^{12}C$ ratio or $^{15}N/^{14}N$ of the sample.

The isotopic signature ($\delta^{15}N$) of applied urea was -1.07‰ whereas NPK contained 0.59‰ $\delta^{15}N$. From the total N applied, 65% was applied in the form of urea for all cascades in all seasons on the fertilized strips which resulted in an overall weighted $\delta^{15}N$ signature of -0.49‰ for the applied N fertilizer.

4.4.6 Statistical analysis on spatial variability

A general description of grain yield and biomass for each season was obtained by using the Proc Univariate in SAS v9.2 (Cody and Smith, 2006) separately for the fertilized and non-fertilized fields. A first indication regarding variability was obtained through the coefficient of variation (CV). Variability was considered low when CV < 10% and high when > 90% (Wei et al., 2008). As grain yield and biomass were not normally distributed, Mann-Whitney, a non parametric two level test, was carried out with SAS to compare the rank sums between (i) the –F and +F strips within each season and cascade, (ii) irrigated and rainfed paddies within the summer season, (iii) between fields within a cascade and season. The Spearman rank correlations after running the PROC CORR in SAS were used to test whether yield could be linked with the soil nutrient and textural variability found in each cascade for the spring and summer crop. The Spearman rank correlations were used as the variables showed a non normal distribution.

A more detailed multiple non-linear regression using PROC MIXED in SAS was performed on the extended dataset of the second season (summer crop), in order to assess the impact of crop management (i.e., planting density and fertilizer treatment), distance to the irrigation channel, SOC and sand fraction (all fixed effects) on grain yield. This was done for each sampling point where grain yield was assessed which resulted in a total of 98 samples for Cascade 1 and 125 samples for Cascade 2. The mixed model was used for each cascade separately as both cascades showed different sediment induced distributions of soil nutrients and soil texture along the distance gradient. Furthermore, to evaluate the effect of changes in SOC (ΔSOC) content and sand fraction (ΔSand) by sediment deposition over the two seasons, along the cascade length, on the observed grain yields, a second model for each cascade was developed. For the second model, the fixed effects: planting density, fertilizer application and distance along the cascade remained unaltered whereas SOC and sand were replaced by ΔSOC and ΔSand, respectively. Changes of sand and SOC content for each position within the field were calculated by subtracting the results obtained from the samples taken before planting with the results found after harvesting. The grain yield per hill was log transformed in both model runs in order to obtain a homogenous variance and approximate normality of the residuals.

Finally, the effect of cropping season (spring *vs.* summer crop), cascade (1 *vs.* 2), distance to the irrigation channel, fertilizer treatment and planting density on N use efficiency was assessed using the MIXED model approach. As the N content in the grains were only measured during the stable isotope analysis, only the middle position of each field for each season and each cascade was used which resulted in a total of 34 samples.

4.5 Results

4.5.1 Exploratory analysis of crop performance

On average the grain yield per hill for the non-fertilized (-F) fields in the two cascades, excluding the one rice crop paddies in Cascade 2 (0 to 55 m), amounted to 5.4 ± 1.9 g (4.0 ± 1.4 Mg ha^{-1}) for the spring and 8.1 ± 3.0 g (6.6 ± 2.5 Mg ha^{-1}) for the summer crop, while for the fertilized (+F) fields an average yield per hill of 8.9 ± 2.8 g (6.5 ± 2.1 Mg ha^{-1}) for the spring and

8.4 ± 2.6 g (6.9 ± 2.1 Mg ha^{-1}) for the summer crop was obtained (Table 4-2). Moderate variability in -F and +F fields was found for grain yield per hill (-F: 36/38%, +F: 31/31%) and biomass production (-F: 32/36%, +F: 30/31%) for spring/summer crop, respectively (Table 4-2).

Table 4-2: Descriptive statistics of grain yields and biomass for fertilized (+ F) and non-fertilized fields (-F) of the two cascades during the first and second cropping season. Difference between fertilized (+F) and non-fertilized (-F) strips for the comparison of rice yield and biomass for each cascade within each season using the Chi square results (χ^2) from the Mann-Whitney test (with the number of observations in parenthesis).

Cropping season	Fertilizer treatment	Parameter	N[a]	Min	Max	Mean	Median	SD[a]	CV (%)[a]
Spring	-F	Planting density (hill m^{-2})	49	60	92	73	73	7	9 (5/*10*)
		Yield (g hill^{-1})	49	2	11	5	5	2	36 (26/*37*)
		Biomass (g hill^{-1})	49	4	19	9	9	3	32 (24/*34*)
	+F	Planting density (hill m^{-2})	56	56	92	74	74	8	10 (9/*10*)
		Yield (g hill^{-1})	56	3	17	9	8	3	31 (*26*/28)
		Biomass (g hill^{-1})	56	7	28	15	14	5	30 (*25*/26)
Summer[b]	-F	Planting density (hill m^{-2})	119	52	116	77	76	11	15 (*15*/15)
		Yield (g hill^{-1})	119	4	17	8	7	3	38 (*28*/37)
		Biomass (g hill^{-1})	119	8	36	17	15	6	36 (*22*/36)
	+F	Planting density (hill m^{-2})	112	60	116	81	80	10	12 (*10*/12)
		Yield (g hill^{-1})	112	3	18	8	8	3	31 (26/*29*)
		Biomass (g hill^{-1})	112	8	40	18	17	6	31 (*22*/28)

	Difference between +F and –F treatments			
	Spring crop		Summer crop	
	Cascade 1	Cascade 2	Cascade 1	Cascade 2
Yield (g hill^{-1})	9.70** (28)	32.70*** (21)	0.51$^{n.s.}$ (49)	14.48*** (28)
Biomass (g hill^{-1})	10.58** (28)	32.94*** (21)	2.87$^{n.s.}$ (49)	12.25*** (28)

[a] N number of observations, SD standard deviation, CV coefficient of variation. CV values are based on the entire dataset (Cascades 1 and 2) the CV for each cascade (respectively Cascade 1 and 2) is given in parenthesis)
[b] including one-crop paddies (0 to 55 m, Cascade 2) and flooded fields (> 98 m, Cascade 1)
***: p<0.001, **: p<0.01, *: p<0.0.5, n.s.: not significant

4.5.2 Spatial variability of crop performance at cascade level

In general, the relationship between grain yield and position in the cascades showed significant, but weak to moderate non-linear trends for both seasons. As it can be observed in Figure 4-3, grain yields in Cascade 1, in both +F and -F strips, increased in the spring season within the first 50 m along the cascade whereas further down (100 m) significantly lower yields were obtained as compared to the upper lying fields (+F: χ^2= 8.8, p=0.032; -F: χ^2= 13.9, p=0.003) (Figure 4-3). In the summer season, observed similar trends for Cascade 1 were found to be weak for the +F strip and no significant trend occurred in the –F strip. For Cascade 2 in the spring season, the grain yield in the spring crop declined slightly in both +F and –F strips after the first 40 m (100 m of the total cascade length) compared to the upper lying fields and significantly increased towards the end of the cascade for the +F strip while for –F no significant difference was found compared to the paddy fields above. Yields obtained within the summer season for Cascade 2 showed a linear increase in the two-crop paddies (60 to 170 m of the total cascade length) with increasing distance from the irrigation channel for both fertilizer treatment strips.

A significant difference in grain yield (Cascade 1: p=0.002, Cascade 2: p<0.001) was found between the +F and -F strips for the spring crop whereas for the summer crop a significant difference was found for the two-crop paddies fields in Cascade 2 (60 to 170 m; p<0.001) (Table 4-2).

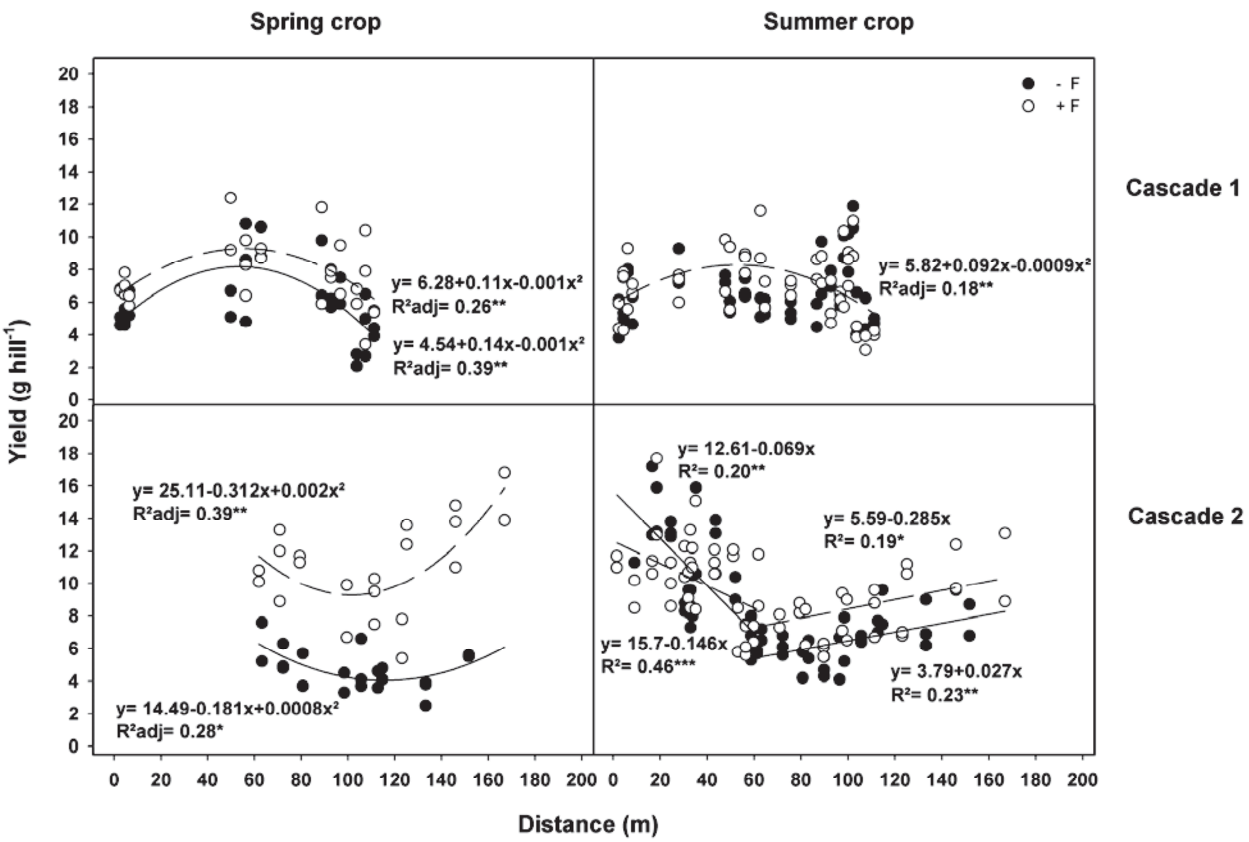

Figure 4-3: Grain yield (g hill^{-1}) for the first (left) and second season (right) along the distance of the cascade from the irrigation channel for the fertilized (+F) and non fertilized (-F) strips. The first 60 m of Cascade 2 represent the rainfed rice paddies. In case of a significant regression respective formula and *R^2/R^2adj* are given. Triple asterisk, double asterisk and single asterisk indicate significance at p ≤ 0.001, <0.01 and <0.05, respectively.

The upper lying one-crop paddies of Cascade 2 (0 to 60m) did not show a significant difference ($p=0.6$) in grain yield between the fertilized and non-fertilized strip. Only the two-crop paddies of Cascade 2 showed a significant difference in grain yield between the spring and summer crop for the -F ($\chi^2= 16.3$, $p<0.001$) and +F strips ($\chi^2= 6.3$; $p=0.012$), overall yields were found to be higher in the summer crop. The upper lying one-crop rice fields in Cascade 2 (0 to 55 m) showed much higher yields compared to the lower situated two-crop rice fields (60-170 m) in both fertilized ($\chi^2= 11.3$, $p=0.008$) and non-fertilized ($\chi^2= 29.1$, $p<0.001$) fields.

4.5.3 Linkage of crop performance with soil fertility

For the spring crop, where the two-crop paddies were planted and spatial variation in water availability did occur along the paddies, a relationship between grain yield and soil fertility parameters was found for Cascade 1 only (Table 4-3). The obtained grain yields for Cascade 1 were significantly negatively correlated with the sand fraction for both fertilizer treatments while for the fertilized strip, yield was found to be also negatively correlated with planting density and positively correlated with SOC (Table 4-3). The summer crops of Cascade 2, however, showed in both fertilizer treatments a significant negative correlation with SOC and planting density and a positive correlation with sand (Table 4-3). The results of the multivariate analysis based on soil data after harvest (model 1) showed for Cascade 1 a significant impact of fertilizer, distance from the irrigation channel and SOC content in the soil on rice yield. Additionally there was an interaction between the distance from the irrigation channel and SOC content and sand fraction (Table 4-4). For Cascade 2, rice yields along the cascade were significantly affected by the distance from the irrigation channel, planting density, SOC content, and sand fraction. Although fertilizer application alone did not seem to be significantly influencing rice yields in Cascade 2, there was a significant interaction between fertilizer and the distance from the irrigation channel (Table 4-4). When sediment induced alterations in SOC content (ΔSOC) and sand fraction (ΔSand) were used in the multivariate analysis (model 2), only fertilizer and its interaction with distance influenced grain yields along Cascade 1 in the summer crop were significant, whereas for Cascade 2, besides planting density and the distance along the cascade, also the changes in SOC content in combination with the distance significantly influenced rice yields (Table 4-4).

Table 4-3: Spearman correlation coefficients (r) between grain yield (g hill^{-1}), planting density (m^{-2}), soil organic carbon (SOC, g g^{-1}) content and sand fraction (g g^{-1}) of the topsoil for Cascade 1 and 2 for the spring and summer cropping season.

Season	Cascade	Fertilizer treatment	Parameter	N[a]	SOC	Sand	Plant density
Spring	1	-F	Sand	12	n.s.	-	
			Plant density	12	n.s.	n.s.	-
			Yield	12	0.77**	-0.88***	n.s.
	1	+F	Sand	12	-0.62*	-	
			Plant density	12	n.s.	n.s.	-
			Yield	12	n.s.	-0.7-*	n.s.
	2	-F	Sand	9	-0.87**	-	
			Plant density	9	n.s.	n.s.	-
			Yield	9	n.s.	n.s.	n.s.
	2	+F	Sand	9	-0.79*	-	
			Plant density	9	0.77*	-0.73*	-
			Yield	9	n.s.	n.s.	0.86**
Summer	1	-F	Sand	49	n.s.	-	
			Plant density	49	-0.69**	n.s.	-
			Yield	49	n.s.	-0.39**	n.s.
	1	+F	Sand	49	n.s.	-	
			Plant density	49	n.s.	0.34*	-
			Yield	49	0.34*	-0.52**	-0.41**
	2	-F	Sand	63	-0.83**	-	
			Plant density	63	0.36**	n.s.	-
			Yield	63	-0.51**	0.45**	-0.44**
	2	+F	Sand	62	-0.91**	-	
			Plant density	62	0.36**	-0.36**	-
			Yield	62	-0.35**	0.34**	-0.61**

[a] N= number of observations

**, *: Correlation is significant at the p<0.05 level and <0.01 level (2-tailed) respectively.

Table 4-4: The influence of crop management (fertilizer and planting density), distance (distance to the irrigation channel), soil organic C (SOC) and sand fraction and their changes (Δ Sand and Δ SOC) due to sediment deposition along the cascade on the spatial variability of grain yields within each cascade for the summer crop.

Grain yield (Pr>F)			
Model 1 Soil after harvest[b]		Model 2: Sediment deposition[c]	
Cascade 1 (df =1)			
Fertilizer	0.015	Fertilizer	0.020
Distance	0.001	Distance	n.s.
Distance*Distance	n.s.	Distance*Distance	n.s.
Fertilizer*Distance	0.061	Fertilizer*Distance	0.035
Planting Density	n.s.	Planting Density	n.s.
Sand	0.074	ΔSand	n.s.
Sand*Distance	<0.001	ΔSand*Distance	n.s.
SOC	0.027	ΔSOC	n.s.
SOC*Distance	0.005	ΔSOC*Distance	n.s.
Cascade 2 (df =1)			
Fertilizer	n.s.	Fertilizer	n.s.
Distance	<0.001	Distance	0.003
Fertilizer*Distance	0.024	Fertilizer*Distance	n.s.
Planting Density	<0.001	Planting Density	<0.001
Sand	0.022	ΔSand	n.s.
Sand*Distance	<0.001	ΔSand*Distance	n.s.
SOC	0.025	ΔSOC	n.s.
SOC*Distance	<0.001	ΔSOC*Distance	0.029

[a] df = degree of freedom, n.s. = non significant

[b] Model 1 = mixed model with SOC and sand fraction representing soil characteristics

[c] Model 2= mixed model with sediment deposition resembling the changes in sand fraction :
$\Delta Sand = Sand_{after\ harvesting} - Sand_{before\ planting}$ and ΔSOC content $= SOC_{after\ harvesting} - SOC_{before\ planting}$

4.5.4 Spatial variability in water availability and $\delta^{13}C$ signals in rice

The carbon isotope discrimination found in rice grains in the first, well watered, two-crop paddy fields in each Cascade (e.g. Field 1 for Cascade 1 and Field 6 for Cascade 2) ranged between -

28.7 and -28‰ (Figure 4-4) and between -28 and -27‰ for leaves in both cropping seasons (data not shown). A linear increase of $\delta^{13}C$ values in rice grains (Figure 4-4) and leaves (data not shown) were found with increasing distance from the irrigation channel for both cascades in the first season for the non-fertilized and fertilized strips. The increase of the $\delta^{13}C$ values was more pronounced for the non-fertilized fields of the cascades. For the second season, Cascade 1 showed also a linear, but less pronounced, trend of the $\delta^{13}C$ values of rice grains and leaves as in the first season (i.e. a linear increase of $\delta^{13}C$). However, no relationship between distance and ^{13}C discrimination was observed in the second season for Cascade 2.

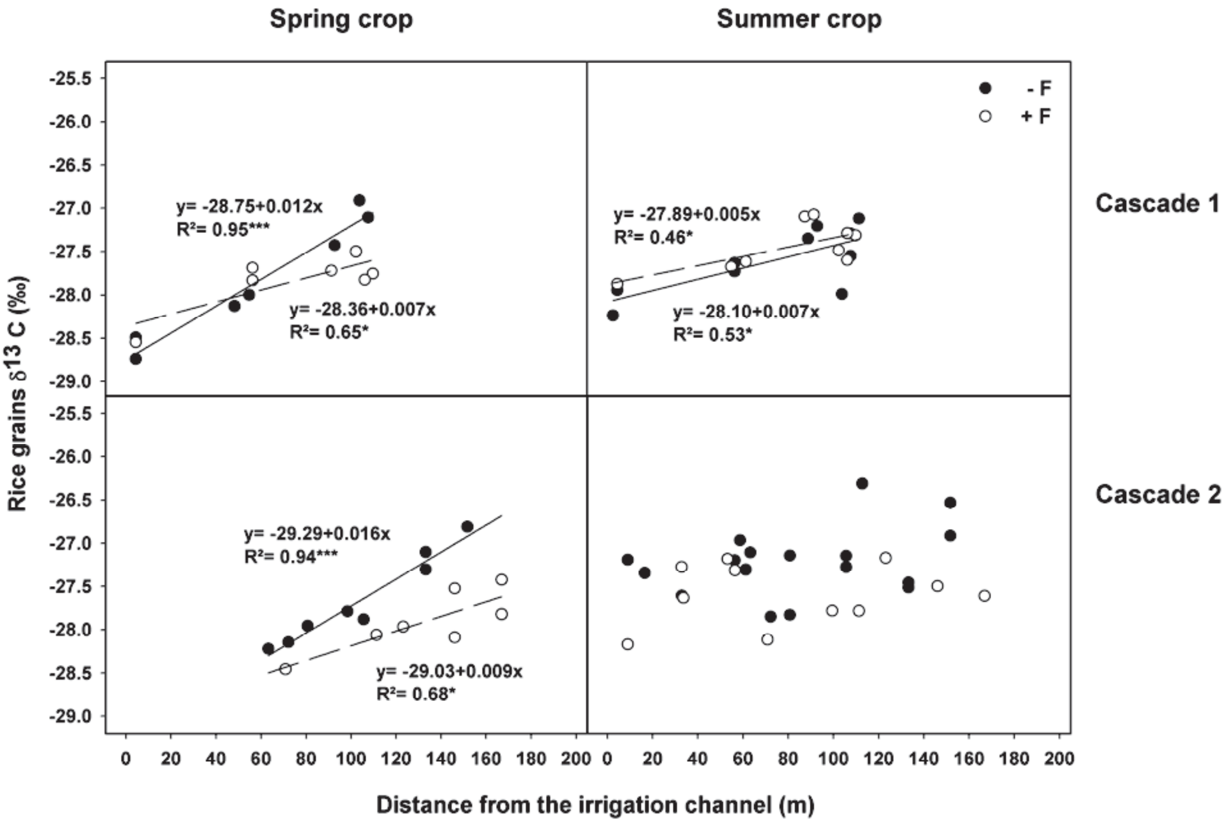

Figure 4-4: $\delta^{13}C$ (‰) of rice grains at harvest according to the distance from the irrigation channel (Distance, m) for both cascades in season 1 (spring crop, left) and 2 (summer crop, right) for the non-fertilized (-F) and fertilized (+F) fields. The first 60 m of Cascade 2 represent the rainfed rice paddies. Triple asterisk, double asterisk and single asterisk indicate significance $p \leq 0.001$, <0.01 and <0.05, respectively.

4.5.5 N use efficiencies and $\delta^{15}N$ signals in rice and soil

The total N content in the harvested grains was significantly increased by the fertilizer addition but was not affected by cropping season, planting density, cascade or distance along the cascade (Table 4-5). However, besides the fertilizer application, the cropping season significantly influenced the internal N use efficiency (i.e. higher in spring crop compared to summer crop) (Table 4-5). The recovery efficiency (RE_N) was significantly different between cascades and was not significantly depending on field position within the cascade due to a strong variation over the cascade. The highest RE_N was found at the end of both cascades in the first season and Cascade 2 in the second season (Table 4-5). Overall, fields with higher RE_N also showed higher agronomic N use efficiency. Despite the lack of a systematic spatial trend of the estimated N use and recovery efficiency for both seasons, the $\delta^{15}N$ values of the harvested rice grains showed a clear and significant linear decrease in each fertilizer treatment with increasing distance from the irrigation channel for the two cascades with R^2 ranging from 0.69 to 0.35 (Figure 4-5). The $\delta^{15}N$ values of the grains in the +F fields exhibited a significant lower $\delta^{15}N$ value compared to those in the –F fields in all cascades in the spring (Cascade 1: χ^2= 6.3, p= 0.012; Cascade 2: χ^2= 9.1, p=0.003) and summer season (Cascade 1: χ^2= 4.2, p=0.041; Cascade 2: χ^2= 11, p=0.009) (Figure 4-5).

Furthermore, the slope of the linear regression was equal for both fertilizer treatments in Cascade 1 whereas in Cascade 2 the -F fields showed a slightly stronger decrease in slope compared to the +F treatment (Figure 4-5). A similar decrease of $\delta^{15}N$ values was observed in the top soil samples taken after harvest of the second season and represented in general the $\delta^{15}N$ trend found in the rice grains in the fertilized treatment (Figure 4-5). The ammonia content found in both cascades showed a linear decrease with increasing distance from the irrigation channel with values ranging from 71 to 20 mg kg^{-1} for Cascade 1 and 44 to 14 mg kg^{-1} for Cascade 2. For nitrate, a linear increase was found in Cascade 1 (0.1 to 44 mg kg^{-1}) whereas a low and slightly opposite trend was observed for Cascade 2 (0.1 to 2 mg kg^{-1}) at the end of the first cropping cycle. The isotopic ratio of ^{15}N in the topsoil within the two seasons was for each cascade negatively correlated with the total N content of the soil samples measured after harvest (Cascade 1: *r*= -0.76, p<0.05 and Cascade 2: *r*= -0.94, p<0.01) but no significant correlation was found with the available N (data not shown). Finally, for the non-fertilized strip a strong, negative correlation was found between $\delta^{15}N$ and $\delta^{13}C$ in the rice grains of Cascade 1 (*r*= -0.82, p<0.05) and of Cascade 2 (*r*= -0.93, p<0.001). However, this correlation was not observed for the fertilized strips (Cascade 1: *r*= -0.20, p=0.747; Cascade 2: *r*= 0.25, p=0.589).

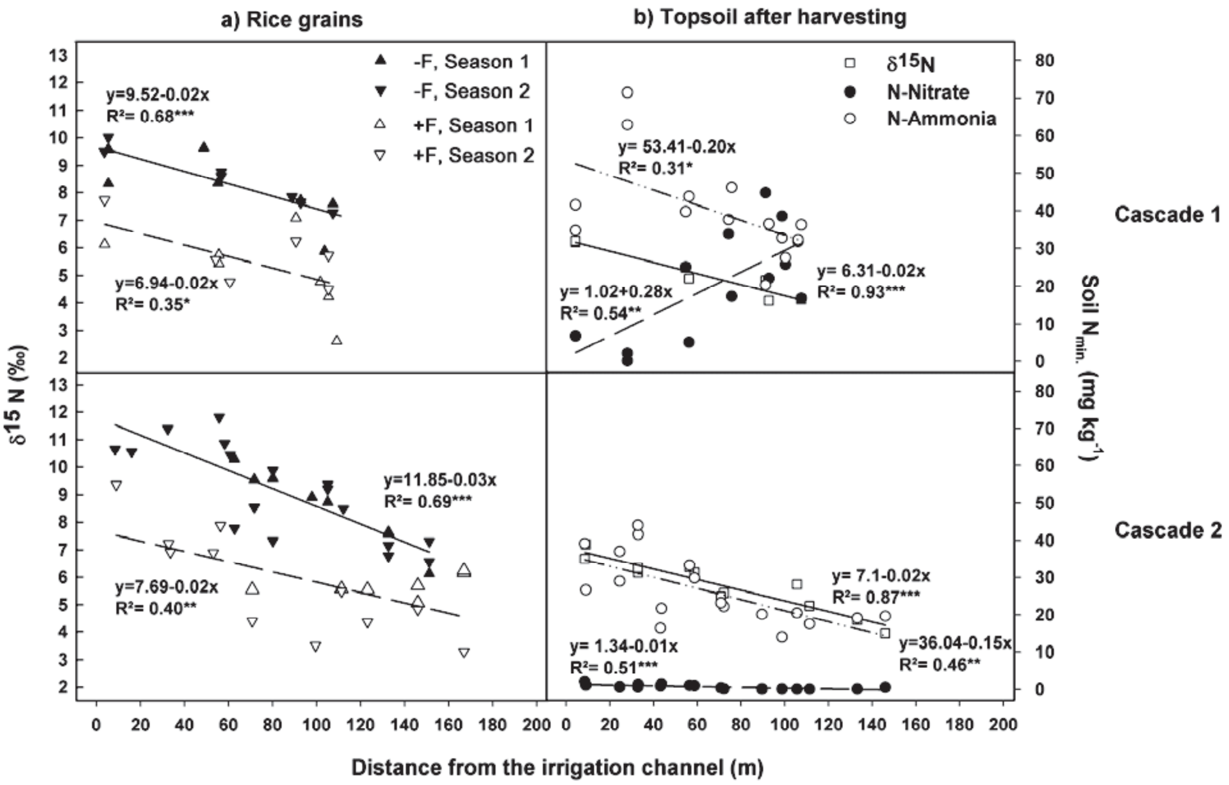

Figure 4-5: a) $\delta^{15}N$ (‰) of rice grains at harvest according to the distance from the irrigation channel (Distance, m) for both cascades in season 1 and 2 for the non-fertilized (-F) and fertilized fields (+F) and b) total soil $\delta^{15}N$ (‰) , N-ammonia and N-nitrate of the topsoil taken after harvest for Cascade 1 and 2. The first 60 m of Cascade 2 represent the rainfed rice paddies. Triple asterisk, double asterisk and single asterisk indicate significance at p ≤ 0.001, <0.01 and <0.05, respectively.

4.6 Discussion

4.6.1 Sediment induced spatial variability in crop performance depending on sediment origin

The observed average grain yields for the fertilized strips in both seasons (6.8 Mg ha^{-1}) were of similar magnitude as those reported by Duang et al. (2008) who cited an average yield of 5.6 Mg ha^{-1} in Chieng Khoi in 2007 but were higher than the average yields of 4.9 Mg ha^{-1} reported by FAO for North Vietnam (FAO Stat, 2009).

Table 4-5: Effect of season, cascade, distance, fertilizer treatment and planting density on N use efficiencies of rice grains.

Season	Cascade	Distance [a] (m)	Planting density (hill m^{-2})	Ngrain (-F) [b] ($x10^{-4}$ kg m^{-2})	Ngrain (+F) [b] ($x10^{-4}$ kg m^{-2})	IE_N (-F) [c] (kg kg^{-1})	IE_N (+F) [c] (kg kg^{-1})	AE_N [c] (kg kg^{-1})	RE_N [c] (%)
Spring	1	4	74	40	59	63	64	7	10
		58	79	76	73	54	48	1	9
		89	68	48	56	58	58	4	7
		106	70	33	67	63	44	4	18
	2	72	79	34	57	73	62	20	37
		102	68	27	60	68	57	12	25
		139	74	31	130	57	57	37	65
Summer	1	4	76	46	58	52	52	3	6
		58	82	57	106	45	36	8	36
		89	72	50	45	58	46	*-1*	8
		106	90	49	41	45	30	*-5*	8
	2	13	78	122	103	35	30	*-10*	*-13*
		33	72	58	111	68	41	11	53
		59	95	55	69	49	36	5	34
		72	81	54	78	52	42	7	27
		102	86	58	84	60	50	3	14
		139	83	64	133	56	41	11	46

Parameters	Ngrain [d] (Pr>F)	IE_N (Pr>F)	AE_N (Pr>F)	RE_N [d] (Pr>F)
Season	0.135	0.004	n.s.	n.s.
Cascade	0.136	0.18	n.s.	0.007
Distance	n.s.	n.s.	n.s.	n.s.
Fertilizer treatment	0.002	0.001	-	-
Planting density	n.s.	n.s.	n.s.	n.s.

[a] Distance: distance from the irrigation channel (m)

[b] Ngrain (-F) and (+F): nitrogen content in kg per m² of harvested grain,

[c] IE_N (-F) and (+F): internal nitrogen efficiency = (grain yield/ total N uptake) x 100,

AE_N: agronomic nitrogen efficiency = ((grain yield$_{+F}$ -grain yield$_{-F}$)/($N_{applied}$)) x 100; RE_N: recovery nitrogen efficiency of rice plant = ((N uptake$_{+F}$ –N uptake$_{-F}$)/($N_{applied}$)) x 100;

[d] results for Ngrain were log transformed while for RE_N the square root of was taken for the analysis

The spatial variation in grain yield observed in each cascade showed a clear, although different, dependence on the distance from the irrigation channel within each season (Figure 4-3). In Cascade 2, the increase of grain yield along the cascade with increasing distance from the irrigation channel resembled the soil fertility pattern observed in the topsoil (i.e. an increase of SOC and decrease of sand content, (Chapter 3). A similar spatial variability of grain yield has been reported by Homma et al. (2003), Rüth and Lennartz (2008) and Haefele and Konboon (2009) who observed increasing grain yields due to deposition of nutrient rich fine sediments at the end of a toposequence. In Cascade 2, for the wetter second season (summer crop), the SOC content and sand fraction significantly affected the obtained rice yields (Table 4-4, model 1), with higher yields at lower situated rice fields containing a higher SOC and lower sand content. The positive effect of the incorporation of SOC enriched sediments in lowland rice paddy fields on grain yield was also pointed out by Mochizuki et al. (2006). In irrigated rice fields, irrigation water from surface water reservoirs has been identified as, depending on its origin, a considerable source of additional particulate N and organic C to be transported into irrigated fields (King et al., 2009). Similar observations were made for furrow irrigated systems, in which transported sediments accounted for up to two-thirds of the total C increase (Poch et al., 2006).

Besides irrigation water, runoff from the surrounding steep slopes could be identified as an additional pathway of sediment delivery into the paddy fields of our study site influencing strongly the SOC content and textural changes of the paddy soil (Chapter 3). The one-crop (upper) paddies in Cascade 2 received sediments during the rainy season which were low in SOC and total N and high in sand content through runoff from the surrounding uplands. Therefore, the topsoil was significantly lower in SOC content and higher in sand fraction, as compared to the lower lying paddy fields which were irrigated with the water from the channel. Grain yields in those one-crop (upper) paddies were surprisingly significantly higher compared to the yield of the two-crop paddies of the same cascade. Therefore grain yields over the entire cascade were found to be negatively correlated with SOC content and positively correlated with the sand fraction. As the upper paddies of Cascade 2 were only cultivated once a year during the summer crop, it is suggested that the effect of sediment deposition, even being of less quality (lower SOC and total N content), on rice yields were positive due to the accumulation of available nutrients, such as available N in the spring fallow phase which was supported by the higher ammonia concentration found in these one crop paddies.

A third and final sediment deposition pathway in our study site was flooding by the river adjacent to the lowest situated paddy fields of Cascade 1 delivering sand enriched sediments (Chapter 3). The grain yields along Cascade 1 showed in both seasons a similar trend of grain yield to soil fertility parameters with an increase towards a distance of 56 to 100 m from the irrigation channel and a decrease thereafter. Therefore, besides the conveyance of sediments through irrigation water (descending position of the cascade) there is flooding through the river which delivers additional sediments in the opposite direction (ascending position) of the cascade. These two sediment deposition pathways enriched the paddy fields situated in the middle of the cascade, resulting in a non-linear addition of SOC content along the cascade. Grain yields along Cascade 1 were indeed not only depending on the sand fraction and the SOC content but also on the interaction between the soil parameters and the distance along the cascade.

In addition, the observed alteration in SOC content (ΔSOC) within the topsoil by sediment deposition along the cascades over both seasons (Chapter 3) could not be related with the obtained grain yield. This lack of relationship can be explained by the fact that fresh deposited sediments and its accompanied nutrients are not all necessarily available within the cropping season that they are deposited but organic bound nutrients will be released by decomposition in the following cropping seasons. Additionally, the nutrients available in the whole root zone play an important role on crop performance. Nevertheless, sediment induced soil spatial variation and grain yield could be related in the study sites, although this link could not be generalized for both seasons pointing to other growth limiting factors (e.g. nitrogen or water limitation due to insufficient irrigation or rainfall) influencing grain yield.

4.6.2 Water and N availability overshadowing sediment-induced spatial variability of rice yield

Our data, such as those from other authors, point to the complexity of correlating soil fertility parameters with observed crop productivity due to the presence of additional growth limiting factors (e.g. water or nitrogen availability), distinct from inherent soil fertility (e.g SOC) (Mallarino et al., 1999; Boling et al., 2008; Rüth and Lennartz, 2008; Ye et al., 2008; Haefele and Konboon, 2009). Tsubo et al. (2006) combined the variation in soil fertility with differences in water availability which improved the linkage to rice productivity, as it did in our case.

In order to assess ex post water availability in our study sites, in particular during the first drier cropping season, and determine how it could have influenced the sediment-induced variation in crop performance, ^{13}C discrimination in harvested plant samples was assessed. The observed increase in $\delta^{13}C$ values in the +F rice grains and leaves harvested at the end of the drier spring cropping season with increasing distance from the irrigation channel indicated clearly reduced water availability in the lower lying paddies as N was not a limiting factor in the +F strips. This was due to the limited water availability in the reservoir at the beginning of the rainy season, leading to insufficient water supply to lower lying paddy fields. During the wetter second season the one-crop and two-crop paddies of Cascade 2, on the contrary, showed no distinct spatial pattern of $\delta^{13}C$ values along the cascade with increasing distance from the irrigation channel, suggesting that sufficient water was available over the cascade and hence water availability did not influence the sediment-induced spatial variation in crop performance. Also for cascade 1, for the summer season, the less strong relationship between the $\delta^{13}C$ values and slope position confirmed this. As N limitation plays an additional role in ^{13}C discrimination (Yin and Raven, 1998), this has to be taken into account in the -F strips. An increase of plant available N can result in an increase (less negative) of $\delta^{13}C$ values in C_3 plants (Yin and Raven, 1998; Clay et al., 2001b) and thus suggesting higher plant available N in the lower paddies of the cascades which coincided with the observed increase in total N and SOC content in the lower situated fields of Cascade 2 (Chapter 3). An increase of $\delta^{13}C$ values was as well found at the end of Cascade 1 (100-120m) which could not be explained by the associated soil fertility as the lower situated fields tended to have a rather non-linear trend with a decrease of SOC and total N after 100 m. This indicated that the increase in $\delta^{13}C$ values at the end of Cascade 1 was solely due to reduced water availability as no diseases or salinity occurred in those fields. The accumulation of nitrate found at the end of this cascade also confirmed this, as nitrification increases with enhanced alternation of wetting-drying cycles which coincides with the observed less negative $\delta^{13}C$ values. Based on the delta $\delta^{13}C$ values, it can be concluded that the observed systematic spatial variation in water availability can mask the sediment-induced variability in rice crop performance in the studied cascades, in particular in the drier cropping season. This confirms the results found in the analysis of the correlation between soil fertility parameters and crop performance for the first season, which showed lower correlation coefficients for Cascade 2 as compared to the second wetter season.

The question remains why there was a clearer and stronger spatial pattern in crop yield in Cascade 2 in the first drier season as compared to crop yield in the same paddies for the second wetter season. Even crop yield was higher in the lower part in this cascade in the spring season compared to the summer season. For rice crops, N is a highly demanded nutrient (Shibu et al., 2006). In the fertilized strips the assumption was made that there was neither a N deficit (application of 213 kg ha^{-1} N) nor a deficit in P and K due to the recommended application of NPK fertilizer. Nevertheless, the measured N recovery efficiency was found to be low in most fields and higher RE_N values were mainly obtained at the end of the Cascade indicating higher fertilizer use efficiency in these lower situated paddy fields. Although, the highest RE_N values (37 – 65%, Table 4-5) found in our study resembled the values found by Zhao et al. (2009), the lower values were far below their obtained results. And more important, the highest N recovery was found in Cascade 2 in the first drier season. Based on these observations, it is suggested that the difference in N uptake along the cascade did not overshadow or reduce the effect of sediment-induced spatial variation in crop yield, but strengthened this spatial variation.

Examination of the $\delta^{15}N$ of grains in both seasons suggested a significant fertilizer N uptake across the cascades. There was a clear dilution of the $\delta^{15}N$ signal through fertilizer application as the overall averaged weighted signature of the fertilizer had a value of -0.49‰ $\delta^{15}N$ for both cascades in both seasons which indicated high N fertilizer uptake by the plant. A decrease in the isotopic ratio of $\delta^{15}N$ due to the uptake of inorganic fertilizer was also found by Nishida et al. (2007) for rice. However, as no significant impact of fertilizer application on grain yield was observed in the summer season, this indicates that other limiting factors such as light could have influenced overall rice productivity as $\delta^{15}N$ in rice grains showed no limiting effect of N, P and K were assumed to be applied in sufficiently high dosage and no deficiency symptoms of P and K occurred. The total amount of sun hours was found to be 883 and 562 for the spring and summer crop, respectively. As the summer season is additionally characterized by higher night temperatures, increasing respiration will lead to lower productivity as assimilates are used to sustain plant growth.

In Cascade 2, the difference in $\delta^{15}N$ enrichment in the grain between the fertilized and non-fertilized treatment decreased towards the end of the cascade (140 to 160 m), especially in the spring cropping season, indicating that nitrogen from the soil reserves is contributing relatively more in the lower part of the cascade to the N uptake of the crop as compared to the nitrogen derived from the fertilizer which is consistent with the higher SOC levels found in the lower situated fields. The same $\delta^{15}N$ signal in the grains, which followed the trend of the $\delta^{15}N$ signal observed in the topsoil, also further confirmed at the same time the influence of sediment-induced soil spatial variation on rice yields along the cascades. The decrease of the $\delta^{15}N$ signal found in the topsoil corresponded with the increasing soil fertility along the cascades (Chapter 3), which was attributed to the deposition of nutrient rich fine material, transported by irrigation water, with increasing distance from the irrigation channel. Runoff samples from plot measurements in the surrounding intensively cultivated uplands in our study area resulted in an estimated loss up to 67 kg ha^{-1} of organic carbon and 60 kg ha^{-1} total N depending on slope position and years of cultivation per rainy season. King et al. (2009) and Poch et al. (2006) reported that yearly 0.03 Mg ha^{-1} and 0.02 Mg ha^{-1} of organic C, respectively and 0.07 Mg ha^{-1} of total N are transported to sunflower fields in California which are irrigated by surface water. Besides N transformation as discussed above, external N inputs such as from sediment deposition can influence the $\delta^{15}N$ signal when the sediment source is lower enriched in $\delta^{15}N$ (Bernot et al., 2009). A lower ^{15}N signal in the topsoil of the lower paddies could be thus as well be a result of the deposited finer soil fractions having a lower enrichment in $\delta^{15}N$ together with the lower overall $\delta^{15}N$ signature of the upland soils (unpublished results).

In addition, the isotopic ^{15}N discrimination found in the rice grains and soil followed the same trend as the ammonium fraction of the soil mineral N found in the topsoil samples taken after harvest of the first season. Overall the rice grains were enriched in ^{15}N relatively to the soil which was associated with the discrimination process related to the increased ammonium production under anaerobic conditions (Yoneyama et al., 1991b; Handley and Raven, 1992). Ammonium uptake in rice favors ^{14}N enriched ammonium contributing to an increase of ^{15}N isotopic ratio of the topsoil (Yoneyama et al., 2001a). Also, due to anaerobic conditions, the nitrification process and linked nitrate production and isotopic discrimination were restricted. Billy et al. (2010) found an enrichment of $\delta^{15}N$ in soils with a longer period of saturation and therefore increased denitrification periods. The higher ammonium and enrichment of $\delta^{15}N$ found in the topsoil and in the rice grains, which was strongly correlated with the lower (more negative) $\delta^{13}C$ found in the rice grains, in the upper part of the non-fertilized cascades, indicated thus once more the increasing importance of wetting-drying cycles, and hence lower water availability, with increasing distance from the irrigation channel.

4.7 Conclusions

The present study indicated that spatial variation of rice production in the cascades could be linked to sediment induced soil fertility and textural changes in the topsoil. Although the impact of seasonal sediment deposition onto the topsoil could not be directly linked with the measured grain yields, the overall sediment-induced soil fertility trends in the topsoil along the cascades, due to the continuous process of sediment depositions and the long term cultivation of these paddy fields, showed clear effects on rice productivity. Depending on quality and quantity of the sediments and the deposition pathways, rice performance increased when finer nutrient-rich sediments were deposited. The linkage between soil fertility and crop productivity however, was not always straight forward demonstrating the complexity of combining soil fertility and crop performance when other drivers are unknown. Using ^{15}N and ^{13}C stable isotopes improved the understanding of the complexity of sediment deposition and its effect on crop productivity when other driving factors, such as changes in water availability occurred which masked the effect of inherent soil fertility on rice yields.

Climate change studies have pointed out that extreme rainfall events and typhoons will continue to occur more frequently in these regions, increasing the runoff on steep slopes and hence the probability of flooding events and associated large sediment inputs of low nutrient content. In tropical mountainous areas, the current rice production systems are not well adapted to these expected climatic changes as they depend strongly on irrigation infrastructure which is often very fragile, poorly managed, and silting up rapidly due to increasing erosion of the soil of the surrounding intensive cultivated uplands. However, until present, as this study showed, sediments play an important role in enhancing spatial variation of rice performance within tropical mountainous regions and providing nutrients to these ecosystems. The question remains how far sediment deposition in the long term, as its quality tends to decrease over time in erosion prone areas with degraded soils, will continue to help to balance the nutrient output from the rice paddy systems.

CHAPTER 5

WHY DO PEOPLE NOT LEARN FROM FLOOD DISASTERS? EVIDENCE FROM VIETNAM'S NORTHWESTERN MOUNTAINS

5 Why do people not learn from flood disasters? Evidence from Vietnam's northwestern mountains[4]

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5.1 Abstract

This article explores how the causes and impacts of a flood event as perceived by local people shape immediate responses and future mitigation efforts in mountainous northwest Vietnam. Local flood perception is contrasted with scientific perspectives to determine whether a singular flood event will trigger adjustments in mitigation strategies in an otherwise rarely flood-affected area. We present findings from interdisciplinary research drawing on both socio-economic and biophysical data. Evidence suggests that individual farmers' willingness to engage in flood mitigation is curbed by the common perception that flooding is caused by the interplay of a bundle of external factors, with climatic factors and water management failures being the most prominent ones. Most farmers did not link the severity of flooding to existing land use systems, thus underlining the lack of a sense of personal responsibility among farmers for flood mitigation measures. We conclude that local governments cannot depend on there being a sufficient degree of intrinsic motivation among farmers to make them implement soil conservation techniques to mitigate future flooding. Policy makers will need to design measures to raise farmers' awareness

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of the complex interplay between land use and hydrology and to enhance collective action in soil conservation by providing appropriate incentives and implementing coherent long-term strategies.

5.2 Keywords

Flood response; agro-environmental perception; attribution theory; mitigation strategies; interdisciplinary research; Vietnam.

5.3 Introduction

Flooding is the most common environmental hazard worldwide and appears to be occurring ever more frequently around the globe, intensifying in some areas and also spreading into new regions (Douben, 2006; IPCC (Intergovernmental Panel on Climate Change), 2007). The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) predicts that the number of people affected by flooding worldwide will continue to rise from 13 million currently to a staggering 94 million annually in the course of this century; almost 80% of those affected live in disaster-prone areas in South and Southeast Asia (ARDC, 2000; Cruz et al., 2007). Apart from the loss of human lives and increased health risks, the impact of flooding on people's economic livelihood has also been a major issue, especially in rural areas, where agriculture and aquaculture together make up a high proportion of household income (Few, 2003; Moench and Dixit, 2004). A series of recent studies, especially in the flood-prone countries of Asia, have focused on understanding how local communities cope with flooding and the increasing risk of flood hazards (Kundzewicz and Kaczmare, 2000; Few, 2003; Paripurno, 2006; Shaw, 2006; Eakin and Appendini, 2008; Tran et al., 2008). Many of these studies, point to a tendency to "live with the flood" rather than call for costly engineering solutions, as has often been done in the past (Blaikie, 1994; Mileti, 1999). However, the majority of cases concentrate on larger river basins and valley locations, while little scientific attention has been paid to mountainous regions.

Situated in the tropical monsoon zone close to the typhoon center of the Western Pacific, Vietnam is one of the most disaster-prone countries in the Mekong region. Floods are an almost annual event for people living in coastal and lowland regions and the central highlands of Vietnam. They occur much less frequently in the northwestern mountains of the country, where in autumn 2007 the typhoon “Lekima” confronted people and local institutions with a flood of extraordinary dimensions, the like of which they had never previously experienced. In this mountainous region, the degradation of natural resources associated with deforestation and the intensive cultivation of annual crops on hill slopes are widely regarded as major factors that exacerbate runoff (Dung et al., 2008). These factors, together with increasing demand for water in agriculture and the complex irrigation systems created to meet this demand, substantially alter the hydrological cycle. In the past, several long-term development projects conducted by foreign donor agencies (such as GTZ or Action Aid Vietnam) as well as a long-term research project exploring sustainable land use practices had promoted an array of soil conservation and sustainable land use techniques. The success of these efforts was limited, however, reflected in low adoption rates and the frequent discontinuation of such practices when subsidies or other incentives were phased out (SFDP (Social Forestry Development Project Song Da), 2001; Saint-Macary et al., 2010).

Drawing on a case study conducted in one flood-affected commune, we explore to what extent the causes and impacts of an unusual flood event as perceived by local people shape immediate responses and future mitigation efforts and what lessons can be derived from this for future sensitization strategies and policy making. More specifically, the article seeks to answer the following questions: How did people perceive the flooding, what causal relations did they observe, and how did they assess the flood’s impacts? How do these perspectives relate to a scientific analysis of the causes and effects of flooding? What lessons can be learnt for the future regarding mitigation and risk minimization? In order to find answers to these questions, we present findings from an interdisciplinary research team composed of agricultural and environmental scientists, development economists and rural sociologists.

The remainder of this paper is organized as follows: In section 5-2 we briefly describe the context in terms of the nature of floods and their influence on the agro-environment and the rural population. In section 5-3 we provide details of the research area and the flood event, followed by a description of the interdisciplinary methodology and conceptual framework in section 5-4. Section 5-5 discusses local stakeholders’ perceptions of the causes and impacts of the flood and contrasts them with scientific explanations. In section 5-6 we identify coping strategies and behavioral changes among local people aimed at addressing future flood events. We discuss our results in the light of other authors' findings in section 5-7 and conclude with policy recommendations and suggestions for further research needs in section 5-8.

5.4 Excess water, anthropogenic interference and attribution theory

Flooding is something of a catch-all term, referring to an array of events varying in magnitude and underlying causes. As a physical event, floods vary greatly depending on geography, onset, velocity and flow dynamics (Parker, 1999). Handmer et al. (1999) put together a typology of flooding comprising overflow of rivers produced by prolonged seasonal rainfall, rainstorms, snowmelt and dam-breaks, accumulation of rainwater in low-lying areas with high water tables or inadequate storm-drainage, and intrusion of seawater onto the land during cyclonic or tidal surges. Most broadly, a flood can be described as "too much water at a certain location within too short a time". Analogous to the perception of water as *too much*, otherwise irreplaceable water needed for household consumption and agriculture becomes excess water, endowing the word with the meaning "something to get rid of" (Blaikie, 1994).

Heavy rainfall is deemed the most common cause of floods. Magnitude, speed of onset and duration of the flood are – among other factors – influenced primarily by topography, river course and alteration, vegetation and soils. Different kinds of soil covera ge affect the permeability of ground surfaces and the water buffer capacity of the soil, and alter runoff rates significantly (Chaplot et al., 2005b; Dung et al., 2008; Pansak et al., 2008; Valentin et al., 2008). Anthropogenic interference is a major factor in altering hydrological characteristics. Land use changes, such as forest conversion into intensive types of agriculture, have been considered a primary factor in this respect (Bruijnzeel, 2004). In South and Southeast Asia, due to increased drought periods and the necessity of an increase in cropping seasons to nurture growing populations (Cruz et al., 2007), the area of irrigated agriculture is also steadily increasing. Local irrigation systems are often poorly maintained, which leads to an accumulation of sediment deposits and reduced water buffer capacity; this exerts an additional negative impact on the hydrological characteristics of a catchment.

More than any other environmental hazard, floods bring losses as well as benefits (Smith and Ward, 1998). Particularly in agriculture, flooding is by no means regarded as a hazard of solely negative consequences. Beneficial side effects – such as refilling reservoirs used for irrigation, leaching salts and toxins off the soil and nutrient deposition – are acknowledged in many influential studies (e.g. Zhang et al., 2003). It is crucial to recognize this two-faced nature of flood effects. The meaning of harm and benefit has a subjective component and thus varies between places and individuals (Hewitt, 1997). Few (2003) notes that the recognition of subjective and thus varying perceptions "helps explain why many residents of developing countries take an ambivalent attitude towards flood events, and partly underpins the logic of policies of 'living with floods' rather than attempting to prevent them through large-scale engineering interventions."

Another major cognitive factor determining how people deal with floods and what conclusions they draw for future flooding is what causes people attribute to it, and – conversely – what role people attribute to their own actions in terms of influencing the scope and dimension of the flood. This perspective is rooted in the attribution theory of motivation (Heider, 1958) (Weiner, 1974 ; Weiner, 1986; for some current applications see Vockell, 2001). The theory starts with the premise that people try to bring order into their lives by developing personal – sometimes also considered 'implicit' – theories about why things happen the way they do. One important aspect in this is whether the causes of a certain occurrence are perceived as something that can be influenced by oneself (by means of either one's abilities or certain efforts) or are only influenced by impersonal factors (depending on the context or situation, or simply good or bad luck) (Table 5-1).

Table 5-1: Attribution scheme with perceived scope of influence

	Internal	External
Fixed	Ability	Situation
Variable	Effort	Good luck/ bad luck

Modified after Weiner (1986).

From the attribution theory perspective, the way people perceive the causal relationships and impacts of a flood and explain them by attributing responsibility to themselves, to others, or simply to 'destiny', will make them conclude how influential their personal abilities and efforts might be in the future mitigation of similar events, thus influencing their behavioral responses (Baldassare and Katz, 1992). For example, people who believe their land use practices have a direct impact on the area’s hydrology are more likely to undertake direct action to prevent or mitigate such impacts. This impact of direct experience on learning and perception is well documented in the experimental psychology literature (Semper, 1990; Chawla, 1999). Fortner et al. (2000) hold that experience may also motivate people to seek further information in order to improve their understanding and inform their future responses.

Measures aimed at tackling the impacts of flooding can be divided into actions taken before, during and after the flood event. Actions before the event are commonly denoted *preventive*, actions during it are called *emergency interventions*, and actions after it may be called *reconstruction* or, more precisely, *adaptation* (Lebel et al., 2006). Seminal papers that have studied people’s coping strategies make a distinction between “structural” and “non-structural” responses to flood (e.g. Smith, 2004). The former generally refers to engineering interventions (e.g. river canal modifications and reservoirs designed to control the flow of rivers or dams to restrict the spread of flooding). The latter have gained greater prominence as structural measures have proven limited; they refer to measures designed not to prevent floods but to reduce their impacts (Smith, 2004). Some examples of non-structural responses are the declaration of polder areas with adapted land use, vegetation that increases soil infiltration, water governance closely geared towards local conditions, and improved insurance schemes, to name but a few. A range of studies report increased attention to non-structural flood reduction at the community and household level (for SE-Asia e.g. Hoang et al., 2007; Eakin and Appendini, 2008; Tran et al., 2008; López-Marrero and Yarnal, 2009).

5.5 Mountainous northwestern Vietnam in October 2007

The study was carried out in the commune of Chieng Khoi, Son La province, 20°37’0N, 106°4’60 E which is located on a mid-level plateau at an altitude of approximately 350 m a.s.l., between a steep mountain range and the valley of Yen Chau, where the district capital of the same name is located (Figure 5-1). The flat plateau is used exclusively for paddy rice (*Oryza sativa* L.) cultivation, mainly for farming families’ own consumption, while the peripheral upland fields on the steep hill slopes (up to 86% of the total area) are planted with various annual crops, with a major emphasis on maize (*Zea mays* L.) as a cash crop partly intercropped with cassava (*Manihot esculenta* Crantz). Fishponds for aquaculture play an important role in the availability of proteins for human consumption, with almost each household having at least one fishpond. With both its topography and current land use, the structure of the commune is typical of the wider area. Chieng Khoi is one of 13 communes in the district and comprises 6 villages with a total of 2885 people (Yen Chau People's Committee, 2006). The area is inhabited largely by people belonging to the Black Thai ethnic group, with settlements having a history of several hundred years.

The 800 ha watershed studied 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 to September (Figure 5-2). Taking into account the total rice crop area of 60 ha, the water required for an entire rice crop period in Chieng Khoi amounts to 1.0 10^6 m^3. Long term weather data recorded close to Chieng Khoi reveals that average precipitation during the spring and summer crop season is 360 mm and 650 mm respectively, thus accounting for only about 30% and 50% respectively of the amount of water needed.

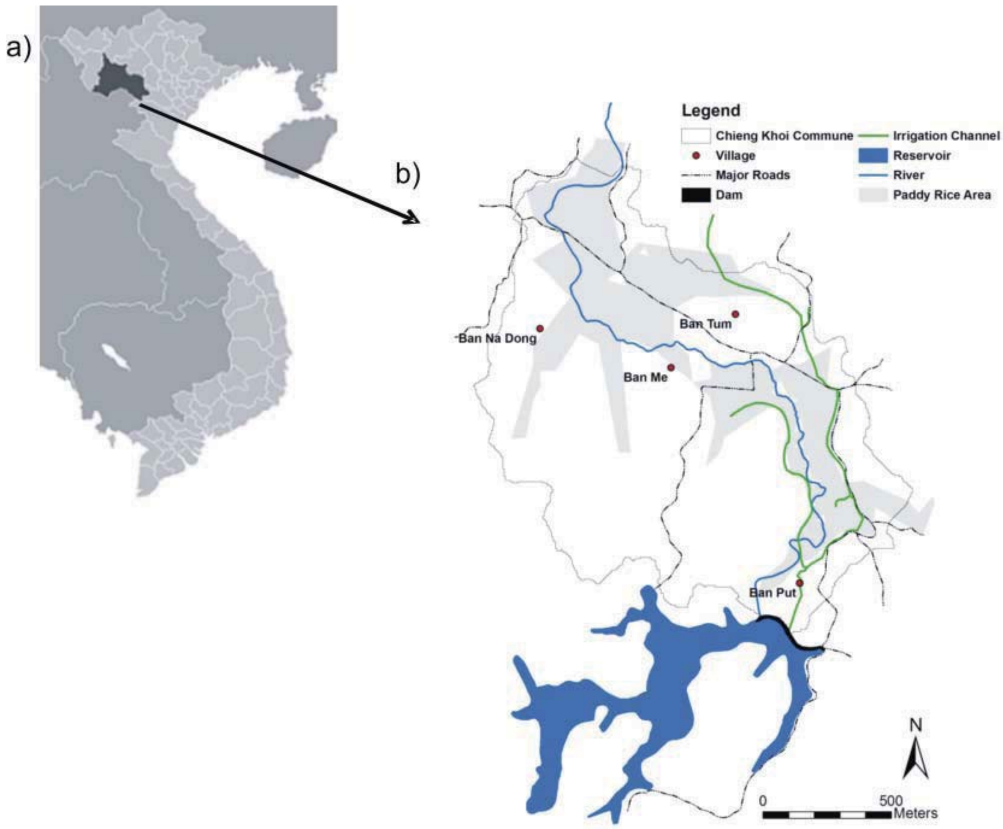

Figure 5-1: a) Location of Son La province in Northern Vietnam. b) Overview of the Chieng Khoi catchment.

In order to meet the high demand for water, a reservoir was built between 1962-68 by damming up a stream which originates from the nearby Karst mountains. The height of the main dam was increased at one point in the mid-1970s, with a later extension of two smaller dams that turned the original river into an artificial lake. This now endows Chieng Khoi relatively well with water resources for irrigation and pond water supply. Irrigation water from the lake supports two rice crops per year, with the first crop (mainly irrigated) grown from February to May ('spring crop') and another – mainly rain-fed – crop from July to October ('summer crop') (Figure 5-2). A spillover controls the water level and feeds the old river from the mid-rainy season onwards as an additional source of irrigation for paddy areas in the lower part of the catchment (see Figure 5-1 b, upper part). In normal years, the lake can buffer large amounts of water from the upper catchment and release or store it in a controlled way.

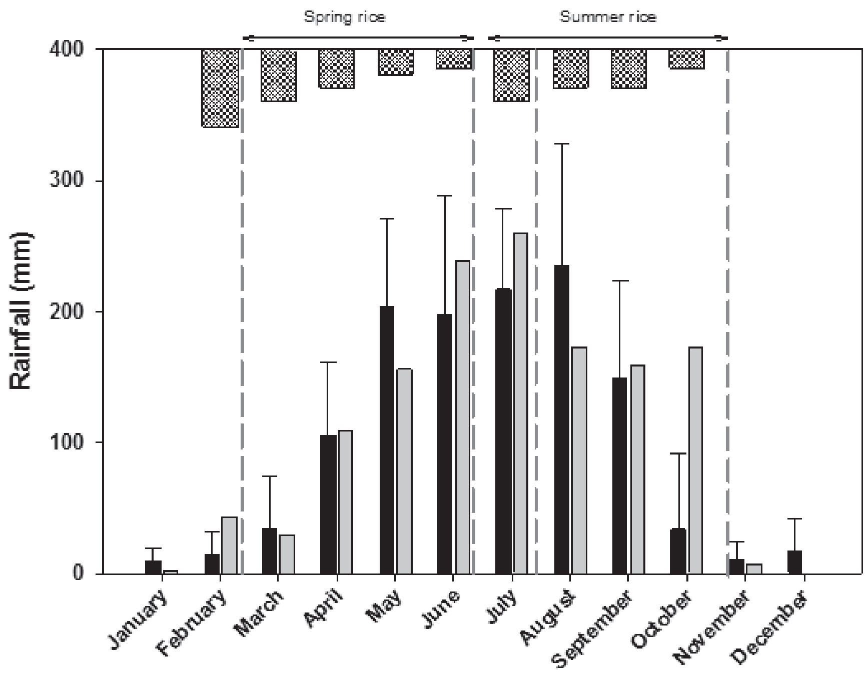

Figure 5-2: Comparison of the rainfall distribution for 2007 (dark gray bars) and average (1998-2007) rainfall (black bars) during the two rice crop seasons (spring and summer crop) in Yen Chau[5].

[5] Standard deviation of the rainfall from 1998-2007 is given by error bars. The cross hatched bars indicate the water requirement, where the height of the bars represents the high to low water requirement classes during rice cultivation

The degradation of natural resources through accelerated deforestation and intensive cultivation of annual crops often leaves hill slopes bare and unprotected in the winter season from late September to March, exacerbating surface runoff and underscoring the importance of the lake as a buffer for water storage and controlled release. This seasonal problem gained momentum in the course of the national reform policy *doi moi* ('renovation') which started in 1986, when land titles were allocated to households and deforestation activities on upland plots were intensified in order to create space for farmland (Sikor and Truong, 2002; Ward and Trimble, 2004).

A major flood hit Vietnam in October 2007, caused by typhoon Lekima, which triggered three days of intensive rainfall. While flooding is regarded as a more or less chronic disaster phenomenon in the two deltas of the Mekong and Red River and in the central part of the country, it rarely happens in the mountainous northwest of Vietnam, where rainfall triggered by Lekima caused the biggest flood within living memory. The attention of the international press and foreign relief work was focused on the central provinces of Ha Tinh and Quang Binh, where there was a human death toll of 71 and more than 70,000 residential houses were destroyed (Vietnam News, 2007); little attention was paid to the situation in the uplands in northwestern Vietnam. Apart from the unusual amount of rainfall and the intensity of the event, it was also its off-seasonal occurrence that surprised people (Figure 5-2). According to the damage report produced by Yen Chau district, Chieng Khoi commune was among the four most severely damaged communes (Yen Chau People's Committee, 2007).

5.6 Interdisciplinary approach to data collection and analysis

Investigating flooding poses a particular challenge in the mountainous regions of northern Vietnam, where complex ecological, economic and socio-cultural conditions determine and influence each other, as outlined in section 2 and depicted in Figure 5-3. Traditional disciplinary boundaries needed to be expanded and bridged in this respect. First, researchers from hydrology, crop and soil science, economics and rural sociology were involved in an interdisciplinary approach where interactions between disciplines ranged from jointly formulating hypotheses to harmonizing methodology and carrying out joint data analysis. Second, local farmers' perceptions and their intimate knowledge of the environment were brought into the picture and compared with the research findings. And third, interaction was actively sought with national research and policy implementation institutions, extension services and local authorities.

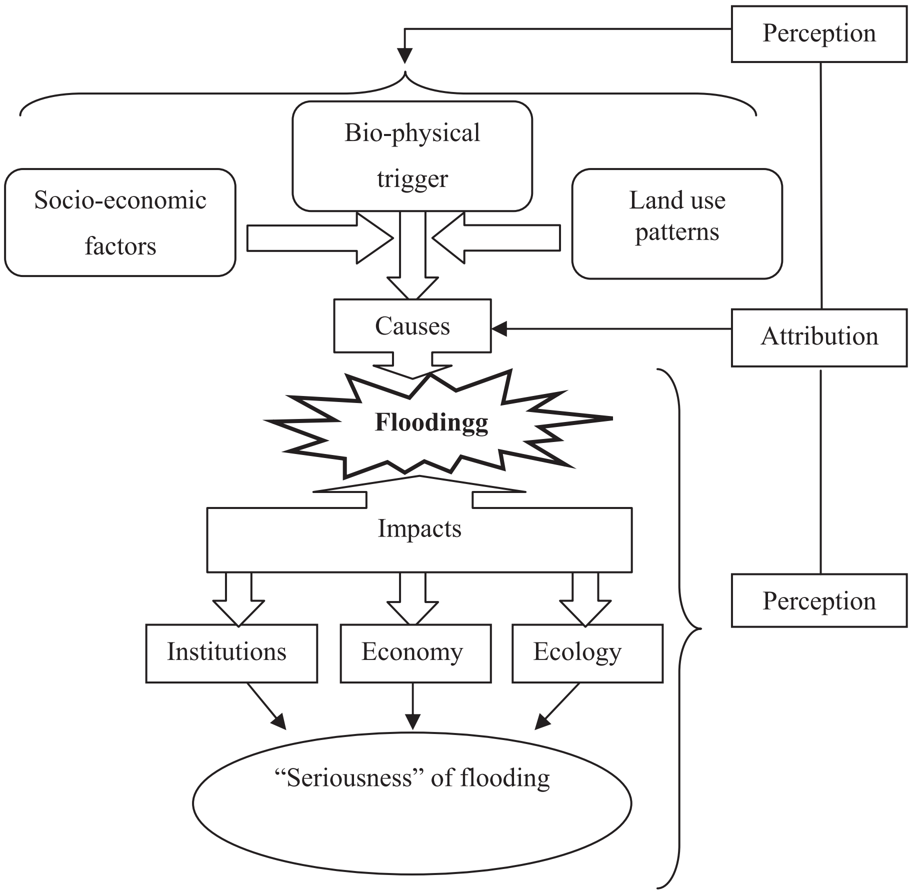

Figure 5-3: Biophysical, economic and social factors to be considered in studying causes and effects of flooding.

In June 2007, a weather station (Campbell Scientific, Inc., USA) was installed in the centre of the Chieng Khoi catchment. The weather station provides data on air temperature, relative humidity, solar radiation, wind speed, and precipitation. In direct proximity to the spillover of the reservoir, water heads are measured continuously in the natural stream by means of automatic pressure sensors (ecoTech, Bonn, Germany). The water heads are converted to flow rates using stage-discharge relationships determined by means of the velocity-area method (Herschy, 1995). Furthermore the effect of flooding on rice production was investigated by measuring soil fertility and rice performance on fields situated close to the river and compared with non-flooded fields. A more detailed overview of methods used can be found in Chapter 3.

The microeconomic consequences of the flood were assessed using a dataset constituted from a survey of 300 randomly selected households throughout Yen Chau district, and an additional sample of 36 households situated in Chieng Khoi. Households in Chieng Khoi were selected in order to allow a merging of data with the aforementioned crop science and soil science research and thereby increase up-scaling capacity. Selected households manage paddy fields that are located within two villages, Ban Put and Ban Me (Figure 5-1), where a substantial number of households' fields were affected by the flooding. Each of the 336 households was visited before and after the Lekima rainfall, and each time an adult household representative was interviewed using a structured questionnaire. The survey covered a wide range of topics, including a section on the flood's impact on agricultural production and local livelihoods.

For the qualitative part of the social research, respondents were selected by purposive sampling with the aim of representing the perspectives of the whole range of stakeholder groups at the household, village and commune level, i.e. flood-affected households, village and communal authorities, and administrative staff beyond the commune level. Data collection for this study comprised two stages: The first involved a series of qualitative research methods, such as semi-structured interviews (16 in total) and focus group discussions (5 in total), supported by ranking exercises and risk mapping in order to examine modes of governance of excess water as well as perceived causes, preventive measures, impacts and responses to the flood at household and community levels. In the second stage of the research, a local assistant speaking the local dialect asked another 10 members of flood-damaged households and 2 key representatives of the village management board to write narrative essays on any aspect of the flood they regarded as important. This information was cross-checked with that obtained in the interviews, to see if any important aspects had been left out in the first stage of research. All events were recorded, translated into English and transcribed, followed by qualitative data analysis supported by the use of MAXQDA software.

5.7 Flood perceptions and governance: Local perspectives and scientific findings

5.7.1 Institutions of water management and flood handling

The communal water governance system of the Thai people – known locally as *muang-fai* – in Chieng Khoi has developed over centuries and represents a technologically and socially sophisticated setup[6]. The social organization of the management of the *muang-fai* system gradually came to rely on officials, such as the *Liep (Nam) Na*, as managers of the systems on behalf of the ruler. The duties of water managers in the traditional Black Thai society included coordination of the construction of weirs and canals and their maintenance, which was required after each rainy season. While disaster prevention and risk mitigation were not explicitly assigned to any of the legal bodies, responses to any damage caused by floods were coordinated by the *Liep Na*, who was authorized to solicit sufficient labor from each household.

Since the agricultural collectivization in the 1970s when new economic and administrative units were formed, the traditional institutions of water governance have undergone major changes (Neef et al., 2006). Old institutions and organizational bodies such as the *Liep Na* were either abandoned or integrated into the new management boards on different administrative levels, the so-called *Ban Quan Ly*. After the de-collectivization process in the mid-1980s, villages emerged as the smallest administrative units, with the village management board – consisting of the village headman, the treasurer and the accountant – as the decision-making and executive institution responsible for all social, political and agro-economic issues. Despite maintaining the strict top-down hierarchy, in which the local authorities are obliged to follow recommendations made at higher levels, the management of water systems remained relatively autonomous (Neef et al., 2006), with the village headman setting priorities in water system maintenance activities and serving as head of the respective *Ban Phong Chong Lut Bao*, translated literally as "disaster committee" (Figure 5-4).

The completion of the Chieng Khoi dam in 1975 and the laying out of the reservoir accelerated the formation of more pluralistic water governance structures. The Provincial Department for Irrigation created the position of 'lake manager' under its direct supervision. Together with his two co-workers, the lake manager represents the provincial level in communal water affairs, bringing in an additional layer of hierarchy, as Figure 5-4 illustrates. The lake management team consists of residents of places other than Chieng Khoi, with less developed contacts within the local communities, thus estranging the locals further from their traditional involvement in water management.

[6] The *muang-fai* system, common among most Thai/Tay groups in the northern uplands of Vietnam, Thailand and Laos PDR, is used on fast flowing streams, across which weirs (*fai*) are built. The *fai* holds back water and directs it into major and minor canals (*muang*) in which gates control flow rates. The way *fai* are built allows water to pass through and over the barrier while restricting the rate of flow sufficiently to raise the water level.

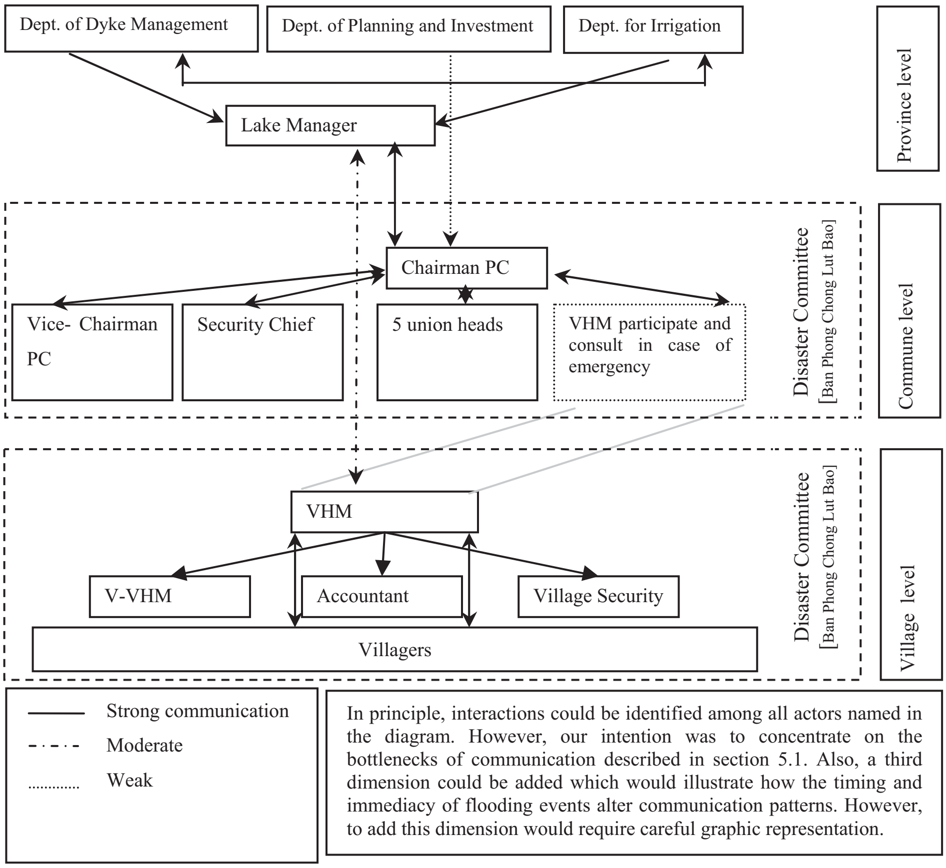

Figure 5-4: Water governance and institutions involved in coping with the flood.

The major duties of the lake manager are to follow the weather forecast and adjust water management accordingly, to measure the water level on a daily basis, to regulate the water outflow of the lake, and to maintain and repair lake- infrastructure, particularly the dam. A contract between the user villages in Chieng Khoi and the provincial department for irrigation determines moderate fees for irrigation water[7]. 40% of this money is given to the lake management team as remuneration and 60% is used to maintain the communal *muang-fai* system. However, the decision on how much water is fed through the canals and allocated to farmers is the decision of the commune chairman. The right to request larger allocations or suggest a different timing allows villagers to participate to some degree in water management decisions.

[7] Fees for spring crop irrigation are higher because the irrigation period falls in the dry season when water levels in the lake are very low (Information from early 2008).

One major institutional innovation has been the establishment of a department of dyke management, flood and storm control at the national level, with provincial branches and disaster management units. Its primary duties include the annual stipulation and implementation of disaster mitigation plans down to communal level. Although these plans do not go beyond allocating responsibilities in case of hail or flash flooding (besides pointing out a few places where people can shelter), this appears to indicate a growing concern about disasters and also formalizes the terms of reference for all members of the *Ban Phong Chong Lut Bao*. Along with the new department, a disaster relief fund system was implemented in 2001. Its objective is to provide quick loans for reconstruction, both to communities as well as to individuals (Lebel et al., 2006). Each citizen has to contribute an annually variable but relatively low fee on a mandatory basis.

5.7.2 Hydrological explanation for the flood of 2007

The usual seasonal fluctuation of the reservoir level is determined mainly by the annual precipitation pattern. Typical water level patterns for the reservoir are depicted in Figure 5-5. In general, the reservoir level declines continuously throughout the dry season, reaching its annual minimum of about 4 m in May. With the onset of the rainy season in June incipient rain events yield to a rapid refilling of the reservoir within a few weeks. Throughout the rainy season the water level of the reservoir remains fairly constant at around 11 m. Runoff from the reservoir to the receiving stream is triggered once the reservoir water level exceeds about 11.9 m, which is the critical level at which unregulated outflow is initiated by means of spillover. However, 2006 was an extraordinarily dry year so that the reservoir did not refill until the end of July, and so the lake manager piled up sandbags at the spillover "in order to store additional water for the dry season because I [the lake manager] recognized that water levels have steadily decreased over the past years" (interview with the lake manager). This was done in consultation with both higher (Department of Dyke Management) and lower (Communal PC) institutions in the hierarchy, although the final decision to dam up the excess water was taken by the lake manager under consultation of his co-workers. Older members of the communal PC who had witnessed the flood of 1975 reminded their younger peers of the collapse of a minor dam at that time, which was provoked by allowing the lake to rise to water levels never experienced before.

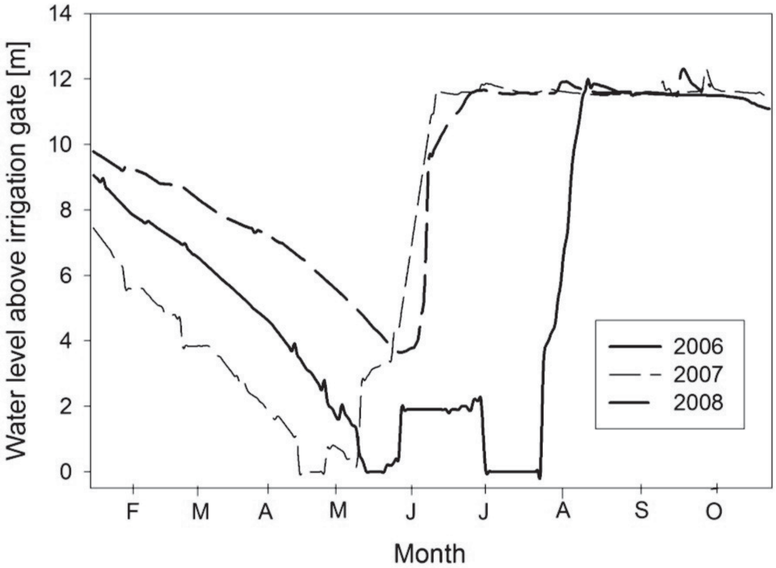

Figure 5-5: Water levels of Chieng Khoi reservoir measured for the years 2006, 2007 and 2008.

In early October 2007 a series of meteorological events created unprecedented and unforeseen flooding along the Chieng Khoi catchment. At this time, extremely high water levels were experienced on the stream between October 5 and 7 due to widespread and intensive rainfall. This intensive rain event came on the back of a previous deluge that had occurred one week earlier and had already generated saturated ground conditions. These back-to-back deluges meant that sloped soils were unable to cope with the copious amounts of water entering the catchment, leading to tremendous surface runoffs to the reservoir. The flash flood event was triggered by intensive rainfall starting on October 4 and lasting about 36 hours (Figure 5-6). During this 36-hour period, the catchment received a total rainfall amount of 165.8 mm[8]. On October 5 the rainfall pattern peaked between 1 p.m. and 3 p.m., owing to an extremely high precipitation rate of nearly 20 mm h^{-1}. Prior to this rain event the reservoir was already filled to a level of 11.5 m, that is, only 0.4 meter below the critical control level. As a consequence of the intensive rainfall pattern the water level of the reservoir rose at the rapid rate of 2.5 cm h^{-1}, accounting for an additional incoming volume of about 6500 m^3 h^{-1}. About 24 hours after the onset of the rain event the reservoir water exceeded the critical level of 11.9 m, initiating overflow of the spillover (October 4, 11 p.m.). This initial push of water entailed a pronounced

[8] It is worth noting that this amount of rainfall is equivalent to five times the average monthly rainfall in October.

swelling of the stream, which peaked on October 5 at about 11 a.m. Within a period of 24 hours the stream discharge rose sharply from less than 0.5 m^3 s^{-1} to a maximum of 45 m^3 s^{-1}, causing one of the biggest flood events within living history.

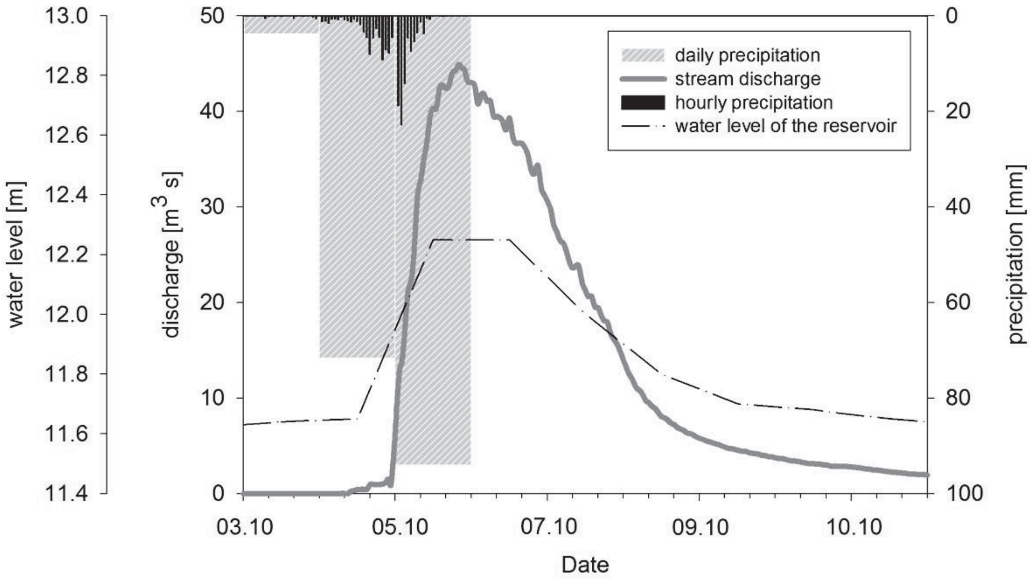

Figure 5-6: Daily and hourly precipitation, water level of the reservoir, and stream discharge recorded in Chieng Khoi catchment during typhoon Lekima.

5.7.3 What triggered the event from the local people's point of view?

For ordinary people in Chieng Khoi, the flooding meant that water from the river and irrigation canals inundated rice fields and fishponds and eventually damaged residential areas, as well as flushing high quantities of sediments into the fields. The flood was triggered by what people described as "bad rain", given its duration, intensity and amount. A further criterion was its timing: At the end of the rainy season, the lake is usually filled up and there is little space left to buffer additional water, which in turn would require the lake manager to release water through the spillover gate, controlling the amount depending on the intensity of the rain. The more water the soil can absorb, the more rain is desired. Absorption capacity is observed to have decreased over the past few years, a fact that locals attribute to intensifying deforestation, which started in 1986. Farmers have largely understood this causal relationship, and one of them expressed it in his essay as follows: "When it rains a little and soil moisture increases, it is good for the crop. But if it rains too heavily, top soil from the upland fields will be washed away because there are now fewer forests and perennials than in the past, so the water-holding capacity of the soils in upland fields has been reduced. For this reason, top soil will be easily washed away when there is heavy rain and it will harm agricultural development. So what was 'good rain' in the past might be considered 'bad rain' today".

The flooding took people by surprise, although all interview partners who own a TV stated they had heard about the irregularly high rainfall in the weather forecast at least one day in advance. Most interviews in the study area confirmed that people underestimated the warnings because "the weather is so diversified in the northern mountains of Vietnam, and the forecast is never really precise. Also, in October we do not get rain, and if it does happen, it is usually only a little" (a farmer). Nevertheless, the flooding was attributed by the locals to general weather changes causing irregularities in rainfall amounts which are acknowledged to have gained speed over the past ten years. All commune level representatives interviewed stated that heavy rain later than September would almost automatically have disastrous impacts on people's livelihoods, if abundant precipitation occurs within a short time only: the lake is usually full by then and excess water cannot be drained off in a controlled way.

However, the majority of farmers interviewed attributed partial responsibility for the flood to mismanagement on the part of the lake manager. The accusations were even stronger in the narrative essays, which are particularly worth mentioning in the Vietnamese context, given that written opinions are more likely to be regarded as "sensitive" than in non-socialist South-East Asian countries (Scott et al., 2006). Farmers blamed the lake manager for not having followed the weather forecast, as well as not having taking seriously recommendations from the Department of Dyke Management to preventively increase the buffer capacity of the lake by discharging water through the gate well before the rain. All village headmen in Chieng Khoi agreed with this view, when the interviewer confronted them with their fellow villagers' opinion. A lack of experience owing to his young age was thought to have determined the lake manager's perceived failure in preventing the flood.

The lake manager, by contrast, identified the meandering of the river – which is mainly caused by the construction of fishponds and which he believed narrowed the stream artificially – as the main reason why draining unusually high amounts of water accelerated the flooding. Hence the examples of lake management in two neighboring communes revealed that in both cases the lake managers decided to dam up the water and that not unloading the sandbags helped to prevent major damages. Although this is an effective and commonly practiced tool for storing additional water, past experiences like the dam breaks in the Red River Delta following the major flooding in 1975 have proved the risks of this measure (CCFSC (Central Committee for Flood and Storm Control), 2006). The reduced capacity of the lake due to sediment accumulation is considered another important factor in the inability to buffer flash floods, something recognized only by the lake manager and a few individual communal officials. Following the initiative of the former, a meeting was held with communal officials and the village headmen in early March 2008 on “the future of the lake”. Together with his assistants, the lake manager proposed to restrict cultivation of annual crops around the lake and suggested planting “economically attractive tree crops such as rubber trees” as one promising option to prevent erosion and induced sedimentation into the lake and maintain economic benefits at the same time. In addition, he proposed to use the dry winter season to dig out sediments from the lake in order to increase water buffer capacity for the next season.

However, this proposal appears to be in sharp contrast with his fatalistic stance towards flood mitigation: “Every year, the commune announces a plan to prevent flooding [the “disaster mitigation plan”, as introduced under 5.1] but when it really comes to a strong rain, you can forget about the plan and we cannot do anything.” He further predicted that, as a consequence, the intervals between flood events will be reduced and economic damages will increase because of further population growth and a lack of economic alternatives to intensive upland fields use.

5.7.4 Facts and perceptions of agro-environmental impacts

As bio-physical research has shown, the flooding had both short and long-term impacts on the agro-environment. During the flooding, several fishpond dykes broke, and the water level of the river rose beyond the neighboring ponds, causing significant losses of fish. Furthermore, the rice yields of the flooded fields were 5% lower compared to the yields obtained in the same fields during the first cropping season earlier that year when no flooding occurred. In addition to these direct effects of flooding on rice cultivation, soil fertility parameters were altered, which can affect rice cultivation adversely on the long run. Total nitrogen and soil organic carbon were decreased by 40% and 24% respectively after the flooding occurred. Alongside the decrease in soil fertility, the deposited sediments found on the flooded fields were dominated by sand.

Increasing the sand fraction by 41% alters infiltration on these fields and has impacts on water use efficiency regarding irrigation practices during rice cultivation. However, when soil fertility is reduced drastically by infertile sedimentation, fertilizer application in succeeding rice crop seasons needs to be increased in order to meet the rice requirements of the households.

All respondents unanimously regarded the loss of fish after pond inundation, the damage to rice plants in paddies close to the river and to irrigation canals, and infrastructure damage as severe. Yet whether sedimentation – mentioned as the most important impact of flooding during several ranking exercises in group discussions – was beneficial or harmful was a matter of lively debate among the interviewees. Paddy field owners agreed that a modest amount of sediments can have fertilizing effects on the paddies, with the fertility depending on the origin of the sediments. These beneficial effects outweigh potential threats of crop failure.

A majority of farmers noted in the essays that they had observed increasing nitrogen content in the sediments over the past years, although there were no precise answers to the question of how this was detected. This is generally regarded as an asset, although farmers complained that the high amounts of nitrogen "are responsible for high mortality of pond fish after sediment inflow", along with "suppressing oxygen in the water" (a group interview). The eutrophication process described by the farmers points to the nitrate-rich runoff water from the upland fields and the phosphorous attached to the sediments, which promotes algae growth and consumes the available oxygen in the water. Table 5-2 provides a summary of the various impacts discussed by the farmers. Controversy arose when farmers discussed the hydrological effects of soil conservation techniques such as the permanent re-greening of upland areas on the occurrence of flooding. Some believed that the amounts of excess water would decrease; reducing flood events, while others felt the only effect was the reduction of sediment transport and deposition. A similar perspective was presented by the deputy head of the communal People's Committee after he was asked whether the perennial greening of upland fields might alter the impacts of future heavy rainfall. While he stated that amounts of excess water would remain the same, he was sure "soil flooding" (as locals referred to sediment-loaded runoff water) would be reduced (which was also suggested by Pansak et al., 2008 as well as Dung et al., 2008). It was common sense that heavy rainfall causes loss of topsoil on sloping fields and transports sediments to lower parts of the catchment. While farmers referred to upland plowing as enhancing erosion, they held that zero tillage was impossible since it would “cut yields by half at least and double labor requirements for weeding” (a village headman).

Table 5-2: Effects of sedimentation in different agricultural contexts.

Characteristics	Paddy area	Fish ponds	Upland fields
Chemical	Varying fertility indicated by color, granulation, field position	Fish may die because of sediments loaded with agrochemicals	Loss of fertility
Physical	Harmful to plants in March/April and August/September	Fish may die because of reduced oxygen in water, siltation of ponds	Shrinking layer of topsoil may result in loss of arable land
Management	High labor requirements in very short time	Fast reconstruction in many cases only feasible using expensive machinery	Leveling of rills and ditches

5.7.5 Flood impact on household economy

The consequences of the flooding on household economy were addressed during structured interviews with farmers who were asked to evaluate impacts on agricultural production, marketing, houses and other durable goods and finally on cash income. The data collected emanate from a sample of 36 households living in Chieng Khoi and a second sample of 300 households randomly selected all around Yen Chau district used here as a comparison (cf. section 5.7.4). The farmers’ responses suggest that there was relatively little damage done at an individual household level. Of all the households interviewed in Yen Chau, 16% stated they had suffered negative effects from the floods, compared to 17% of farmers among the Chieng Khoi sample. Most damages occurred on agricultural production in general and on fishponds in particular (Table 5-3). In total, there was little direct damage to household incomes: those who were affected in Yen Chau declared a 6.4% loss on annual cash income on average, and those in Chieng Khoi a 3.3% loss. These results appear surprisingly low at first glance, given the strength of the flood and its exceptional character as perceived by the farmers themselves.

Table 5-3: Yield losses due to the flood.

	Yen Chau sample (n=300)				Chieng Khoi sample (n=36)			
	Number HH[a/] negatively affected	Harvest loss (%)	Min. (%)	Max. (%)	Number HH[a/] negatively affected	Harvest loss (%)	Min. (%)	Max. (%)
Paddy rice	8	20.8	6	40	2	25.5	21	30
Upland rice	1	10.0	-	-	0	-	-	-
Maize	17	14.5	1	50	1	10.0	-	-
Cassava	0	-	-	-	1	20.0	-	-
Fish pond	15	72.0	30	100	4	52.3	0	99

[a] HH=Sample household

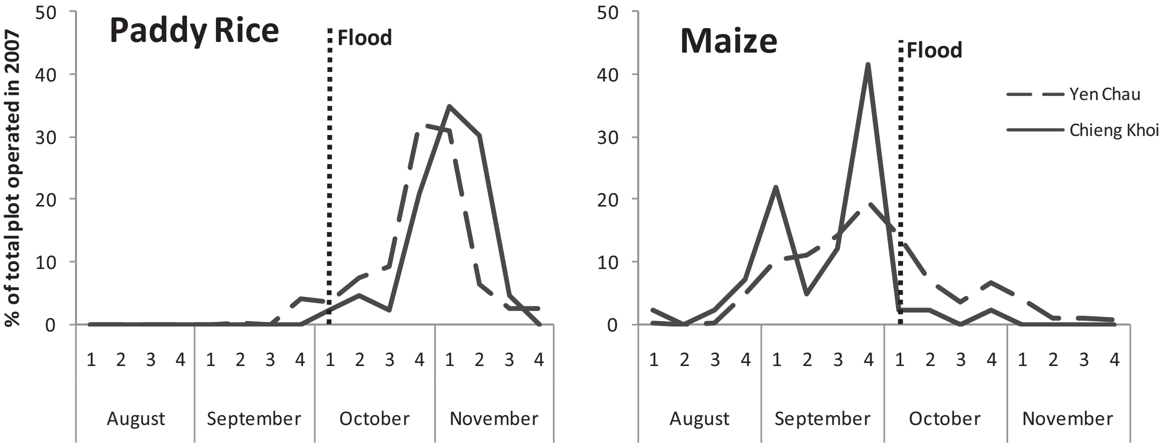

Figure 5-7: Harvest timing of paddy rice and maize – rainy season 2007.

An initial explanation is given in Figure 5-7, which shows that the typhoon occurred after most farmers had already harvested their maize fields. Maize is by far the most important source of cash income for farmers in the district, accounting for 65% of annual cash income on average in Yen Chau (27% in Chieng Khoi). If the flood had occurred a few weeks earlier, it would have incurred supposedly higher losses and more severe effects on people's livelihoods. However, despite the occurrence of the flood before the main harvest of paddy rice, the yield was not greatly affected. Regarding damage to fish production, the effects on household finances were minor, as selling fish contributes only a moderate share to overall incomes, while the loss of animal protein for household consumption was not taken into consideration by locals. In sum, our data indicate that the flood had a limited impact on household incomes. The damage reports collected from commune and district departments, however, show that significant damage occurred to public infrastructure, which affected communities rather than individuals (Yen Chau People's Committee, 2007).

5.8 Local responses and local non-responses

The quick onset of the flood prevented people from taking action that may have reduced the spread and penetration of flood waters through physical means. Instead, emergency interventions concentrated on protecting public infrastructure, such as community houses and bridges. A compilation of private and public damages conducted by the village disaster committees marked the initiation of reconstruction activities. The survey method differed throughout the villages between individual reporting and group appraisals. After transmission to the communal People's Committee and some 20 spot checks of farmers by delegates of the commune, a general assessment report was handed over to the district levels. Reconstruction of streets and public buildings was started right after the flood by the communal PC, which authorized village headmen to mobilize labor and reconstruction material as well as money needed to recover damages within the village from village resources. Each household had to contribute one person to work for an indefinite period of time on the reconstruction of streets and major irrigation canals. Required materials, especially wood and bamboo, were obtained from community forests, while in one village each household that owned a section of forest had to contribute a specified amount of material.

Physical recovery measures had to be done without support from any institution beyond the communal level. District authorities' efforts concentrated on restoring traffic infrastructure around the district capital and national road No.6 to Hanoi. In one group discussion, the farmer participants even accused the Department of Dyke Management of directing commune officials not to engage in these issues so "farmers are just on their own; even the communal officials do not find enough time to care for the villagers any longer". Hence, the farmers' considerable frustration was targeted at the national disaster fund, which did not put any support at the communes' disposal. Moreover, people from Chieng Khoi criticized the fund's non-transparency in terms of the allocation of money and its final use. In a group discussion with three senior villagers who had witnessed the flood of 1975, assumptions were expressed that the fund money was more likely to be given to central and economically more influential provinces. It was stated that even a small contribution might "make us recognize the state remembers us". The rapid appraisal and conciseness of the damage report raised expectations that there may potentially be compensation available. The spot checks of delegates from the commune further fuelled hopes for financial assistance, although the national press did not make any promises or intimations of damage compensation. The single concession to farmers was the remission of the irrigation water fee for the spring rice crop in 2008.

In sum, respondents at the village level lamented an overall lack of support – both in terms of resources and expertise – from the administration side, while the little assistance provided showed a clear tendency towards restoring the pre-flood conditions rather than helping to adapt to future flood risks. The momentum of increased risk awareness that might have been used to work out land use maps of flood prone areas or to re-integrate farmers into water governance schemes was largely wasted. Minor changes, like the conversion of some fish ponds into rice fields to prevent fish loss in case of future flooding, was driven by private initiatives and confined to a few cases only.

5.9 Discussion

Flood prevention and mitigation is perceived mainly as a public concern rather than an issue the individual can address. Rather than encouraging individuals' engagement in flood adaptation as an inherent property of the social and ecological geography of Chieng Khoi, a combination of public interventions in the region's hydrology and growing institutional pluralism have substantially estranged farmers from water governance and their sense of personal responsibility within it. The shift of local power to higher levels in particular, arising from the introduction of the lake manager's position, has reduced the accountability of local people in water governance and, as a consequence, induced a withdrawal from community action.

Apart from some village elders, it was the first time for most people in Chieng Khoi to suffer flooding of such seriousness. The recent history of the area does not provide evidence of how to prepare for flooding and handle its incidence. Experience is likely to alter perceptions of the necessity to undertake preventive measures, as Keller et al. (2006) assert. According to Baldassare and Katz (1992), direct experience not only affects how individuals learn about and perceive risks but also influences their behavioral responses. In our particular case, evidently, individual potential to exert influence on flood mitigation is superimposed by the common conviction among farmers that flooding is caused by the interplay of a bundle of external factors, with water management failures being the most prominent one. The majority of locals concluded the rainfalls, which were regarded as unusual in terms of intensity and duration, struck the area at an "inconvenient" time, where "inconvenience" referred broadly to the limited buffer capacity of excess water at that time of the season. The overall problem of structural inadequacies in the engineering of irrigation and drainage, however, and the need to alter land use systems was only acknowledged by higher level authorities. Those who ascribe the flood to management failures (external attribution) are less likely to recognize their own potential influence on flood mitigation than those few locals who credited their land use systems and top soil management (internal attribution) with having favored or intensified the flooding. These findings correspond with scholarly work that applied attribution theory to behavioral responses to flooding (Grothmann and Reusswig, 2006; Griffin et al., 2008). Additional support can be found in Slovic's (1987) thesis that (mal-)attribution of a singular event experienced can lead to risks and individual influence on it being misjudged. Following his thesis, once individuals have determined an assessment of a particular risk (and the factors by which it is triggered), their opinions can prove difficult to change; this can help explain the seemingly paradoxical phenomenon that direct experience of a disaster can exert a negative influence on the response or willingness to adapt to future ones (cf. Botterill and Mazur, 2004).

On the methodological side, the use of attribution theory outside its original field of learning motivation research proved its usefulness in understanding that people's short and long-term reactions to a flood event are heavily influenced by their understanding of causal relations. It was shown that due to the reasons ascribed to the flooding, the majority of people do not consider land use systems as having any substantial impact on the severity of flooding. It needs to be recognized that each individual or organizational actor behaves entirely rationally under the given administrative and incentive structures. By taking into account the way in which people estimate their own options and abilities to prevent future flooding, along with the effectiveness of these options, one can get a much clearer picture of why people do not make any significant changes in their land use practices. Instead of a prolonged discourse on long-term adaptation measures – with altering land use systems and soil conservation at its center – discussions within the local community revolved around management failures and the lack of preventive actions on the officials' side (Hoang et al., 2007; Tran et al., 2008).

The discrepancy between attention to and perceived severity of flooding ("biggest flood catastrophe within living memory") and the lack of motivation to implement mitigation measures in the upland case described in this article as well as in the lowland studies cited can be explained by both the relatively low flood-related impact on yield losses and household level respectively. This is not to say that flooding does not represent a material and crop loss to households. Yet the numbers appear too small to create sufficient incentives for individual households to change agricultural practices or even invest in costly soil conservation measures.

At the same time, even if there had been heavier economic losses at household level, Lin (2008) maintains that the threshold of losses affecting individuals' willingness to adopt mitigation measures is higher than that of the public in general. Lopéz-Marrero et al. (2009) found that individuals rank a number of different risks (e.g. weather extremes other than flood, family health) higher than flooding, whereas society as a whole tends to attribute higher risk levels to flooding. In this light, given the damage to public infrastructure, concerted political and/or collective strategies for action seem more likely to respond effectively and with greater lasting effect to increasing flood risks.

5.10 Conclusions

Without any doubt, the causal relations of upland flooding are more complex than in lowland regions. The intensive cultivation of annual crops in the upland area and the related impact on lower lying areas is a serious problem from both ecological and economic perspectives. Although the relevance of upland field cultivation and its effects on water buffer capacity were recognized in their essential features by local stakeholders, the overall understanding of the local ecology and its linkages to flood disasters proved to be fuzzy.

As this study shows, the administration cannot count on a sufficient degree of intrinsic motivation alone, and there are also no additional motivational triggers from a flood disaster, to make farmers implement soil conservation techniques to mitigate future flooding. Hence, effective policies will have to provide appropriate incentives, and a coherent long-term soil conservation strategy will need to be designed and implemented with the participation of all local stakeholders. Integrating traditional water management structures into decision-making processes and ensuring the transparency of mitigation plans and allocation of relief funds are essential in this respect. Ultimately, information and training on soil-water interdependencies as well as disclosure of crucial information among stakeholders are key to appropriate flood responses at both institutional and practical levels. Hence, local government officials are well advised to take local perspectives into account when it comes to designing effective flood mitigation strategies. In other words, decision makers need to understand how local people develop their own causal explanations of flood events and how they seek information and make decisions, rather than designing mitigation strategies based solely on expert findings and narrow hierarchical structures and economic constraints.

The interdisciplinary research design of this work gave a more complete picture of the controversy about the interrelation of land use and hydrological characteristics. Moreover, it pointed to the need to integrate environmental and socio-economic findings with cognitive factors determining flood mitigation and coping mechanisms. The narrative essays, in particular, provided a beneficial opportunity for multiple perspectives to emerge and highlighted the most important aspects of flooding from the individuals' points of view. The writers' disregard for political correctness, which researchers tend to face when doing face-to-face interviews, was remarkable, suggesting that the tool is an appropriate one for future application and methodological research.

Beyond the findings of our study, further theoretical and applied research is needed on how to improve people's perception of soil-water interaction and raise awareness of necessary behavioral changes as a complement to structural means of flood mitigation. Flood prevention communicators may need to make special efforts to render flood causes and soil-water interactions accessible and understandable to those whose perspectives and causal analyses differ from their own.

CHAPTER 6

GENERAL DISCUSSION

6 General discussion

6.1 Are upland derived sediments sufficient to sustain irrigated rice production in the lowland of northern Vietnam?

The results of this research revealed that irrigation management is an important input factor when investigating C and N balances in paddy terraces (Chapter 2) as the sustainability of rice production systems is highly depending on the nutrient in-and output (Maruyama et al., 2008; 2010). Although significant amounts of total N and organic C were irrigated to the paddy fields during rainfall events, the contribution of the reservoir (Figure 6-2) was found to be more important than the Hortonian overland flow draining into the channel (Chapter 2) (Figure 6-2).

Figure 6-1: Sediments draining to the irrigation reservoir during a heavy rainfall event (85 mm with an average intensity of 33 mm h^{-1}) in 2007.

Figure 6-2: Hortonian overland flow draining into the irrigation channel.

The total loads irrigated during two cropping seasons (Feb. – Oct.) were estimated to be 0.72 Mg ha^{-1} total N and 1.3 Mg ha^{-1} organic C. The actual yearly addition of N and organic C to the paddy fields remains uncertain as the trapping efficiency within paddies were not within the framework of this study. Nutrients can be trapped within the paddy fields as pointed out by Yan et al. (2010) or removed to surrounding water bodies by internal runoff-deposition processes during land preparation and storm events (Kim et al., 2006; Maruyama et al., 2008; Zhao et al., 2009). Zhao et al. (2009) reported that 0.3% of total N in paddy fields was removed during runoff and leaching processes while Maruyama et al. (2008) found values up to 8.6%.

Figure 6-3: Irrigation channel supplying sediment rich water to lowland paddy fields.

Antonopolous (2010) modeled total runoff/leaching and volatilization losses up to 34.2% and 18.2%, respectively. Using these latter results, as seepage seems to be rather large in the paddy fields (La Nguyen, personal communication within the SFB), it would indicate that there would be an estimated net N surplus of 0.34 Mg ha^{-1} yr^{-1}. On average that would be 0.17 Mg ha^{-1} per cropping season. In addition 1.61% additional N can be expected from the rain induced runoff entering the irrigation channel during the summer season (Chapter 2). These estimates are the upper limit of N deposition as the assumption is made that 0.72 Mg N ha^{-1} is deposited within the rice paddy fields before leaching, runoff or volatilization processes start. However, depending on irrigation management (e.g. water discharge) N will not be deposited uniformly and losses will occur along the way. Moreover, runoff and percolation losses are highly dependent on water management and soil structure (Tsubo et al., 2005; Boling et al., 2008). Although paddies are known to be able off trapping N, denitrification can account for enormous N losses. Yan et al. (2010) estimated soil denitrification rates of 150 kg N ha^{-1} yr^{-1} which would mean that 44% of the 0.34 Mg ha^{-1} deposited within a year would be lost by denitrification resulting in a net surplus of 0.19 Mg ha^{-1}.

The average plant N uptake in the non-fertilized fields contained 98 kg N ha^{-1} which lies within the range (i.e. 7 to 130 kg ha^{-1}) of values found by Dobermann et al. (2003) in various N omission plots throughout Asia. Furthermore the rice grains contained 53 kg N ha^{-1} and 78 kg N ha^{-1} in the non-fertilized and fertilized fields, respectively. This indicates that, in the fertilized fields, 67% of the N uptake was supplied by the soil, which lies within the range of 60-70% given by Zhang and Wang (2005). In the summer season (wet season) there was no significant decline in rice yields in the non-fertilized fields neither in the N-uptake compared to the spring crop. Additionally, no significant difference was found in grain yield between the fertilized and non-fertilized fields in Cascade 1 within the summer season although fertilizer was taken up sufficiently as demonstrated by the $\delta^{15}N$ signal in the grains (Chapter 4). This could indicate that the irrigated N was an important source in the wet season regarding plant - N supply. In general N fertilizer recommendations in paddies are highly depending on cropping intensity, soil type, climatic conditions and variety (Dobermann and White, 1999) and ranges in Asia between 100 and 150 kg N ha^{-1} in the dry and between 60 and 90 kg N ha^{-1} in the wet season (International Plant Nutrition Insitute, 2010).

As wetting-drying cycles play an important role on the N cycle, the duration of the anaerobic conditions influences the mineralization of organic N compounds into ammonium and therefore their availability for plant uptake. Furthermore, the bioavailability of N is highly depending on the organic C content of the soil (Kögel-Knabner et al., 2010). Often the surplus N is stored in organic matter pools that are not readily available for plant uptake (Cassman et al., 1998). Therefore, besides the addition of N through irrigation water, the irrigated organic C is of high importance as well when looking at sustainability of paddy fields as it will influence N mineralization processes (Kaewpradit et al., 2008). The sequestration of additional organic C input into SOC is highly depending on the quality and quantity as it also determines the rate of soil C sequestration (Kong et al., 2005). According to Gillabel et al. (2007) and King et al. (2009), organic C addition through irrigation water has to be taken into account when calculating C sequestration in irrigated agricultural systems. When soil organic carbon (SOC) is translocated within the catchment to aquatic ecosystems, up to 1.14 Pg C yr^{-1} can be mineralized and converted to CO_2 (Lal, 2004). The question whether irrigation enhances C sequestration or rather increases greenhouse gas emissions remains uncertain and is highly depending on climate, soil type, tillage practices, crop and irrigation management practices (Entry et al., 2002; Lal, 2004; Gillabel et al., 2007).

When comparing SOC and total N content of the paddy topsoil before planting and after harvesting, a slight increase was found in the paddy fields which were receiving only sediments through irrigation (Chapter 3). This suggests once more the positive effect of sediment associated nutrient deposition on soil fertility in paddy fields. The actual benefit of sediments in relation to sustainability of paddy fields, however, will highly depend on the form in which organic C and total N are irrigated, where they are deposited and the mineralization processes and losses occurring in the paddy fields as they are highly depending on fertilizer and water management practices (Li et al., 2010). Furthermore, K balances are often found to be negative in intensified upland cropping systems (Dung et al., 2008) but also in many intensive irrigated lowland rice fields throughout Asia (Dobermann and Oberthür, 1997; Dobermann and Cassman, 2002). Therefore, apart from the irrigated C and N surplus, adjusted fertilizer applications regarding N, P and K supply are necessary in order to improve sustainable rice production systems.

6.2 Do the spatially induced fertility patterns necessitate site specific fertilizer recommendations?

Spatial variability in soil chemical properties was found within and between cascades (Chapter 3) indicating that the C and N fluxes provided by the irrigation water were not equally distributed. Additionally, the impact of sediment deposition on C and N variation in the topsoil along cascades was found to be influenced by the sedimentation pathway (i.e. irrigation, flooding (Figure 6-5) or upland runoff (Figure 6-4) in the case of rainfed paddy fields). An increase was found in SOC and total N with descending position along the cascade when fields received only irrigation water. Other sedimentation pathways, such as flooding and upland runoff, lowered SOC and total N content in the topsoil (Figure 3-3, Chapter 3). The enrichment of lower paddies by irrigation water was proven to enhance rice production as grains in these paddies showed a higher N uptake compared to the upper fields (Chapter 4). Similar findings of enrichment in the lower lying paddies were observed in rainfed paddies and related to downward movement of nutrient rich sediments (Homma et al., 2003; Tsubo et al., 2006; Boling et al., 2008; Rüth and Lennartz, 2008). The $\delta^{15}N$ enrichment in grains harvested in the non- fertilized fields indicated that the soil reserves contribute relatively more in the lower parts of the cascade, confirming the effect of sediments on soil fertility and therefore crop performance. The fertilized fields in this study all received the same amount of fertilizer based on the local recommendation and the area of the field. Nevertheless, the N uptake by grains as well as the $\delta^{15}N$ signal in grains of the fertilized fields followed the same trend as the non-fertilized fields. This would indicate that although sufficient N was applied, the sediment induced soil fertility alterations played an important role. The spatial differences in indigenous N

Figure 6-5: Flooding of paddy fields neighboring the river during typhoon "Lekima" in 2007.

Figure 6-4: Deposition of upland runoff in rainfed paddy fields during a heavy rainfall event (85 mm with an average intensity of 33 mm h^{-1}) in 2007.

supply therefore would call for specific fertilizer recommendations. According to Dobermann et al. (2003) the indigenous nutrient supply (INS) in an irrigated system can be measured by omission plots and encompasses the nutrients delivered by (i) biological N_2 fixation, (ii) chemical and biological transformations due to the redox conditions, (iii) atmospheric deposition and (iv) solutes and sediments deposited during irrigation or flooding. The mean INS for nitrogen over both seasons and cascades was estimated to be 53 kg ha^{-1} and varied strongly within and between cascades (Chapter 4). However, the indigenous nutrient supply of N, P and K has a high spatio-temporal variation and its influencing factors are scale dependent (Dobermann et al., 1997; Dobermann et al., 2003; Tsubo et al., 2006; Lennartz et al., 2009). For example the growing season, irrigation and crop management practices will have an impact on indigenous nutrient supply on field or cascade level whereas parent material, climate and crop management cause large variability at regional, national and continental scale (Dobermann et al., 2003). Often fertilizer recommendations for rice are made at district or regional scale and distributed to the local extension offices. The recommendations do not account for the various nutrient inputs entering the system such as rice straw incorporation, irrigation, organic or chemical fertilizer which influences soil fertility in the long term (Li et al., 2010). Site specific fertilizer recommendations are complex as N mineralization-immobilization are highly depending on land management, flooding and climatic conditions (Cassman et al., 1996b). Therefore, laboratory experiments often fail in accurately predicting the nutrient release in irrigated rice fields (Dobermann and Cassman, 2002). Furthermore, the availability of soil organic matter and its decomposition plays an important role in the mineralization of N (Cassman et al., 1996a; Kimura et al., 2004; Kaewpradit et al., 2009). Therefore besides the estimated INS supply, measures are needed for estimating the N release during the cropping season as a function of additional nutrient inputs. This on its turn has to be combined with regional and seasonal differences in yield potential, crop and water management in order to create local-specific guidelines for N application (Dobermann and Cassman, 2002; Dobermann et al., 2003). Dobermann and Cassman (2002) pointed towards the beneficial use of soil-crop models in order to predict seasonal nutrient availability and crop demand in order to define dynamic nutrient management approaches. Nevertheless, the adoption of specific nutrient management strategies will highly depend on its economic benefit and associated risks as pointed out by Dobermann and White (1999) and Haefele et al. (2010). This would mean that for the irrigated paddy fields in Chieng

Khoi, where there is no flood risk, farmers would be willing to reduce fertilizer consumption if the current system is proven to be sustainable. For rainfed rice fields and fields which are prone to flooding, however, farmers will tend to reduce the risk of yield losses and therefore hesitate in adopting innovative fertilizer management strategies.

6.3 What would be the influence of soil conservation practices on the redistribution of carbon and nitrogen across the landscape

The results of Chapter 2 showed that during the 25 studied storm events, on average significant loads of organic C (61 kg ha^{-1}) and total N (8 kg ha^{-1}) were transported by Hortonian overland flow and drained into the irrigation channel. The total organic C transported over the 25 events was estimated to be 1.1 Mg while total N loads were estimated to be 0.1 Mg. However, the measured rainfall events only accounted for 18% of the total rainfall in 2008. At the beginning of the rainy season, where soil cover on the steep slopes is found to be low (i.e. establishment phase of maize). Therefore, overall Hortonian overland flow will be significantly higher, transporting large amounts of organic C and total N (Tuan et al., 2010). Furthermore, extreme rainfall events, such as the typhoons occurring in September-October after the maize harvest, will contribute to the water-erosion induced removal of organic C and total N from the uplands. Last but not least, the linear segments in the landscape can as well add to organic C and total N removal in the uplands (Ziegler et al., 2004). A part of the Hortonian overland flow will be deposited along the way depending on landscape topography, land use and soil characteristics and thus not reach the irrigation channel or the rice fields (i.e. rainfed paddies) directly (Chaplot et al., 2005). Nevertheless, the average Hortonian overland flow per rainfall event indicated that the upland soils under their current practice are degrading rapidly, jeopardizing agricultural productivity in the future (Clemens et al., 2010).

Additionally, the results showed that the overland flow from the hills surrounding the reservoir are trapped in the reservoir and the nutrients are slowly released through irrigation during the rice cropping seasons. Although, the additional nutrient loads irrigated to the paddy fields are found to be beneficial in terms of soil fertility and crop productivity (Chapters 3 and 4), there are as well several negative off-site effects related to the degradation and associated nutrient and sediment transport from the upland area. Firstly, the buffer capacity of the reservoir is decreasing rapidly due to sediment deposition, causing water scarcity and associated irrigation deficiency during the dry season (i.e. spring season) (Chapter 4). The average sedimentation rate in the reservoir was found to be 3.3 cm yr^{-1}. When the surrounding uplands were completely under intensive cultivation, the reservoir would be estimated to silt up in 59 years (Weiss et al., 2008). As a result, the decrease in buffer capacity also increases flooding probability downstream as it is unable to buffer extreme storm events at the end of the rainy season. Paddy fields, fish ponds and local infrastructure can be seriously affected in the short or long term (Chapters 3, 4 and 5). The results of the interdisciplinary study (Chapter 5) showed that the (mal)-attribution of farmers, the relatively low direct economic losses due to flooding and the absence of additional motivational triggers associated with flooding will not stimulate the adoption of soil conservation practices. Additionally, the continuous supply of new hybrid varieties and the increase in chemical fertilizer application is currently masking the degrading soil fertility in the upland (Wezel et al., 2002a; Wezel et al., 2002b). Furthermore, the insecurity related to land tenure and reallocation policies, negatively affects adoption rates of soil conservation technologies (Saint-Macary et al., 2010). The relation of decreasing buffer capacity of the reservoir, downstream flooding and land use intensification was only acknowledged by the local authorities and not by the farmers. Therefore, it is believed that soil conservation practices can be implemented successfully if the local governments officials take into account the local perspectives of farmers regarding flooding, provide appropriate incentives, invest in explaining the causal relationship between agricultural practices and flooding for all local stakeholders involved (Chapter 5).

When designing soil conservation strategies it is important to take into account the socio-economic as well as the biophysical factors. Strategies such as hedgerow (e.g. ruzi grass barriers or leucaena hedges) systems need a 2-3 year establishment phase in order to effectively reduce erosion and runoff (Pansak et al., 2008). Often they are economically not attractive or found to be too labor intensive as in the short term no direct benefits can be seen (Knowler and Bradshaw, 2007). The local farmers who were interviewed in Chapter 5 did believe that water would be reduced or at least sediment transport would be reduced when soil conservation techniques would be applied. Ziegler et al. (2006) predicted that the effective slope lengths for buffering surface runoff would lie between 30 and 100 m depending on the slope gradient. However, the farmers preferred runoff water above sediment deposition as the water is used for rice cultivation on fields without access to the irrigation system (Chapter 5). Therefore, soil conservation practices which strongly reduce erosion losses but only moderately runoff, such as minimum tillage and mulching, would be an appropriate solution. The cumulative runoff associated N losses over three years related to minimum tillage and mulching were found by Pansak et al. (2008) to range between 12 and 15 kg mineral N ha^{-1}. Although the losses decreased significantly between the first and the third year, the authors found that the runoff associated losses were overall three to five times higher than when hedgerows were established. Compared to the estimated Hortonian overland flow (8 kg ha^{-1} for 25 events) these values seem relatively high. However, as probably the total N losses on yearly basis will be higher as indicated earlier, there can be a reduction of N losses expected when using mulch. Furthermore, the combination of mulching and relay cropping with N_2 fixing legumes can compensate partly for the N losses through the delivery of additional N (Pansak et al., 2008). Jin et al. (2008) showed that reduced tillage only decreased SOC losses by 29%, indicating that still sufficient organic C would be removed from the upland fields. When minimum tillage and mulching would be promoted and applied throughout Chieng Khoi, a lower amount of C and N loads would be trapped within the reservoir and slowly released through irrigation to the paddy fields. As a result, the positive effect of C and N through irrigation on soil fertility and crop productivity would be reduced. On the other hand, soil conservation practices would reduce the low quality sediment entering the rainfed rice fields (Chapter 3). There is a clear trade-off between soil preservation in the upland, decreasing sediment deposition of low quality in the rainfed rice fields and the positive effect of sediment redistribution through irrigation on crop performance in the lowland.

6.4 How will climate change affect the sustainability of rice production systems in the future?

Climate change studies have pointed out that extreme rainfall events and an increase in drought periods will continue to occur (Bates et al., 2008; Cruz et al., 2007). Water demand for agricultural and non-agricultural use will continue to increase although water availability will be challenged in the future (Xiong et al., 2010). Cruz et al. (2007) stated that due to water scarcity, rice yields will drop at the end of the 21st Century by 3.8% in Asia. The seasonal water shortage will call for improved irrigation systems and water management in order to meet the increasing food demand (Kirby and Mainuddin, 2009; Turral et al., 2010). Alternative wetting-drying was found to save up to 15% of irrigation water without significantly decreasing yield (Belder et al., 2004). Bouman and Tuong (2001) reported that keeping the fields at saturated conditions without ponding layer would decline yields by 6%. The adjustment of irrigation practices in the future will have an impact on the redistribution of C and N found in the study. When during the dry season (i.e. spring season), alternative wetting-drying would be applied in Chieng Khoi, less C and N will be irrigated. Simultaneously, the wetting-drying cycles will increase C decomposition, CH_4 and CO_2 production and N mineralization (Kaewpradit et al., 2008). Therefore, a decrease in SOC and N content can be expected in the paddy fields due to the assumed increases of gaseous C and N losses.

The extreme rainfall events (e.g. typhoons) mainly occur at the end of September – October when maize is already harvested and the steep slopes are left bare. The increase of typhoons during the wet season (i.e. summer crop) will increase nutrient losses through erosion and runoff causing soil degradation in the uplands and siltation of reservoirs. The flooding risk of the downstream paddy fields will increase significantly due to the decreasing buffer capacity of the irrigation reservoir (Figure 6-5). Sediment deposition through flooding was found to degrade the paddy fields neighboring the river significantly by decreasing the SOC and total N content in the topsoil (Chapter 3), reducing rice performance (Chapter 4). In absence of soil conservation practices, one could expect that the increase of extreme rainfall events will continue to degrade the intensively cultivated upland fields through erosion and runoff. In consequence the number of flooding events will also increase, as well as the quantity of less nutrient rich sediments which will be deposited during these flash floods in paddy fields. The continuous decrease of SOC and total N content in these fields can become a serious threat to the sustainability of the system. The negative impact of climate change on lowland soil fertility and productivity clearly demands for adequate soil conservation practices. However, due to the lack of intrinsic motivation among local farmers there is need for policy makers to raise the farmers' awareness regarding upland-lowland linkages and the crucial role of soil conservation practices (Chapter 5).

6.5 Conclusion and outlook

The study pointed towards the vulnerability of intensive cultivated upland slopes regarding nutrient transport and its impact on rice production in the lowland. Although, Hortonian overland flow is significant during big storm events, its impact on overall nutrient redistribution is highly depending on the sedimentation pathway (Chapters 2 and 3). The overland flow trapped by the reservoir played a more important role on nutrient redistribution to the lowland compared to the one draining directly into the irrigation channel. A significant amount of C and N is reallocated to the paddy fields through different sediment delivery pathways: (i) irrigation, (ii) direct deposition (i.e. in rainfed rice fields) and (iii) flooding; or transported into of the subwatershed (Chapter 2). The various pathways each contributed to the overall spatial variation found within and between cascades (Chapter 3). The sediment induced soil spatial variation was positively correlated with rice yields when nutrient rich sediments were deposited and negatively when sediments were sandy (Chapter 4). Climate change, however, will put the sustainability of rice cultivation in tropical mountainous areas under debate. The probability of extreme rainfall events could result in more flooding events. Flooding in the study area was found to deposit sediments of low nutrient content. As a result, a decrease of soil fertility in the paddy fields and lower yields can be expected in the long term. Although, appropriate soil conservation practices could help mitigate flooding events in the future, adoption by farmers remains very low. The complexity in understanding farmers' behavior towards adoption of mitigation strategies clearly calls for interdisciplinary research when designing soil conservation techniques. Besides the extreme rainfall events, an increase in drought periods is foreseen as well, calling for improved water management strategies reducing water input. The combination of soil conservation and water management strategies not only preserves soil fertility in the upland and improves water productivity in the lowland but also will alter nutrient redistribution to the paddy fields. For example, the decreasing soil fertility in the flooded paddy fields as well as in the intensively cultivated uplands could stagnate or even improve, depending on management practices (e.g. residue incorporation, fallow). There is a clear trade-off between uplands and lowlands in the mountainous regions of SE Asia as the application of soil conservation practices would reduce, not only the degradation in the upland, but also would decrease the C and N loads to the paddy fields. However, in the scope of meeting the future food demand it is believed that it is more important to preserve and even improve soil fertility in the upland. Additionally, the use of adequate management strategies (e.g. residue incorporation) in combination with adjusted water management in rice fields can substitute the losses of beneficial sediments that are transferred to the irrigation water.

The combination of techniques, used in this study, was useful in order to understand the influencing factors behind sediment redistribution in the lowland as it is important with regard to ecosystem analysis at landscape level. Sediment delivery along the catchment is not a linear process and highly depending on scales addressed (Chaplot et al., 2005). Therefore, extrapolation and upscaling are not straightforward. Mid infrared spectroscopy (MIRS) showed to be suitable when addressing soil spatial variation. Therefore, in combination with geostatistics (Cobo et al., 2010), it can assist in the assessment of soil spatial variation due to sediment deposition within larger lowland valleys. Furthermore, the decrease of soil fertility in the upland as a consequence of land use intensification and associated erosion and runoff can be monitored in a similar way. The monitoring of the decrease in SOC and N content within the sediments will assist in forecasting the long term effect of climate and/or land use change, not only in the upland but also in the irrigated lowland.

Monitoring C and N dynamics along the catchment using automatic water samplers is costly as a large number of samples are taken in order to understand storm event processes. Furthermore, a high probability exists that a storm event is not well sampled. In order to reduce lab analysis and increase the number of monitored events, continuous monitoring with turbidity sensors could be a solution. However, turbidity sensors are a proxy and C and N loads would be estimated depending on the turbidity (i.e. reflection of the light beam) of the water (Gao, 2008). This indicates that each station should be separately calibrated during storm events of different magnitudes as sediment source will play an important role on C and N transport. Sediment sources will differ in its particle size composition and therefore differences in C and N concentrations will differ significantly (Ziegler, 2007). After a good calibration the use of turbidity sensors would provide a continuous data set covering multiple years. This would allow for assessing differences in sediment quantity and quality or even changes in sediment transportation patterns within a larger time frame. Additionally, it can be used for calibration and validation of land use models in order to understand the impact of land use changes on nutrient redistribution.

As mentioned above the identification of sediment sources and the chemical composition of sediments are necessary with regard to upscaling as the chosen scale plays an important role in SOC enrichment (Chaplot et al., 2005; Schiettecatte et al., 2008). Current research has suggested that stable isotope (^{13}C and ^{15}N) analysis of organic matter in soils and the improved method of compound specific isotopes can assist in identifying sediment sources (e.g. forest, surface coal mining, etc.) and erosion processes (e.g. stream back or surface soil erosion) (Fox, 2009; Fox and Papanicolaou, 2007). The combination of MIRS, geostatistics and isotope analysis can therefore be used to estimate long-term sediment sources in the upland but also delineate sediment induced enrichment and depletion zones in the lowland. Remote sensing can be a good alternative compared to field measurements in identifying spatial variation of crop performance and water productivity at larger scales (Kamthonkiat et al., 2005; Zwart and Leclert, 2010). Using remote sensing in combination with the obtained sediment enrichment/depletions zones could help in explaining partly the variability found in crop performance besides the already known factors such as variety and management practices.

Although large quantities of C and N are irrigated to the paddy fields throughout the year it remains unclear how much is actually deposited within the rice system and how much is transported by drainage water to lower lying areas or even water bodies. The assessment of a full nutrient and carbon balance, which can be done using stable isotopes as tracer, would be necessary in defining the final net C and N input. Moreover, assessment of SOC decaying rates and N mineralization in paddy fields in relation to improved water management are necessary. Combining this information is necessary in order to design specific fertilizer recommendations suitable for the various sediment enrichment/depletion zones within the lowland. In a latter step the recommended fertilizer rates can be tested in fertilizer trials in order to assure the sustainability of the current intensified rice systems. However, due to the continuous alterations in sediment quantity and quality depositions in the long term, the site specific fertilizer recommendations need to be adjusted on a regular basis. This can be done by selection of monitoring zones where occasional soil fertility and rice yields are measured which can be performed by local extension offices.

A combination of the above mentioned techniques would help in understanding the missing processes and help in creating a dataset that can be used for calibration and validation of landscape models. The successful application of spatially explicit dynamic landscape models depends on a full understanding of the occurring processes at larger scales. These landscape models can assist local policy makers in assessing the environmental services related to land use changes and to understand the impact of climate change on current agricultural practices regarding food security.

CHAPTER 7

SUMMARY

7 Summary

As a result of demographic pressure, governmental policies and improved market access, agricultural practices were intensified in the tropical mountainous areas of Southeast Asia. The traditional swidden agriculture in Northwest of Vietnam, which combines swidden (shifting cultivation) in the steep upland slopes with permanent rice cultivation in the lowland, shifted into a more continuous monocropping system of maize and cassava in the uplands and irrigated rice paddies in the lowland. The construction of reservoirs allowed storing rainfall and runoff water in order to feed irrigation systems, supporting a second rice crop outside of the rainy season. Water-induced erosion due to land use intensification not only causes severe soil degradation on steep slopes but also sediment associated nutrients are transported downwards and redistributed in the landscape. The goal of this thesis which was conducted in Chieng Khoi, Yen Chau District, Son La Province, Northwest Vietnam was to: (i) trace and quantify sediment associated organic carbon and total nitrogen fluxes in irrigation water, (ii) assess whether sediment deposition enhances soil spatial variation and crop performance along toposequences of paddy rice terraces and (iii) to understand the influence of flooding events on farmers' perception in relation to agricultural practices and adaptation of mitigation strategies.

C and N fluxes within the Chieng Khoi subwatershed were traced during 25 rainfall events from May till September 2008 using automatic water samplers installed in a concrete irrigation channel and programmed to take flow proportional water samples. In absence of rainfall events, the irrigation water derived from the reservoir had an average baseline concentration of 29 ± 4.4 mg l^{-1} inorganic C, 4.7 ± 1.2 mg l^{-1} organic C and 3.9 ± 1.6 mg l^{-1} total N. Cumulative over the 25 storm events, the loads transported by Hortonian overland flow from the uplands which drained into the irrigation channel were estimated to be 61 kg ha^{-1} organic C and 8 kg ha^{-1} total N. The organic C / total N ratio of the overland flow fluctuated between 2 and 7 depending on rainfall intensity and duration, pointing towards the contribution of different land uses to nutrient transport. However, the direct overland flow contribution towards the irrigated nutrients loads was negligible relatively to the reservoir. When the entire irrigation period was considered, the reservoir played an important role in the redistribution of C and N as it acted as a sediment trap during storm events and slowly released nutrients throughout the year, providing up to 97 -

99.5% of the irrigated C and N loads. Extrapolating these findings to the two irrigated rice seasons per year would roughly indicate an irrigated load of 1.3 Mg ha^{-1} organic C and 0.72 Mg ha^{-1} total N. This demonstrates that irrigation is an important sediment conveyer which needs to be taken into account when looking at the sustainability of rice production systems as it is a potential source for additional nutrients and organic matter.

As sediment deposition depends on the particle size, traveling distance and velocity an unequal distribution of sediments is expected in the lowland. Therefore, various sediment deposition pathways (i.e. flooding, irrigation and direct runoff) and its effect on soil spatial variation along paddy rice toposequences were investigated. Topsoil samples were taken during two subsequent rice cropping seasons (e.g. before planting and after harvesting) and analyzed using a combination of conventional lab analysis and mid infrared spectroscopy. Sediment delivery through the irrigation system resulted in a significant enrichment in the lower paddies following a linear trend for soil organic carbon (SOC (g $100g^{-1}$) = 1.4 + 0.02 Distance (m), $R^2 = 0.31\text{-}0.62$), total nitrogen (TN (g $100g^{-1}$) = 0.11 + 0.004 Distance (m), $R^2 = 0.33\text{-}0.61$) and a significant linear decrease in the sand fraction (sand (g g^{-1}) = 0.3 – 8 E^{-04} Distance (m), $R^2 = 0.28\text{-}0.48$) with increasing distance from the irrigation channel along the cascade. Paddies close to the irrigation channel received less nutrient rich sediment, which resulted in a decrease of SOC and Total N content and an increase in sand fraction. Sediment delivery via flooding (or direct runoff, in the case of rainfed paddies) strongly decreased soil fertility as these were nutrient poor - sandy sediments.

The various sedimentation pathways altered soil fertility of rice fields and induced characteristic patterns of soil spatial variation along toposequences. As soil fertility has a significant impact on crop productivity, rice performance was monitored within two successive cropping seasons (i.e. spring and summer crop) within the toposequences. In order to distinguish between sediment induced effects on rice production and spatial variation in water or nitrogen availability, stable isotopes (^{13}C and ^{15}N) were used. Rice yields were found to be strongly and significantly correlated to sediment induced soil fertility (e.g. SOC: r = 0.34/0.77 for Cascade 1 and 2, respectively) and textural changes (e.g. sand: r = -0.88/-0.34). However, besides sediment induced spatial variation, water availability played an additional role in the spatial variation of crop performance. The isotopic $\delta^{13}C$ values found in the harvested grains of the dry season clearly showed that limited water availability overshadowed the expected yield trends in Cascade

2. A decrease in water availability was found with increasing distance from the irrigation channel. The effect of water availability on N mineralization and therefore N uptake was related to natural ^{15}N abundance within the topsoil. The use of ^{13}C discrimination in grains provides a snapshot covering the water availability during one season whereas the natural abundance of ^{15}N in the soil reflects long term N cycling processes depending on N input but also on the reducing conditions (i.e. wetting-drying cycles). The combination of stable isotope techniques, field measurements and mixed models helped in understanding the linkage between upland erosion and lowland sedimentation and moreover on crop productivity at toposequence level.

According to several climate change studies, extreme rainfall events and typhoons would increase in the future putting tremendous pressure on the sustainability of current agricultural practices in Southeast Asia which was also demonstrated by this study. In order to understand farmers' willingness to adopt mitigation strategies and apply soil conservation techniques, an interdisciplinary study combining socio-economic and biophysical approaches to assess the impact of a typhoon on a commune in Northwest Vietnam. The results showed that individual farmers' willingness to adopt mitigation strategies was influenced by the economic impact of flooding at household level, external factors (e.g. climatic factors, water management failures) and a lack of understanding of the linkage between upland and lowland agricultural practices. Successful implementation of soil conservation techniques therefore will depend highly on local policy makers as they need to invest in raising farmers' awareness regarding upland-lowland linkages and providing appropriate incentives.

There is a clear linkage between intensive upland agricultural practices and lowland crop performance. Under moderate rainfall patterns the, through erosion removed, nutrients contribute to the replenishment of nutrients and SOM in the paddy fields. Nevertheless, under the expected climate change with increasing frequency of typhoons in the region both upland fields and lowland paddies will be at considerable risk. However, the understanding of nutrient redistribution processes is not straight forward and has a high spatio-temporal character. The assessment of nutrient enrichment and depletion regions within the lowland can be used in designing site-specific fertilizer and water management practices. Furthermore, the identification of the processes behind nutrient redistribution allows modellers and policy makers to better assess the impact of land use change on ecosystems.

Zusammenfassung

Als Folge von Bevölkerungswachstum und Regierungspolitik sowie eines verbesserten Marktzugangs wurde die Landnutzung in tropischen Bergregionen Südostasiens intensiviert. Die traditionelle Waldbrandrodungswechselwirtschaft Nordwestvietnams, die Feldbau in steilen Hanglagen mit Nassreisanbau in Tallagen kombiniert, wurde von permanentem Anbau von Mais und Maniok als Monokultur in Hanglagen und bewässerten Reisanbau in Tallagen abgelöst. Der Bau von Stauseen erlaubt das Speichern von Niederschlägen und oberflächlich abfließendem Wasser für die Bewässerung. Dies ermöglicht vielerorts eine zweite Reisanbauperiode außerhalb der Regenzeit. Bodenerosion infolge von Niederschlägen gepaart mit einer Intensivierung der Landnutzung verursacht jedoch nicht nur eine erhebliche Degradierung der Böden auf steilen Hängen, sondern bewirkt auch eine talwärtige Verlagerung von Sedimenten einschließlich daran gebundener Nährstoffe und deren Umverteilung in der Landschaft. Ziel dieser in Chieng Khoi im Yen Chau Distrikt der Son La Provinz von Nordwestvietnam durchgeführten Studie war es, 1) die an Sedimente gebundenen, organischen Kohlenstoff- und Gesamt-Stickstoffflüsse im Bewässerungswasser zu verfolgen und zu quantifizieren, 2) zu beurteilen, welchen Einfluss Sedimentablagerungen in Reisterrassen auf die räumliche Variation von Bodenparametern und die Ertragsleistung von Nassreis haben und 3) den Einfluss von Überflutungen auf die Wahrnehmung der Bauern in Bezug auf Landbewirtschaftung und Gegenmaßnahmen zu verstehen.

Zwischen Mai und September 2008 wurden C- und N-Flüsse anhand von Wasserproben untersucht, die innerhalb einer Untereinheit des untersuchten Wassereinzugsgebietes von Chieng Khoi mit Hilfe von automatischen Wasserprobennehmern an einem Bewässerungskanal aus Zement bei 25 Starkregenereignissen proportional zum Abfluss genommen wurden. Ohne zusätzliche Niederschläge hatte das aus dem Stausee kommende Bewässerungswasser eine durchschnittliche Ausgangskonzentration von 29 ± 4.4 mg l^{-1} anorganischem C, 4.7 ± 1.2 mg l^{-1} organischem C und 3.9 ± 1.6 mg l^{-1} Gesamt-N. Der Eintrag des Hortonischen Oberflächenabflusses in den Bewässerungskanal wurde, kumulativ über 25 Starkregenereignisse, auf 61 kg ha^{-1} organischen C und 8 kg ha^{-1} Gesamt-N geschätzt. Das Verhältnis organischer C/Gesamt-N des Oberflächenabflusses schwankte in Abhängigkeit von Niederschlagsintensität und –dauer zwischen 2 und 7, was auf den Beitrag unterschiedlicher Landnutzung zum Nährstofftransport hinweist. Der direkte Beitrag des Oberflächenabflusses zum Nährstoffeintrag mit dem Bewässerungswasser war jedoch im Vergleich zu dem des Wasserreservoirs vernachlässigbar. Über die gesamte Bewässerungsperiode betrachtet spielte der Stausee eine wichtige Rolle in der Umverteilung von C und N, da er als Auffangbecken für Sedimente während Starkregenereignissen agierte und die Nährstoffe langsam über das Jahr verteilt freisetzte. Dies entsprach 97 - 99.5 % des Eintrages an C und N über das Bewässerungswasser. Extrapoliert man diese Werte auf zwei bewässerte Reisanbauperioden pro Jahr, entspricht diese Menge ungefähr einem C-Eintrag von 1.3 Mg ha^{-1} organischem C und 0.72 Mg ha^{-1} Gesamt-N über das Bewässerungswasser. Dies zeigt, dass die Bewässerung per se ein wichtiges Vehikel für die Sedimentverteilung in der Landschaft ist, die bei der Betrachtung der Nachhaltigkeit von Nassreisanbausystemen als Quelle für zusätzliche Nährstoffe und organische Substanz berücksichtigt werden muss.

Da die Sediementablagerung von Partikelgröße, Transportdistanz und -geschwindigkeit abhängt, kann eine ungleichmäßige Verteilung der Sedimente in den Tallagen erwartet werden. Daher wurden verschiedene Sedimentationswege, wie z. B. Überschwemmung, Bewässerung und direkter Eintrag über Oberflächenabfluss, sowie deren Einfluss auf die räumliche Variation von Böden entlang von Toposequenzen aus Nassreisfeldern untersucht. Hierzu wurden Oberbodenproben während zwei aufeinanderfolgenden Reisanbauperioden (vor dem Verpflanzen und nach der Ernte) genommen und mit Hilfe einer Kombination aus klassischen Labormethoden und Mittel-Infrarotspektroskopie analysiert. Die Sedimentverlagerung führte im Bewässerungsperimeter zu einer signifikanten Anreicherung der organischen Bodensubstanz und Gesamt-N in tiefer gelegene Felder bei einem linearen Trend (org. Bodensubstanz (g $100g^{-1}$) = 1.4 + 0.02 Distanz (m), $R^2 = 0.31\text{-}0.62$; TN (g $100g^{-1}$) = 0.11 + 0.004 Distanz (m), $R^2 = 0.33\text{-}0.61$) und einer signifikanten, linearen Abnahme in der Sandfraktion (Sand (g g^{-1}) = 0.3 – 8 E^{-04} Distanz (m), $R^2 = 0.28\text{-}0.48$) innerhalb einer Reiskaskade mit zunehmender Entfernung vom Bewässerungskanal. Näher zum Bewässerungskanal gelegene Nassreisfelder erhielten weniger nährstoffreiche Sedimente, was zu einer Abnahme der organischen Bodensubstanz und Gesamt-N sowie einer Zunahme der Sandfraktion führte in diesen Feldern führte. Die Sedimentanreicherung durch Überschwemmungen (oder direkten Oberflächenabfluss im Fall von Reisfeldern unter Regenfeldbau) bewirkte eine starke Abnahme der Bodenfruchtbarkeit, da dieses Wasser nährstoffarm war und sandige Sedimente mit sich führte.

Die verschiedenen Sedimentationswege änderten die Bodenfruchtbarkeit und riefen eine charakteristische räumliche Variation des Bodens entlang einer Toposequenz hervor. Da die Bodenfruchtbarkeit eine Wirkung auf die Produktivität von Kulturpflanzen hat, wurde die Ertragsentwicklung bei Nassreis innerhalb von Toposequenzen über zwei aufeinanderfolgende Anbauperioden (Anbau im Frühling und Anbau im Sommer) beobachtet. Um die Auswirkung von Sedimenteinträgen und die hierdurch induzierte räumliche Variation von Wasser- und Nährstoffverfügbarkeit sowie deren Einfluss auf den Reisertrag unterscheiden zu können, wurden stabile Isotopenmethoden (^{13}C and ^{15}N) angewendet. Die Reiserträge waren stark signifikant mit der durch Sedimentablagerung beeinflussten Bodenfruchtbarkeit (z.B. organische Bodensubstanz: $r = 0.34/0.77$ für Kaskade 1 bzw. 2) und Veränderungen der Textur (z.B. Sand: $r = -0.88/-0.34$) korreliert. Neben der durch Sedimentation verursachten räumlichen Variation spielte die Wasserverfügbarkeit eine zusätzliche Rolle bei der Ursachenforschung der räumlichen Variation der Ertragsbildung. Die $\delta^{13}C$-Werte von Reiskörnern, die in der Trockenzeit unter Bewässerung durch den Stausee angebaut wurden, zeigten dass die Wasserverfügbarkeit die erwarteten Erträge in Kaskade 2 überlagerte. Eine Abnahme der Wasserverfügbarkeit war mit einer Zunahme der Entfernung vom Bewässerungskanal assoziiert. Der Einfluss der Wasserverfügbarkeit auf die N-Mineralisation und hierdurch auf die Stickstoffaufnahme wurde mit dem natürlichen Vorkommen des ^{15}N Isotops im Oberboden in Beziehung gesetzt. Die Anwendung der ^{13}C Diskriminierung in den Körnern ermöglicht eine Darstellung der Wasserverfügbarkeit innerhalb einer Anbauperiode, während das natürliche Vorkommen des ^{15}N Isotops im Boden den langfristigen Stickstoffumwandlungsprozess in Abhängigkeit von N-Zugaben, aber auch der reduzierenden Bedingungen (in Folge von Austrocknung und Wiederbefeuchtung) reflektiert. Eine Kombination von stabilen Isotopenmethoden, Felderhebungen und gemischten statistischen Modellen verbesserte das Verständnis der Kopplung zwischen Erosion auf Hanglagen und Sedimentation in den Tallagen sowie auf die resultierende Ertragsleistung auf Toposequenzebene.

Verschiedene Studien zum Klimawandel sagen eine Zunahme von extremen Regenereignissen und Taifunen vorher, welches einen enormen Druck auf die Nachhaltigkeit der gegenwärtigen Landnutzung in Südostasien hervorrufen wird, wie es auch die vorliegende Studie zeigt. Um die Bereitschaft von Bauern zu untersuchen, Gegenmaßnahmen und Bodenschutzstrategien anzunehmen, wurde eine interdisziplinäre Studie durchgeführt, die sozioökonomische und biophysikalische Ansätze zur Erfassung der Auswirkung eines Taifuns auf eine Kommune in Nordwestvietnam kombinierte. Die Ergebnisse zeigten, dass die individuelle Bereitschaft der Bauern, Gegenmaßnahmen und Bodenschutzstrategien anzunehmen, von der ökonomischen Auswirkung der Überschwemmung auf Haushaltsebene, externen Faktoren (z. B. Klima, Versagen des Bewässerungsmanagements) und dem Mangel an Kenntnissen über Zusammenhänge zwischen Landbewirtschaftung in Hang- und Tallagen beeinflusst wurde. Eine erfolgreiche Implementierung bodenschützender Anbautechniken wird daher stark von den lokalen Entscheidungsträgern abhängen, da sie in der Bereitstellung angemessener Anreize für ein wachsendes Bewusstsein der Bauern im Hinblick auf die naturräumlichen Zusammenhänge zwischen der Bewirtschaftung von Hang- und Tallagen investieren müssen.

Es existiert eine deutliche Verbindung zwischen intensiver Bewirtschaftung der Hangflächen und der Ertragsleistung in Talflächen. Bei moderater Niederschlagsverteilung füllen die durch Erosion zugeführten Nährstoffe die Gehalte an Nährstoffen und organischer Substanz im Boden zumindest teilweise auf. Gleichwohl birgt als Konsequenz des zu erwartenden Klimawandels die Zunahme an Taifunen in der Untersuchungsregion ein erhebliches Risiko für Felder in Hanglagen und Reisfelder in den Tälern. Die Nährstoffumverteilungsprozesse sind jedoch vielschichtig und weisen eine räumlich-zeitliche Komponente auf. Die Identifikation von Bereichen mit Nährstoffanreicherung und –austragung innerhalb der Tallagen kann für die Entwicklung von verbesserten und schlagspezifischen Düngungs- und Bewässerungsmaßnahmen genutzt werden. Darüber hinaus kann die Identifizierung von Prozessen, die der Nährstoffumverteilung zugrunde liegen, Entscheidungsträger und Modellierer in die Lage versetzen, die Auswirkung veränderter Landnutzung auf Ökosysteme besser zu erfassen.

CHAPTER 8

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