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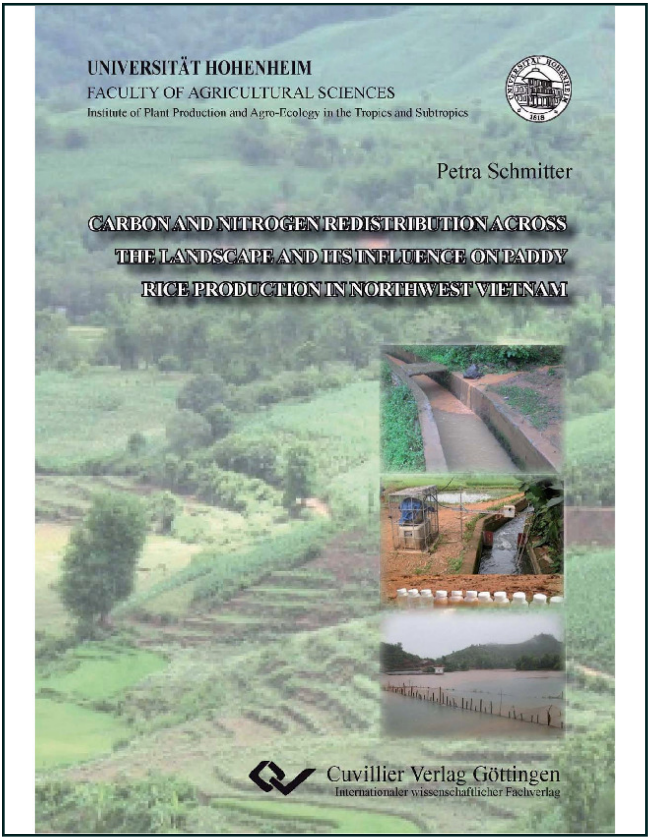
Carbon and nitrogen redistribution across the landscape and its influence on paddy rice production in Northwest Vietnam



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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.

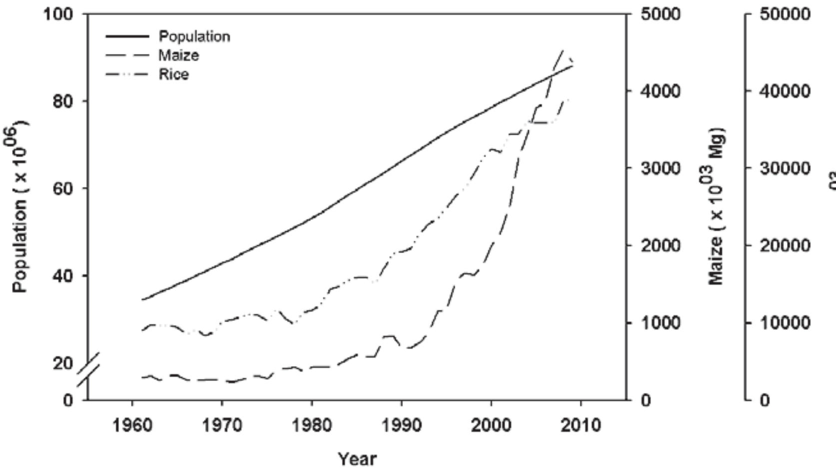

Figure 1-1: An overview of population growth, maize and rice production within Vietnam from 1961 till 2009 (source: FAO Stat, 2010).

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.

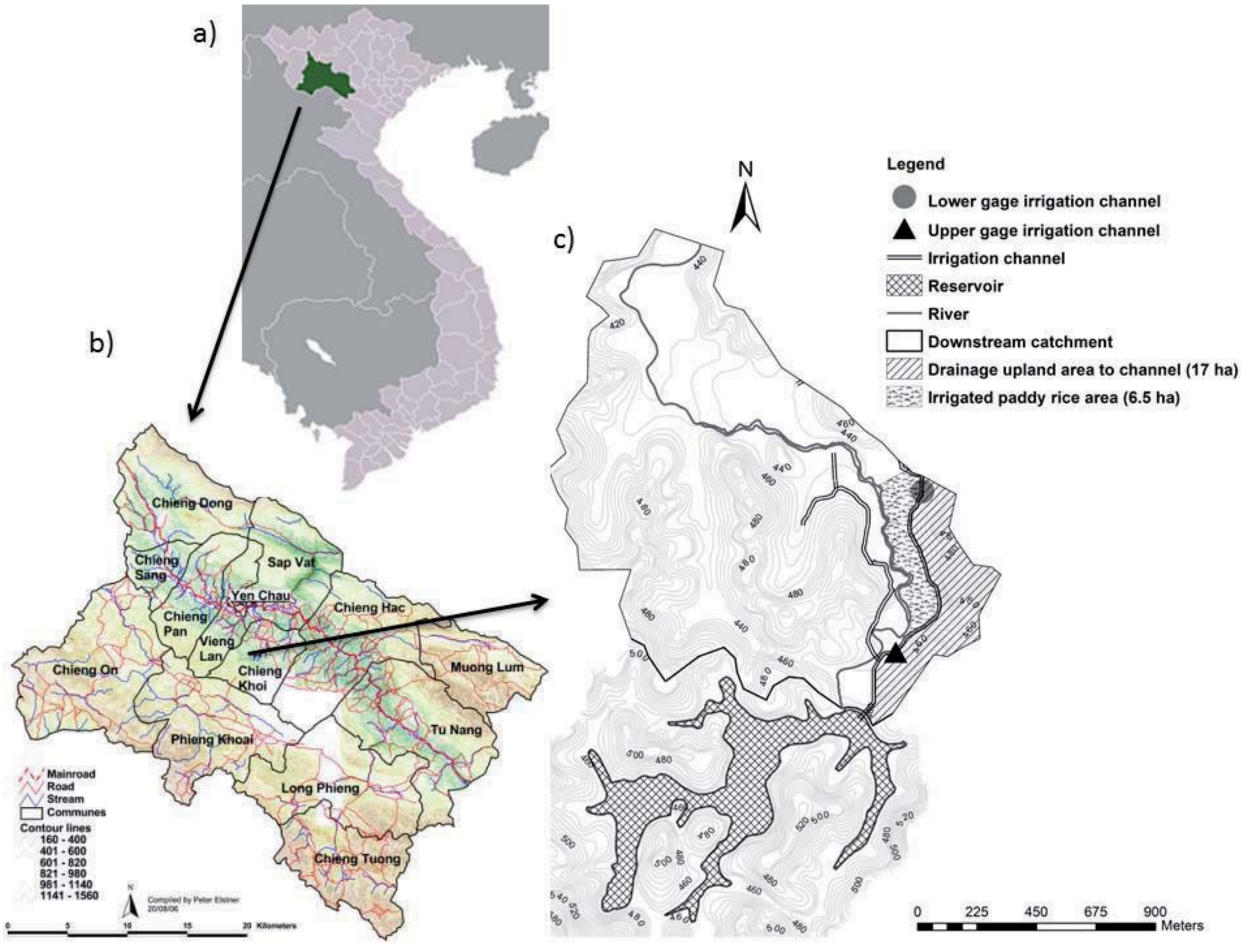

Figure 1-2: a) Location of Son La Province in Northwest Vietnam, b) Overview of communes within Yen Chau District which is situated in Son La province and c) Detailed overview of the study area with the position of water samplers (triangle and circle) and the location of the paddy rice terraces (cross)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

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.

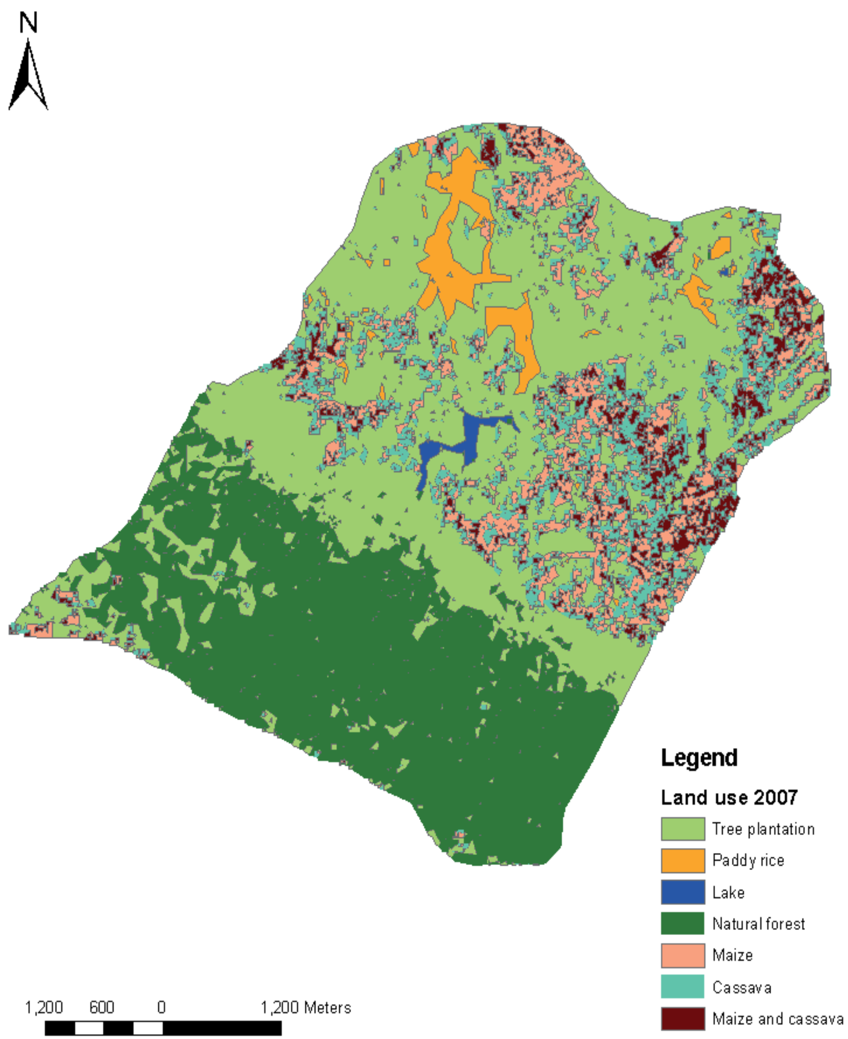

Figure 1-4: Land use classification based on LISS III 2007 satellite image (Nguyen, 2009).

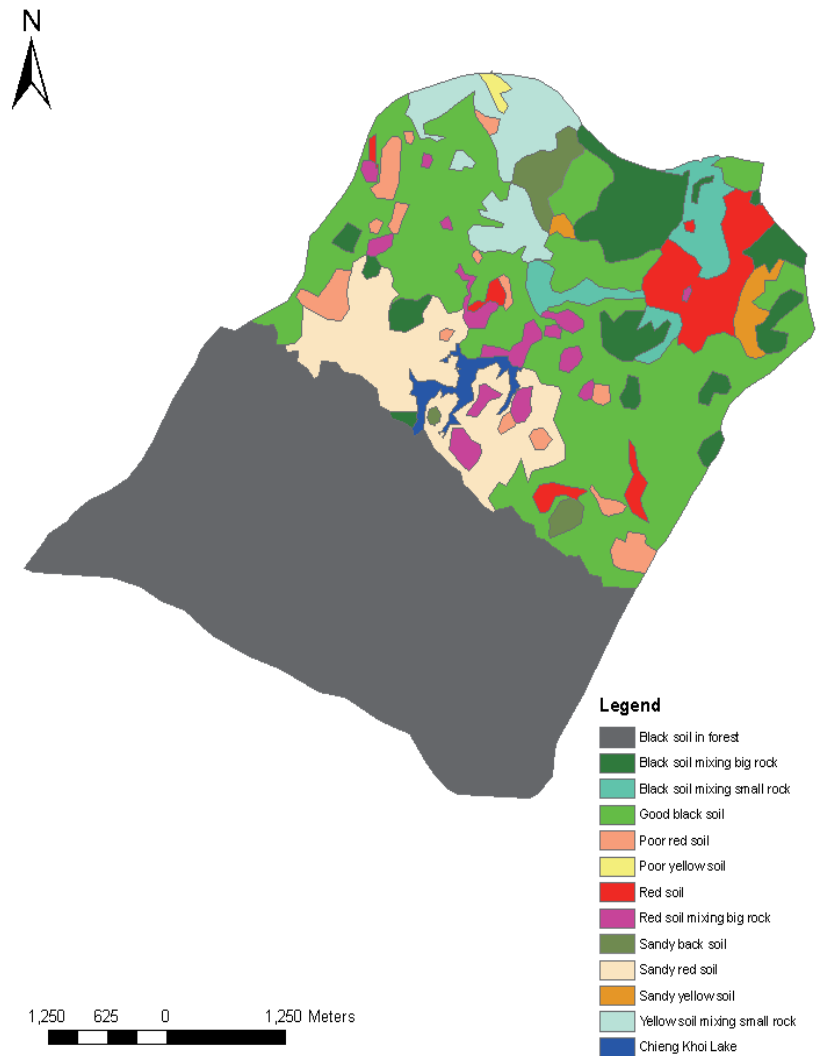

Figure 1-5: Soil type classification based on farmers knowledge (modified after Clemens et al., 2010).