Land use change and its impact on soil properties using remote sensing, farmer decision rules and modelling in rural regions of Northern Vietnam

Thanh Thi Nguyen

FACULTY OF AGRICULTURAL SCIENCES

Institute of Tropical Agricultural Sciences (Hans Ruthenberg Institute)
University of Hohenheim
Field: Agronomy in the Tropics and Subtropics
Prof. Dr. Georg Cadisch

Land use change and its impact on soil properties using remote sensing, farmer decision rules and modelling in rural regions of Northern Vietnam

Dissertation
Submitted in fulfillment of the requirements for the degree
“Doktor der Agrarwissenschaften”
(Dr.sc.agr./Ph.D. in Agricultural Sciences)

to the
Faculty of Agricultural Sciences

presented by

Thanh Thi Nguyen
Born in Hanoi, Vietnam
Submitted in November 2017

This thesis was accepted as a doctoral thesis (dissertation) in fulfillment of the requirements for the degree “Doktor der Agrarwissenschaften” (Dr. sc. agr./PhD in Agricultural Sciences) by the Faculty of Agricultural Sciences at the University of Hohenheim, Stuttgart, Germany, on April 5, 2018.

Date of the oral examination: May 17, 2018

Examination Committee

Chairperson of the oral examination:	Prof. Dr. Markus Rodehutscord
Supervisor and Reviewer:	Prof. Dr. Georg Cadisch
Co-Reviewer:	Prof. Dr. Thomas Berger
Additional Examiner:	Prof. Dr. Torsten Müller

Acknowledgements

I would like to express my deep gratitude and profound appreciation to my supervisors Professor Georg Cadisch and Dr. Carsten Marohn for giving me the chance to work with them and gain from their valuable suggestions, advice and support throughout this study. Especial thanks to Dr. Melvin Lippe, my ‘boss’ during his first PhD field trip in Vietnam, and was then a great officemate, and finally became my third supervisor. Without him, I would not have been able to complete this thesis; he gave me numerous valuable advice and suggestions on structure and writing.

This study was conducted within the framework of ‘The Uplands Program’, subproject C4.2, thanks to DFG-Germany who funded the project. Many thanks to Dr. Clemens, Ms. Hong, Mr. Chanh, Mr Hung, Mr. Hieu for their administrative and transportation support in Vietnam, thank to Dr. Thomas Hilger, Mrs. Rietze and Mrs. Fiedler for their helpful administrative support in Germany.

I would like to thank the members of the Center for Agricultural Research and Ecological Studies (CARES), Vietnam National University of Agriculture for supporting administrative permissions and scientific advice on GIS sharing working skills. My great appreciation to Prof. Dr. Tran Duc Vien for his continuous support and encouragement, despite my required absence from work. Many thanks to Ms Nguyen Thi Ngoc Thuy, my former boss, for her helpful advice and two years of training to improve my working skills before joining the Upland Program in CARES; her belief in me was a greatest motivation.

I gratefully acknowledge the members of Institute 490a (known before as 380a) - Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute) Section Agronomy in the Tropics and Subtropics (490e) - for sharing knowledge, encouragement and support. Thanks to all of you - Thomas, Gaby, Irene, Hanna, Scott, Petra, Juan Cobo, Juan Laso, May among many others. I also thank Dr. Thai Thi Minh for advice on qualitative data collection, detailed online training (via Skype) on using PRA methods and advice on local cultural adaptation during the field stay in Yen Chau district

I would like to thank all - the assistants: Do Thi Hoan, Nguyen Duy Nhiem - Hiwi students: Frieder Lutz, Dusha Manoharan-Hilscher, Aspasia Werner - intern students: Andreas Wimmer, Robert Kahle, Wolfgang Merkle; and, all the farmers who contributed their field works and information. Thanks to Lo Van Keo, Lo Van Chung and all village headmen for their support in contacting farmers and organizing workshops. Many thanks to the ‘Uplanders’, with whom I spent many months living with in the ‘PhD house’ in Yen Chau for a wonderful experience and buiding my confidence through all challenges of roads and paths full of rock and mud.

Finally, I would like to thank to my family, especially my parents and my parents-in-law, who always showed great encouragement. And lastly, thanks to my beloved husband Dr. Heinrich Karl Hagel, who was with me every single moment of my personal and scientific highs and lows in the oscillation curve of PhD life.

Stuttgart, 2017

Table of contents

List of figures

List of tables

List of abbreviations

CEC:	Cation Exchange Capacity
CLUEs:	Catchment Land Use for Environmental Sustainability
DDSAT:	Decision Support System for Agrotechnology Transfer
ENVI:	Environment for Visualizing Images
ESRI:	Environmental Systems Research Institute
FALLOW:	Forest, AgroForest, Low-value Landscape Or Wasteland
FAO:	Food and Agriculture Organization
GOF:	Goodness-of-fit
GPS:	Global Positioning System Ha: hectares
IISD:	International Institute for Sustainable Development
K:	Potassium
LANDSAT:	Land Remote -Sensing Satellite
Li DAR:	Light Detection And Ranging
LISS:	Linear Imaging Self Scanning Sensor
LU:	Land Use
LUC:	Land Use Change
LUCIA:	Land Use Change Impact Assessment MIRS: Mid Infrared Spectroscopy
MP-MAS:	Mathematical Programming-based Multi-Agent Systems
MSS:	Multi-spectral Scanner
N:	Nitrogen
NMR:	North Mountainous Region
NW:	Northwest
OM:	Organic matter
P:	Phosphorus
PRA:	Participatory Rural Appraisal
Radar:	RAdio Detection And Ranging
SAMBA:	Systèmes Agraires de Montagnes (means Mountain Agrarian Systems in French), BA (means three in Vietnamese)
SPOT:	Système Pour l'Observation de la Terre
WaNuLCAS:	Water Nutrients Light Capture in Agro Forestry System

Summary

After the Indo China war in 1954, a dramatic rise in population in Northwest Vietnam led to an increased demand of agricultural land for food security requirements. Slash and burn systems which existed for many hundreds of years were replaced by intense cash crop systems, particularly maize production. Maize cropping was further expanded to steeper sloping areas, resulting in a risk of soil degradation. Therefore, investigating Land Use Change (LUC) and its impact on soil properties were considered in this study.

The study aimed to identify LUC in 1954, 1973, the 1990s and 2007 in Chieng Khoi commune, Yen Chau district, Son La province, Vietnam using available remote sensing data. Furthermore, a detailed land use map classification method was developed using farmers' decision rules. Based on farmers' crop decision rules and, food requirement and population information, a simple LUC model was developed to simulate LUC annually from 1954 to 2007. Moreover, total soil nitrogen and carbon were determined under a chronosequence of intense cultivation. Thus, developing a modelling tool had the aim to assess the impacts of LUC on soil fertility at watershed level.

The first case study (Chapter 3) presented the LUC assessment, using available remote sensing data combined with farmer information. Forest areas decreased from 1954 to 2007, except in the 1990s because of policies that aimed to encourage and support afforestation programmes to increase forest land. However, planted forest has since decreased again since 1999 whereas agricultural land has increased dramatically. Agricultural land expanded to both natural forest and planted forest areas until 2007 legally (with encouragement of agroforestry) and illegally thereafter (at the border between cultivated land and forest). The establishment of an artificial lake in Chieng Khoi commune opened the accessibility to forest land surrounding the lake, with a forest area of 929 ha remaining in 2007 compare to more than 2,500 ha in 1954. Paddy rice areas did not change because of their specific location (lower and flat lands), but production increased and was intensified by two cropping seasons per year due to irrigation improvements and a continuous water supply from the artificial lake.

The second case study (Chapter 4) presented the development of a LUC model, using the outputs from the first case study comprising farmers' decision rules and food requirements for an increased population. For later periods, the influence of market orientation factor was considered. The model successfully simulated the expansion of cultivation areas and replacement of forest land by agricultural land. Simulations were at accepted level of accuracy comparing actual and simulated LUC (Goodness-of-fit - GOF values greater than 0.7 and Figure of merit - FOM values greater than 50%).

The third case study (Chapter 5) demonstrated an investigation of the soil fertility dynamic under intense cultivation and the development of a simple dynamic and spatially-explicit modelling tool to assess the changes in soil fertility. The Dynamic of total Carbon and Nitrogen distribution (DyCNDis) model was constructed using field data combined with literature information. The field data showed that, under a decade of maize mono cultivation in slope areas, both nitrogen and carbon were largely depleted. Furthermore, the DyCNDis model showed an acceptable level of validation (modelling efficiency - EF of 0.71 and root mean square error - RMSE of 0.42) to simulate nitrogen and carbon under intense maize cultivation at watershed level. Additionally, the model identified hotspot areas of 134 ha (18.9% of total upland cultivation areas) that are threatened by soil degradation through intense cultivation over a long-term period.

In conclusion, the combination of qualitative and quantitative approaches allowed assessing impacts of LUC on environmental services such as soil fertility through the developed DyCNDis modeling tool. The combination of improved LUC analysis with a simple spatial dynamic soil fertility modeling tool may assist policy makers in developing alternative implementation strategies for local stakeholders in regions which face data limitations. The modelling tools developed in this study were able to successfully simulate LUC and to identify locations where soil conservation methods at watershed level need most urgently to be applied to avoid soil degradation. The model tools were able to simulate the trends rather than values of agricultural area expansion and reduction of soil nitrogen and carbon. The developed approaches could be linked and coupled to other modelling tools to economically consider benefits or ecological concerns toward sustainable crop production in remote and rural regions.

German summary – Zusammenfassung

Nach Ende des Indochinakrieges im Jahr 1954 führten ein starkes Bevölkerungswachstum und der damit steigende Bedarf an Nahrungsmitteln in Nordwestvietnam zu einer enormen Ausweitung der landwirtschaftlich genutzten Flächen. Intensivierte Landwirtschaft, insbesondere im Maisanbau, ersetzte die traditionellen Landnutzungssysteme, die hauptsächlich auf Brandrohdung basierten und zuvor für Jahrhunderte Bestand hatten. Vor allem der Maisanbau wurde zunehmend auf Steillagen ausgeweitet, was beträchtliche Risiken der Bodendegradierung nach sich zog. Aus diesem Grund, befasst sich diese Dissertation mit der Erforschung der Landnutzungsänderungen (LUC) und ihren Auswirkungen auf die Bodeneigenschaften der betroffenen Flächen.

Das übergeordnete Ziel dieser Dissertation ist die Analyse der Landnutzungsänderungen in der Kommune Chieng Khoi des Distrikts Son La in den Jahren 1954, 1973, den 1990er Jahren sowie 2007. Hierfür wurden verfügbare Fernerkundungsdaten verwendet. Zudem wurde eine detaillierte Klassifizierungsmethode zur Erstellung von Landnutzungskarten entwickelt. Basierend auf den Anbauentscheidungen der Kleinbauern in der Studienregion, Nahrungsmittelbedarf und demographischen Daten, wurde ein einfaches dynamisches und räumlich-explizites Modell zur Simulation der Landnutzungsänderungen im Zeitraum von 1954 bis 2007 erstellt. Außerdem wurden Gesamtstickstoff und der gesamte Kohlenstoffgehalt unter intensiver Landnutzung durch Feldbeprobungen und Laboranalysen bestimmt. Auf diese Weise hatte die Modellentwicklung das Ziel. den Einfluss der Landnutzungsänderungen auf die Bodenfruchtbarkeit im Wassereinzugsgebiet des Chieng Khoi-Sees zu analysieren und zu bewerten.

Die erste Fallstudie dieser Dissertation (Chapter 3) behandelt die Bewertung der Landnutzungsänderungen mit Hilfe von Fernerkundungsdaten und Interviews mit Kleinbauern. Nahezu der gesamte Zeitraum von 1954 bis 2007 war durch Abholzung geprägt. Eine Ausnahme stellen die 1990er Jahre dar, in denen Aufforstung durch diverse politische Maßnahmen gefördert wurde. Diese kurze Phase der Aufforstung endete jedoch bereits im Jahr 1999, als mit massiver Abholzung begonnen wurde. Bis ins Jahr 2007 wurden sowohl Primärwälder, als auch wieder aufgeforstete Flächen zur Erschließung von Ackerland gerodet. Dies geschah zum einen auf legalem Weg im Rahmen von staatlich geförderten Agroforstprogrammen, zum anderen illegal an den Grenzbereichen der Ackerflächen zu Wäldern. Insbesondere die Errichtung des Chieng Khoi-Stausees ermöglichte die landwirtschaftliche Erschließung umliegender Waldgebiete. Als Konsequenz gingen die Waldgebiete von 2.500 Hektar in 1954 auf 929 Hektar in 2007 zurück. Im Gegensatz zu Hanglagen hatte die Errichtung des Stausees lediglich geringe Auswirkungen auf den Nassreisanbau in flachen Lagen und Tälern.

Dennoch wurden auch im Nassreisanbau Veränderungen registriert. Die konstante Wasserverfügbarkeit durch den Stausee ermöglichte die Einführung eines zweiten Produktionszyklus pro Jahr. Außerdem konnten durch intensivere Bewirtschaftungsmethoden die Erträge gesteigert werden.

In der zweiten Fallstudie (Chapter 4) wird ein Modell zur Simulation von Landnutzungsänderungen entwickelt. Hierfür werden die Ergebnisse der ersten Fallstudie, die Anbauentscheidungen der Kleinbauern in der Studienregion und der Nahrungsmittelbedarf einer wachsenden Bevölkerung herangezogen. Mit Hilfe des Modells konnte die Ausweitung der landwirtschaftlich genutzten Flächen sowie die dadurch bedingte Abholzung erfolgreich simuliert werden. Simulierte Ergebnisse lagen beim Vergleich mit historischen Daten im Toleranzbereich.

Die dritte Fallstudie befasst sich mit der Untersuchung der Entwicklung der Bodenfruchtbarkeit in intensiven Ackerbausystemen. Zudem wurde ein einfaches Modellierungstool zur Bewertung der Änderungen der Bodenfruchtbarkeit entwickelt. Das Modell zur Analyse der Entwicklung der gesamten Kohlenstoff- und Stickstoffverteilung (DyCNDis) wurde mit Hilfe von im Feld erhobenen Primärdaten sowie Sekundärdaten aus relevanter Literatur entwickelt. Anhand der Primärdaten konnte gezeigt werden, dass an Hanglagen sowohl der Kohlenstoff- als auch der Stickstoffgehalt im Boden bereits nach einem Jahrzehnt Maisanbau drastisch abgenommen hatte. Zudem konnte das DyCNDis-Modell zufriedenstellend validiert werden. Demnach ist das Modell geeignet, um Kohlenstoff- und Stickstoffgehalte im Boden unter intensivem Maisanbau für Wassereinzugsgebiete zu simulieren. Außerdem konnten Standorte, welche bei dauerhafter landwirtschaftlicher Nutzung besonders von Bodendegradation bedroht waren, identifiziert werden. Diese Standorte hatten eine Gesamtfläche von 134 ha, was 18,9% der gesamten Ackerfläche an Hanglagen in der Forschungsregion entspricht.

Zusammenfassend kann gesagt werden, dass die Kombination qualitativer und quantitativer Forschung eine hinreichende Bewertung der Einflüsse von Landnutzungsänderungen auf Ökosystemdienstleistungen ermöglicht. Dynamische Veränderungen der Landnutzung und Bodenfruchtbarkeit werden, wie in der Vergangenheit, auch in Zukunft auftreten. Besonders in Regionen mit beschränkter Datenverfügbarkeit bietet diese Dissertation politischen Entscheidungsträgern mögliche Umsetzungsstrategien für lokale Stakeholder. Die im Rahmen dieser Dissertation entwickelten Modelle konnten Landnutzungsänderungen zuverlässig modellieren und Standorte identifizieren, an denen eine Einführung von bodenkonservierenden Maßnahmen notwendig ist, um eine Bodendegradation zu verhindern. Darüber hinaus können Modelle zur Einsparung von Kosten und Arbeitszeit bei Feldversuchen verwendet werden, sowie für die Bewertung des ökonomischen Nutzens oder von ökologischen Bedenken zu einer nachhaltigeren Landbewirtschaftung in abgelegenen und ländlichen Regionen beitragen.

Vietnamese summary - Tóm tắt

Sau chiến tranh Đông Dương 1954, dân số vùng Tây Bắc Việt Nam tăng nhanh đã đặt ra yêu cầu tăng về diện tích đất sản xuất nông nghiệp nhằm đảm bảo an ninh lương thực. Hệ thống canh tác du canh du cư tồn tại hàng trăm năm đã được thay thế bởi hệ thống thâm canh cây trồng hàng hóa, đặc biệt là cây ngô. Canh tác ngô đã được mở rộng trên cả những vùng đất dốc, dẫn đến tăng nguy cơ thoái hóa đất, ảnh hưởng đến phát triển nông nghiệp một cách bền vững. Do đó, nghiên cứu này tập trung vào đánh giá sự thay đổi tình hình sử dụng đất và ảnh hưởng của nó đến các đặc tính của đất.

Mục tiêu cụ thể của nghiên cứu nhằm xây dựng bản đồ tình hình sử dụng đất trong năm 1954, 1973, những năm 1990 và năm 2007 tại xã Chiềng Khoi, huyện Yên Châu, tỉnh Sơn La dựa trên dữ liệu ảnh viễn thám sẵn có. Ngoài ra, nghiên cứu này còn cải tiến phương pháp thiết lập chi tiết bản đồ sử dụng đất dựa vào quyết định của người dân. Kết hợp với sử dụng thông tin về quyết định của người dân, nhu cầu thực phẩm và thông tin dân số, một mô hình đơn giản được xây dựng nhằm dự đoán biến động sử dụng đất hàng năm từ năm 1975 đến 2007. Ngoài ra, hàm lượng ni tơ (N) và các bon (C) tổng số cũng được xác định trong các hình thức thâm canh. Do đó, một mô hình dinh dưỡng được xây dựng nhằm đánh giá tác động của thay đổi tình hình đất đến dinh dưỡng đất ở cấp độ lưu vực.

Kết quả ban đầu (Chương 3) của luận án đã đưa ra những đánh giá về sự thay đổi sử dụng đất dựa trên các dữ liệu viễn thám sẵn có kết hợp với thông tin cung cấp bởi người dân địa phương. Từ năm 1954 đến 2007, diện tích rừng bị giảm đáng kể, ngoại trừ những năm 1990 do áp dụng các chính sách khuyến khích và hỗ trợ các chương trình trồng cây gây rừng để tăng diện tích đất lâm nghiệp. Tuy nhiên, diện tích rừng trồng đã giảm trở lại sau năm 1999 trong khi đất nông nghiệp lại tăng lên rõ rệt. Nguyên nhân là do việc khuyến khích canh tác nông lâm kết hợp dẫn đến diện tích đất nông nghiệp được mở rộng trên cả diện tích rừng tự nhiên và rừng trồng cho đến năm 2007; và sau đó việc mở rộng xâm lấn bất hợp pháp vẫn tiếp tục diễn ra ở vùng giáp ranh giữa đất trồng trọt và đất rừng. Việc xây dựng một hồ nước nhân tạo ở xã Chiềng Khoi đã tạo cơ hội cho việc tiếp cận đất rừng bao quanh hồ, dẫn đến diện tích rừng bị giảm rõ rệt. Năm 2007 diện tích rừng còn lại là 929 ha, trong khi con số này năm 1954 là 2,500 ha. Diện tích lúa nước không thay đổi đáng kể do đặc thù vị trí địa hình (ở vị trí đất thấp và bằng phẳng) nhưng sản lượng lúa tăng do được thâm canh hai vụ nhờ cải tiến hệ thống thủy lợi và nguồn nước tưới từ hồ nhân tạo.

Chương sau (Chương 4) của luận án trình bày về mô hình dự đoán tình hình sử dụng đất, dựa trên những kết quả đã tìm ra từ Chương 3, kết hợp với quyết định của người dân và nhu cầu lương thực đáp ứng sự gia tăng dân số. Mô hình đã dự đoán thành công sử mở rộng của đất canh tác trên diện tích rừng. Mô hình có độ chính xác ở mức được chấp nhận bằng phương pháp so sánh sự thay đổi dự đoán và thay đổi thực tế.

Chương tiếp theo (Chương 5) của luận án tập trung về nghiên cứu sự biến động của độ phì đất trong các hệ thống thâm canh và quá trình xây dựng mô hình tiếp cận sự biến động của phân bố dinh dưỡng đất. Mô hình ‘Biến động sự phân bố của ni tơ và các bon tổng số ‘- ‘Dynamic of total Carbon and Nitrogen distribution - DyCNDis’ được xây dựng trên cơ sở số liệu thực địa kết hợp với thông tin thứ cấp. Kết quả của nghiên cứu thực địa cho thấy, khi ngô được trồng thâm canh liên tục trong thời gian dài trên đất dốc, hàm lượng Ni tơ và Các bon đều suy giảm nghiêm trọng. Ngoài ra, mô hình DyCNDis cho độ chính xác được chấp nhận Kết quả từ mô hình dự đoán xã Chiềng Khoi có 134 ha đất canh tác có nguy cơ suy thoái cao, chiếm 18.9% tổng diện tích canh tác trên đất dốc.

Tóm lại, sự kết hợp các phương pháp định tính và định lượng cho phép đánh giá tác động của thay đổi tình hình sử dụng đất đến các dịch vụ môi trường. Thay đổi tình hình sử dụng đất sẽ còn tiếp diễn trong tương lai cũng như biến động của độ phì đất. Do vậy, nghiên cứu này cung cấp những chiến lược tiềm năng cho những nhà hoạch định chính sách cũng như các bên liên quan ở địa phương nơi mà cơ sở dữ liệu còn hạn chế. Hai mô hình giới thiệu trong luận án được xây dựng và áp dụng thành công nhằm dự đoán biến động của tình hình sử dụng đất. Ngoài ra, các mô hình cũng xác định những khu vực có nguy cơ thoái hóa đất cao. Những diện tích này cần được khẩn trương áp dụng các biện pháp cải tạo đất nhằm tránh hiện trạng thoái hóa đất trở lên trầm trọng hơn. Hơn nữa, sử dụng các công cụ mô hình sẽ tiết kiệm thời gian cũng như nhân lực cho các thí nghiệm thực địa. Công cụ mô hình còn đề cập các lợi ích kinh tế kết hợp với đảm bảo chất lượng sinh thái trong sản xuất cây trồng theo theo hướng bền vững ở vùng sâu vùng xa.

Chapter 1. General introduction

Land use change is an importance global issue. This dissertation analyses land use change and the impact on mountainous regions in Northwest Vietnam.

1.1 Initiation of study and terminology

This work was conducted within the collaborative research programme SFB 564: 'Sustainable Land Use and Rural Development in Mountainous Regions of Southeast Asia' (also known as 'The Uplands Program') funded by the DFG (Deutsche Forschungsgemeinschaft) – Germany. The project aimed to provide a scientific contribution to the conservation of natural resources and the improvement of living conditions of the rural population in mountainous regions of Southeast Asia. Within interdisciplinary subprojects, the Upland Program covered many topics on soil and water, fruit production, livestock systems, processing and marketing, socioeconomics and integrated modelling. This study was part of the integrated modelling group subproject C4 - which focused on the modelling of land use dynamics. The specific topic was: 'Impact of intensification on land use dynamics and environmental services of tropical mountainous watersheds'. The overall objective of C4 was to assess the impact of the intensification of land use on productivity and on environmental services. The presented study particularly focused on land use change and its impacts on soil fertility across the Chieng Khoi watershed in Northwest (NW) Vietnam.

Considering the terminology, 'land use change' - or LUC is a transformation process at landscape level by human activities, but also caused by natural disasters. The back and forward transformation occurs between forests, agricultural, residential, industrial, and other purposes. Herein, LUC also considers the transition from one crop to another crop, as well as from mono-crop to multi-crop or *vice versa* in the same cultivation areas (Müller and Zeller, 2002). In general, 'land use' is often defined as the human purpose or intent applied to the attributes, whereas 'land cover' is often defined as biophysical attributes of the earth's surface (Lambin *et al*., 2001). In this thesis, 'land use' (LU) and 'land use/cover' (LULC) terms are used following those definitions with same meaning.

'Land use change impacts' are the consequences of 'land use change' in biophysical and social environment (Veldkamp *et al*., 2004). For instance, LUC was a driving force for modification of socio-economic behaviours such as farmer decisions on type of crop, dynamic crop productivity, soil processes, and food security (Berger *et al*., 2001; Tang *et al*., 2005; Verburg *et al*., 2013). Herein, this study focuses on the impact of LUC on soil fertility. Moreover, soil fertility refers to the ability of soils to supply adequate quantities and appropriate proportions of nutrients and water for plant requirements (Loganathan, 1987; Abbott and Murphy, 2003). Therefore, ‘soil fertility’ directly influences crop productivity and food security at the watershed level (Donahue, 1965; Beeson and Matrone, 1976; Abbott and Murphy, 2003). In this study, total nitrogen (N) and total carbon (C) are used to as indicators for ‘soil fertility’.

1.2 Land use change: From a global issue to regional importance

At the global level, the evidence of LUC was reported though a wide range of phenomena and causes. Lambin *et al*. (2001, 2006) stated that intensification of the agricultural sector was one of the importance causes as well as a consequence. Firstly, the population pressure led to land scarcity and an increase in the quantity and value of agricultural in- and outputs; for example, the dominance of commercial crops in many global regions. Soil degradation has reported across many areas of the world, especially where agricultural production has intensified.

The circumstances of LUC vary from long- to short-term periods. At long-term periods, Ellis *et al*. (2013) synthesized scientific evidence and theory on global history as a process of transformation of the Earth System over >3,000 years. The distribution of land use systems changed over time including land-use intensification, expansion of agriculture, urbanisation, and intensive industrial land-use. Analyses of short-term periods often focus on the reduction of forestry as one of the main issues of LUC in recent. For example, FAO (2015 - Global Forest Resources Assessment) reported a decrease in global forest areas by around 50% during the 1990s to 2015. Tropical forests cover about 10% of the Earth’s surface and play an importance role as carbon pools and natural habitats for half to two-thirds of the world’s species biodiversity. Unfortunately, tropical forest areas are decreasing in all continents, indeed. Lewis (2006) reviewed the change of tropical forests over recent decades and indicated that about 58% of Asian, 19% of African and 28% of Latin American tropical forests were logged for commercial purposes and converted to other land-use types in the mid-1990s. An important LUC driver is the increase in urban populations that exceeded the rural population in 2008 for the first time (Seto and Shepherd, 2009). Urbanization will still occur as one of 15 trends affecting the world’s food system in the near future (Tang, 2005; FAO, 2017a). In addition, FAO (2017a) reported that the world’s population is expected to reach almost 10 billion by 2025. Therefore, satisfying increasing demands on agriculture and economic growth is expected to be one of the upcoming main causes of global LUC.

To examine the causes of LUC drivers and factors, Lambin *et a*l. (2001) summarized the major myths that could be attributed to the driving forces of land cover and LUC.

Their study showed that human activities play an important role. Also, a recent study by Ellis *et al*. (2013) confirmed such ongoing patterns from the recent past. In Southeast Asia, and Vietnam, socio-economic development and population pressure requires the expansion of cultivation areas to feed an increasing population and to satisfy market demands. During the last two decades, Vietnam's market orientation has focused on high yielding and high-value cash crops that have replaced local subsistence and staple cropping systems in NW Vietnam. Consequently, traditional cultivation systems were replaced by modern systems with high yielding varieties, increasing fertilizer and pesticide use, and also encouraging different farming management systems (Mertz, 2009b; Schmidt-Vogt *et al*., 2009).

LUC can lead to the modification of ground surfaces that can in turn lead to a reduction of carbon-stocks followed by rapid increases in greenhouse gas emissions, further modifying micro and macro climates (FAO, 2009). For example, natural disasters and extreme weather events may occur more frequently in regions due to deforestation (IPCC, 2014; Shad *et al*., 2012). Such LUC consequences can further affect human livelihoods and ecosystem heath, potentially leading to further unexpected impacts of LUC (Verburg *et al*., 2013; van Vliet *et al*., 2015; Schad *et al*., 2012). Furthermore, LUC can have serious impacts on natural resources such as soil and water (Lambin *et al*., 2001), indeed, mountainous regions are more susceptible to changing natural conditions when cultivation areas were expanded to steeper slopes and because upland and lowland are strongly connected by streams and rivers systems (Wymann von Dach *et al*., 2013). Rutten *et al*. (2014) also confirmed that LUC is an inter-connected factor of different scales. Thus, LUC and its impacts at the watershed scale can directly contribute to dynamics and impact trends occurring on larger scales. As LUC relates to other factors such as socio-economic development, climate change and food security, a better understanding of the potential impacts of LUC to soil fertility in mountainous areas is highly relevant for a more sustainable agricultural development on upland and lowland regions.

1.3 Potential causes of LUC in mountainous regions Vietnam

For the case of the Northwest Mountainous Region (NMR) Vietnam, LUC transformed many parts of agricultural sectors during the period of the 1950s - 1960s, in particular after the Indo China war. For example, agricultural areas were expanded due to food demand caused by an increasing population (Dao Minh *et al*., 2017; Lentz *et al*., 2011; Lentz, 2017). This period was characterized by a strong focus on subsistence crop production. During the following decades, however, improved infrastructure, market orientation and a continuous pressure due to the population led to a complete transition of local farming systems. For instance, intensive monocultures widely replaced the traditional systems of composite swidden farming, a previously common farming system in many parts of NMR (Schmitter *et al*., 2011; Keil *et al*., 2008). In the swidden system, rain-fed crops were planted on upper slopes, whereas paddy rice was cultivated on lower flat lands. Upland fields were usually set aside as fallow for more than seven years until the next cultivation cycle began (Rambo, 1998; Fox and Vogler, 2005). During the late 1990s, the Vietnamese government began to promote hybrid maize farming systems that required a more intensified cultivation approach (Keil *et al*., 2008). As a result, intensive maize mono-cropping systems expanded and can be widely found on upland hills in NMR. Maize has been one of the most important cash crops in such intensive farming systems, fostering the high demands of local and regional livestock feed (Keil *et al*., 2008). Consequently, farmers' income also increased rapidly during this period which was in strong contrast to previous decades, where most farmers experienced a two to three food scarcity, especially during the beginning of the cropping period. In the early 2000s, the period of food shortage declined (Minh, 2010), leading to a 10 year swift the phenomenon of intensive the hybrid maize cultivation that became one of the most important factors in improving the livelihood of farmers in NMR of Vietnam (Keil *et al*., 2008; Tuan *et al*., 2014; Wezel *et al*., 2002a).

The transformation of local farming systems in NMR that started in the 1950s continued along with the conversion of large forest areas into swidden cropping areas (Hanh *et al*., 2017; Dao Minh *et al*., 2017; Diez, 2016; Haering *et al*., 2014, Minh, 2010). With the intensification of cropping systems in the 1990s, soil fertility started to decline due to a lack of fallow recovery periods, increased occurrence of run-off and soil erosion events, and use of mineral fertilizers (Clemens *et al*., 2011; Haering *et al*., 2014; Tuan *et al*., 2014). The negative impacts of long-term and continuous erosion and run-off were not considered during the governmentally-induced promotion of hybrid maize cropping systems. Consequently, soil degradation has become a serious issue, and will potentially lead to a decrease in maize yields (Tuan *et al*., 2014), making agriculture an impossible endeavor due to the increasing dominance of degraded soils.

Considering the causes of agricultural intensification, government programs play an important role in NMR (Cox and Le, 2014; Minh, 2010; Friederichsen and Neef, 2010; Nguyen, 2012; Yen *et al*., 2013; Minh *et al*., 2011). For instance, during the 1990s and 2000s, government agencies were the main driver in introducing improved varieties (at beginning) and hybrid paddy varieties to increase crop yields and to ensure local food security (Minh *et al*., 2011; Bonnin and Turner, 2014). Moreover, the implementation of new land policies, e.g. land renovation policies (also referred to as Doi Moi - 1986 and Land Law - 1993) resulted in the legalization of land use rights for local farmers.

The policies further aimed to foster rural development, especially in NW Vietnam. Since then, farm income, life expectancy of household members, education, availability of inputs such as fertilizers, as well as crop yields were better comparing to the period without official land use rights. Additionally, these new policies led to spatial and temporal differences of fertilizer use, land productivity, and a diversification of crop management regimes (Nguyen, 2012).

Nevertheless, a common mistake of newly implemented land use plans and policies has been the poor consideration of environmental and ecosystem aspects. Most land use plans for rural development only consider only focused on improving livelihoods or increasing crop/plantation productions (Sikor and Truong, 2002; Diez, 2016; Dieu, 2016).

1.3.1 The expansion of agricultural areas and the intensification in cropping management

Rapid population growth in NRM led to a highly increased demand for food during the early 1960s in NMR Vietnam. Therefore, cultivation areas needed to be extended to satisfy the needs of the growing population. NMR is characterized by low soil fertility and low levels of technology and household capital (Yen *et al*., 2013). After the 1990s, the use of fertilizer, the implementation of hybrid varieties (maize, rice), and herbicides and pesticides have improved crop productivity. However, these developments also led to changing farmers' preferences. For example, before the 1980s cultivation aimed solely towards food self-sufficiency, but then, the purpose of cultivation switched to cash income (Minh *et al*., 2011). The demand for cash income arose rapidly in the 2000s and became a wide spread of phenomenon across the whole region (Keil *et al*., 2008). Consequently, large areas were converted to cultivation areas or from natural forest to production forest, either legally within governmental programs or illegally by individual farmers (Vongvisouk *et al*., 2016; Haering *et al*., 2013).

Besides the expansion of cultivation areas into the forest, crop area expansion to steeper slopes also occurred (Sikor and Truong, 2002; Wezel, 2002a: Clemens *et al*., 2010; Schad *et al*., 2012). For example, Figure 1.1 (a) shows the expansion of cultivation into secondary forest, whereas picture 1.1 (b) and (c) presents the expansion of cultivation toward remaining forest areas and steep slopes. The usual cultivation pattern starts at lower slopes and extends to upper slopes annually or every few years during cultivation, depending on the farmers' needs and labor availability (Haering *et al*., 2013). Nevertheless, this study focuses on the mechanism of cultivation areas rather than forest land. The location and transition linkages between forest and agricultural land, thus, the expansion of agricultural into forest zone need to be examined (see further in Chapter 4). Earlier, Haering *et al*. (2013) confirmed that agricultural areas expanded into forest zones. However, long-term information of the main mechanism to understand the causes of agricultural areas expansion in NW Vietnam is lacking.

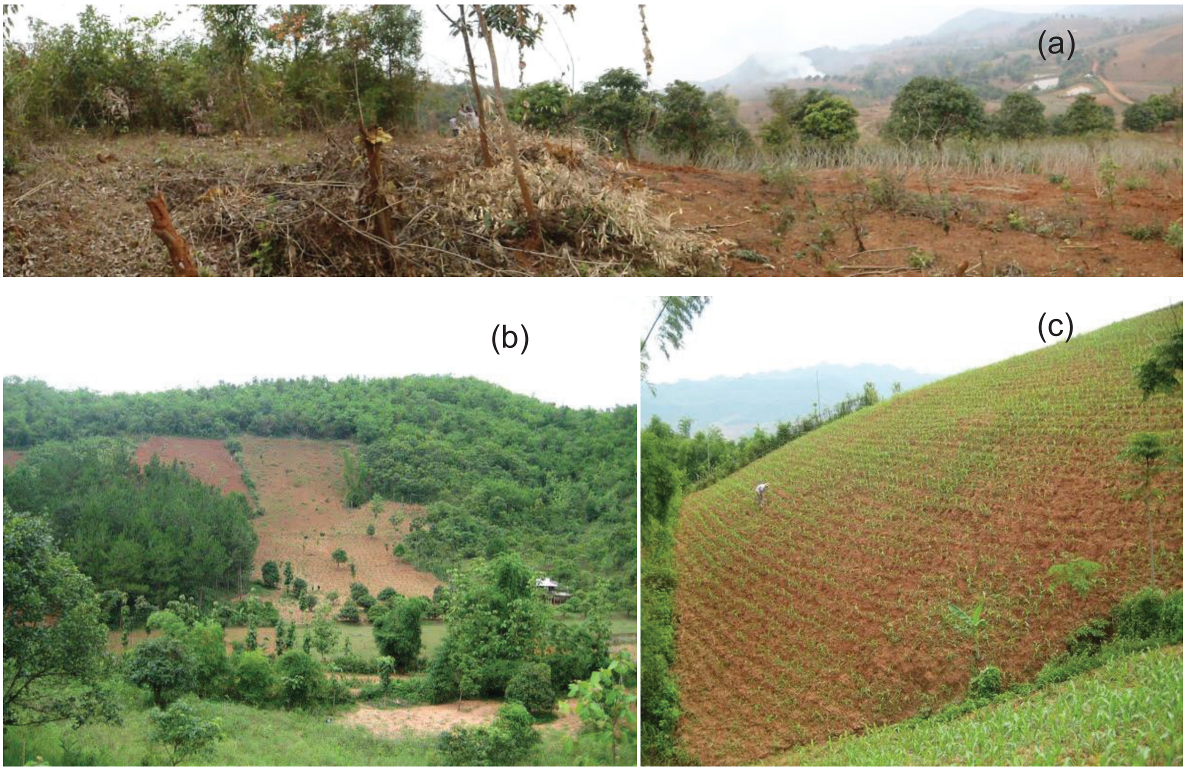


Figure 1.1 Expansion of agricultural areas into the forest (a, b) and toward to steeper slopes (c) in NW Vietnam during 2010 – 2011

Beside the expansion of agricultural areas, the intensification in the cash crop was described in the study region (Mertz *et al*., 2009b; Valentin *et al*., 2008; Dao Minh *et al*., 2017). Cotton, mulberry for worm silk, and hybrid maize were introduced as cash crops during the 1990s (Minh, 2010). However, cotton and mulberry existed for just a few years due to low demand and low producer prices. However, hybrid maize cultivation gained importance because of the high demand from the feed production industrial market (Minh, 2010; Keil *et al*., 2008). Figure 1.2 shows the development of maize production, areas, and yields in Vietnam (FAOSTAT, 2017a,b). A large increase of production, areas, as well as yield has appeared since the 1990s. This increase came along with increasing stocks of pigs and cattle, because maize is the primary source for feed production for domestic demand (Ha *et al*., 2004).

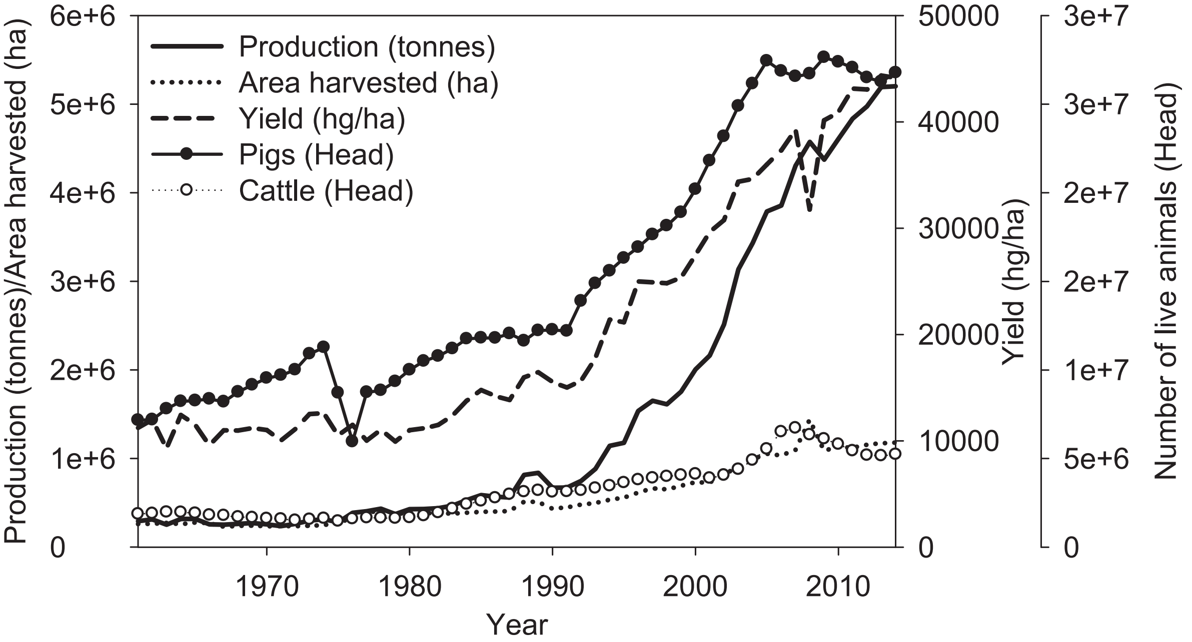


Figure 1.2 Development of maize production, harvested areas, and yield and number of pigs and cattle in Vietnam from 1961 - 2014 (FAOSTAT, 2017a,b)

Before the appearance of cash crops, seeding was done manually, thus minimizing soil disturbance. Crop production was done without chemical fertilizer or manure application (Vien *et al.*, 2007; Ramboo *et al.*, 1997). New farm management approaches, such as tillage and fertilizer became common during the rise of maize cultivation. Figure 1.3 shows the tillage by water buffalo on steep slopes in Son La province, NW Vietnam. Fields were ploughed after slashing and burning the weeds to prepare the soil before seeding the un-irrigated maize crop. Therefore, the hybrid maize system in NW Vietnam was characterized as a tillage system with a high application of chemical fertilizer (Ha *et al.*, 2004; Keil *et al.*, 2008; Wezel, 2000). Typically, seeding was conducted following heavy rain. As uncovered soils on slopes are extremely susceptible to erosion, especially in cases of heavy tropical rain events, the intensive maize production is seen as a threat for the environmental sustainability in the fragile uplands of Vietnam (Keil *et al.*, 2013).

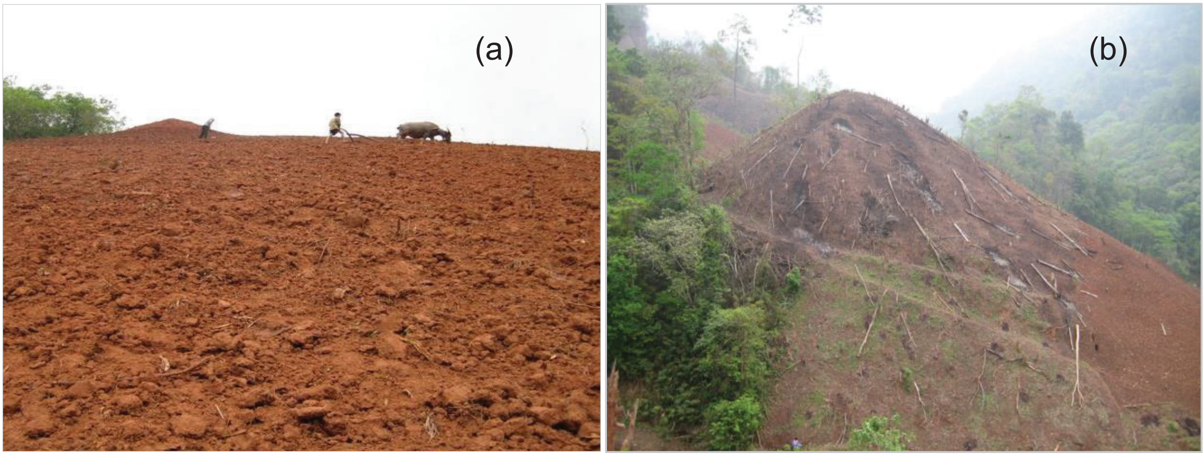


Figure 1.3 Tillage in slope (a) increasing to upper slope (b) in NW Vietnam in 2011

1.3.2 The reduction of soil fertility and the soil degradation threaten food security

Agricultural activities in NMR contributed directly or indirectly to modify and reduce soil fertility, especially for under intensified crop management regimes (Lal *et al*., 1989; Tuan *et al*., 2014; Wezel, 2000; FAO and ITPS, 2015). Abbott and Murphy (2003) divided soil fertility into three main components: physical, chemical, and biological; the level of soil fertility resulting from the interaction between these components.

Considering the chemical properties, this study used total nitrogen (N) and total carbon (C) as indicators for chemical properties. Total N is one of the macronutrients and essential elements for plant growth (Abbott and Murphy, 2003). The C content includes organic and inorganic carbon. Organic C further provides energy for soil microorganisms and is a trigger for nutrient availability through mineralization, contributing to aggregate stability, and water and nutrient holding capacity (Edwards *et al*., 1999). Physical and biological components are highly relevant for soil fertility (FAO, 2006; Schoenholtz *et al*., 2000; Arshad and Coen, 1992). Physical components in soil include texture, structure, consistence, particle density and bulk density, pore space, and colour, among others. Soil biological components include microbial and faunal elements (FAO, 2006; Bergstroem and Kichmann, 1998). Although all components are relevant for assessing soil fertility, this study focuses on the dynamics of total C and N as representatives of *soil fertility*.

In terms of NW Vietnam, the soil C and N contents were reduced due to run off and soil erosion caused by an intensified agricultural system (Tuan *et al*., 2014, Wezel *et al*., 2002a; Haering *et al*., 2013). Contrary to the development of natural soil fertility, high amounts of total N were found, which even exceeded the needs for plant growth in many cases. The main reason for that was over fertilizing by farmers. The dynamic of total C and N in the soil is well-investigated (Dung *et al*., 2008; Nga *et al*., 2016; Wezel *et al*., 2002a, b; Haering *et al*., 2013, Clemens *et al*., 2010). However, the details in speed and future phenomena are still lack of research, especially for mono cropped maize at landscape level in NW Vietnam.

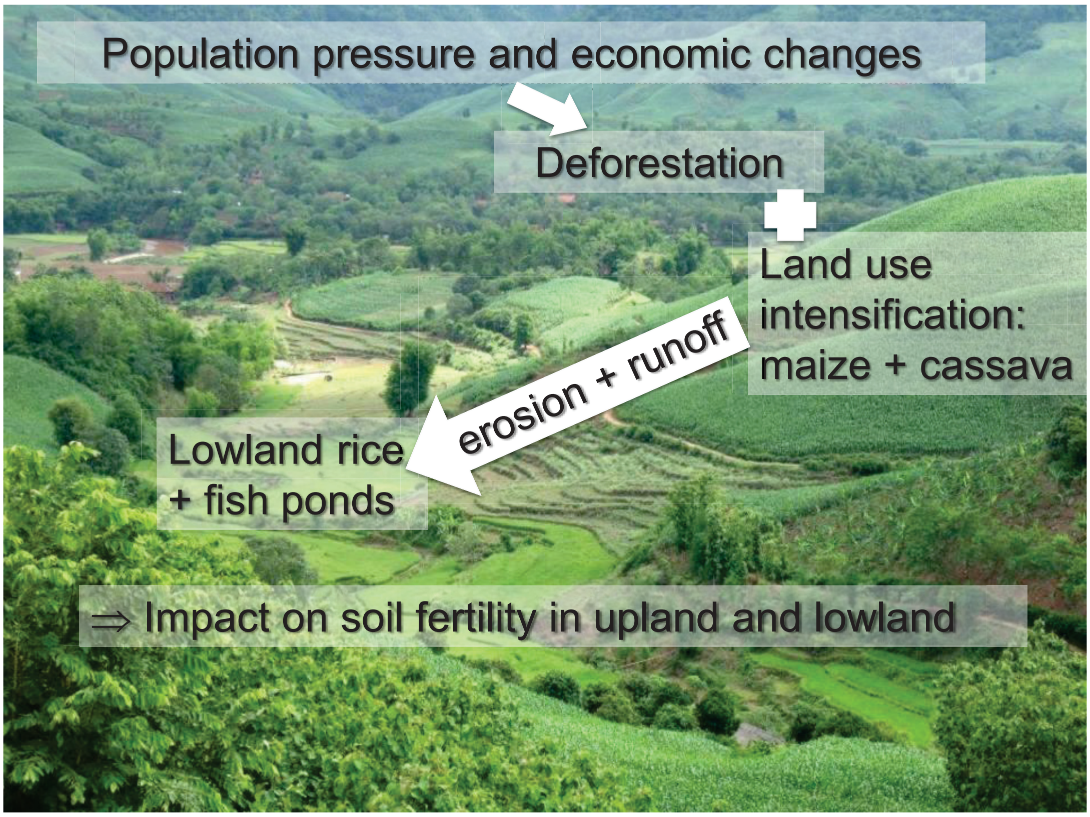


Figure 1.4 Landscape interaction processes (Source: Petra Schmitter, 2015)

Furthermore, a reduction of soil fertility may lead to soil degradation (Lal *et al*., 1989; FAO, 2015). The terminologies of soil degradation and its processes will be reviewed in section 5.2.3. Herein, this work considers the definition of soil degradation commonly used by FAO, which considers the soil health status regarding the ecosystem capacity to provide goods and services. In case of NW Vietnam, the soil was described as mainly under a high risk of soil degradation due to the landscape structure and soil types (Mazzarino *et al*., 1993; Yen *et al*., 2013). Figure 1.3 shows the current situation in a representative watershed in NW Vietnam. The intensification that occurred in the uplands influenced soil fertility in both uplands and lowlands. Furthermore, the sedimentation from upland can go further through river and irrigation channels and therewith spread to wider landscapes (Schmitter *et al*., 2011; Slaets *et al*., 2014, 2016a,b). Consequently, the movement of sediments contributes a negative result in the reduction of soil fertility and crop yields in the low- and uplands (Schmitter *et al.*, 2011; Dung *et al.*, 2008), which endangers the livelihoods of local farming communities in the long-term. The interaction of losing soil fertility processes between low- and upland and at landscape level could cause low household income and reduce available food for sufficient consumption in the future in rural areas such as NW Vietnam (Rutten *et al.*, 2014; Yen *et al.*, 2013; Minh *et al*, 2011; FAO 2017a,b). Therefore, predicting and evaluating potential areas of soil degradation at landscape level is important for future land use planning at the watershed level.

1.4 Challenges in assessing information in a data-limited watershed

Generally, data-limited conditions are a common phenomenon in many rural areas and especially in tropical and sub-tropical South East Asia (Lusiana., 2015; Lippe, 2015). As the definition of LUC illustrates, the transformation from one to another agricultural practice was also considered as LUC. Therefore, information about the past could partly explain various current situations. For example, higher frequencies of flooding were caused by a reduction of natural forest cover. The reduction of crop yields, together with an increased application of chemical fertilizer, was caused by continuous cropping (Schad *et al.*, 2012; Tuan *et al.*, 2014). Considering that agricultural land is human-induced land use type, LUC naturally influences agricultural productivities. The LUC plays an important role for food security which derives from agricultural production (Verburg *et al.*, 2013).

However, accessing the LUC information and its impact is still limited in rural areas such as NW Vietnam. Herein, this study describes three main issues which are potential and remaining constraints in accessing the LUC information and its impacts.

1.4.1 The lack of detailed and historical data

Data-limited conditions can be understood from numerous perspectives; a lack of available data, inequality, quantity, as well as specific types of data (Dawes *et al.*, 2001; Lusiana, 2015; Lippe *et al.*, 2014). Considering the LUC information, a lack of quantity and specific data are common. RS data are commonly used for determining the LUC, where RS consists of information about the objects, areas, or phenomena (Lillesand and Kiefer, 2000). The term RS includes a wide range of applications from digital scanning and optochemical photography from aircraft, satellites, and drones. RS is widely used to analyze ground pattern information and provide true eyes that illustrate the ground. This information quality may be affected by analyzing techniques, not be influenced by personal opinions such as 'the past is better than the present' (Bui *et al*., 2011). Besides, the Geographic Information Systems (GIS) capture, store, analyze, and visualize spatial information including RS. From RS and GIS, spatial analyses can explore, model and visualize the world. Resulting information can be used to investigate complex problems and better understand **what** and **where** something is happening in any parts of the world. Furthermore, data with a geographical component connected to a particular place on the earth, may support assessments for the causes for events such as urbanisation leading to the deforestation of surrounding areas. Changes in driving factors over time are common, especially across the LUC research (Longley *et al*., 2005). RS data are widely used to interpret land use patterns by comparing two (or more) stages of land use patterns to finally determine the LUC (Lillesand and Kiefer, 2000; Longley *et al*., 2005). Therefore, an LUC analysis needs a minimum of two periods to process and detect sufficient information.

Furthermore, at the watershed level, the study size is often small and the focus is often demonstrated through in detailed information. Thus, a small watershed case study requires high data quality. For example, many studies use forest as an individual class. However, Fox and Vogler (2005) subdivided a secondary growth class into three classes: closed-canopy forest, open-canopy forest, and grass, bamboo, and bushes in their study. In the case of NMR Vietnam, the smallholder is the most common farming system. Farmers use their limited land for multiple purposes as well as for several crops (Minh, 2010). Thus, high-quality imagery is often required to detect and analyze ground patterns. For example, the land use classification focuses on the class (such as forest, water body, cultivation, etc.), but at the small watershed level (e.g. at village or commune levels), classes cannot clearly be separated and many classes are mixed or overlapped. Additionally, areas of each class can be relatively small such as a paddy rice field could be 300 - 400 m2, river/stream could be less than 1m wide, or fruit tree plantation and residential areas could scatter (Nguyen, 2009). Thus, high-quality data and highly skilled labor are often necessary to analyze and classify detailed information.

Technological progress has led to improved quality of RS imagery resolution. Imagery resolution includes spatial (area size and detail), spectral (colour-bands), temporal (frequency), and more recently, radiometric (colour depth) information. This study concentrates on the spatial resolution for providing LUC information. The classification of the high and low quality of spatial resolution strongly depends on the scale and aims of the study (Cook *et al*., 2013). Currently, the Satellite imaging corporation (Satellite, 2017) classifies high spatial resolution ranging from 0.41-4 m, and low spatial resolution from 30 -1,000 m. However, Grekousis *et al*. (2015) defined spatial resolution levels greater than 30 m as moderate to coarse spatial resolution when reviewing 21 global and 43 regional land cover map products. Sorbrino *et al*. (2015) classified high-medium resolution as 100 m or less and low resolution between 1000 m and 200 m for a regional scale study size of 100 to 27,000 and 38,000 ha. At watershed level, the quality of RS is often classified as low resolution when larger than 30 m, medium at 5 - 30 m, and high below 5 m (Lillesand and Kiefer, 2000; Mitchell *et al*., 2017). However, high quality images are often costly. The high-quality RS data from satellites and drones such as SPOT, IKONOS, Quickbird are often offered at high prices (Kefyalaw *et al*., 2015; Lippe *et al*., 2014).

Available free of charge imagery is at relatively low resolution that could cover a large area (such as Landsat imagery). Some free imagery is available in high resolution, but still requires corrections before using without the original spectral such as Google Earth.

The lack of historical observed data is one of the main constraints during the procedure of LU mapping, such as validation or ground truth points sampling (Nyssen *et al*., 2016; Newman *et al*., 2014). For instance, the classification from RS data since the 1970s and 1980s may have a difficulty in validating results from observed data. Either no data is available or it contains bias in using events, or farmers' memorial information of long historical periods (Hagel, 2011; Lippe *et al*., 2011, Bui *et al*., 2012; Newman *et al*., 2014). Therefore, RS within a medium to low resolution combining census data, farmers' information on management, events, and decisions on farming practices could be an option for assessing LUC change information. An appropriate method is still required to determine LUC under data-limited conditions.

1.4.2 Trade-offs between complexity and simplicity in modelling at landscape-level

Besides using RS data, modelling tools are another option to obtain the dynamics of LUC. Several LUC models have been used for that purpose. For instance, Agarwal *et al*. (2002) reviewed 136 articles about the use of LUC models during the period of 1995 to 2000. In that period, they found 19 land-use models covering a range of model types such as regression, econometric, dynamic system, and mechanistic GIS models. However, the main constraint of most applications is the requirement of high quality and quantity of input data***.***

One important question was why do we need to model LUC? Land-use models are used to understand the interactions between human activities and natural resources (Marohn *et al*., 2013; Verbung *et al*., 2013; Agarwal *et al*., 2002; Verburg, *et al*., 2004; Lambin, 1997). LUC leads to positive and negative effects. On the one hand, the foreseen scenarios simulated by models could help to avoid negative consequences.

Since the 1990s, Lambin (1997) characterized tropical regions by using modelling tools by time. The results showed land-use morphology within the replacement of shifting cultivation to intensive agriculture by deforestation processes. Similar findings of the reduction of forest cover and increased cultivation occurred in South East Asia (Nguyen, 2009; Minh *et al*., 2011; Dao Minh *et al*., 2017). On the other hand, recommendations could be made based on positive effects. Benefits of LUC should consider the combination of livelihood, environmental, and ecosystem issues. In many cases, recommendations given are based on a single benefit of the LUC that may contribute negative impacts to the other issues. For instance, Marohn *et al*. (2013) used a coupling approach between an agent-based model (MP- MAS - Mathematical Programming-based Multi-Agent Systems) and a biophysical model (LUCIA - Land Use Change Impact Assessment - Marohn and Cadisch, 2011) to investigate the impact of low cost soil conservation measures on erosion issues of maize cultivation in NW Vietnam. Results showed that some soil conservation techniques could reduce the soil loss at plot level. However, the current system is still very sensitive to volatile fertilizer prices and labor requirements. It can be concluded that a simulation of LUC is an appropriate approach to avoid any negative impacts of LUC (Pontius *et al*., 2008; Castella and Verburg, 2007; Lusiana *et al*., 2012) or look for optimizing trade-offs.

Model LUC deals with a complex system. The land use types transform in several directions with various factors that are distributed from global to plot level. The scales are: field, watershed to global level, and each level can have specific factors. In some cases, a combination of same factors could lead to different directions in different regions. In each region, current conditions of economic development, culture, and resource availability could interact with complex combinations of factors and have various impacts on LUC. Therefore, many approaches exist to model LUC (Verburg, 2006, 2004). Traditionally, two approaches have been proposed to characterize LUC: (1) A bottom-up, anthropologic, process-oriented approach, which is based on household surveys and resource based inventory. That could be continuous in space such as agent-based models or finite in space (discrete spatial extent) and cardinality (fixed number of cell) such as cellular-automata. In case of the agent-based models, LUC is simulated based on the decision of an agent and/or interactions between agents. In case of cellular-automata models, LUC is simulated by transition rules based on the history of the cell or relationship with neighbors of each cell (Lippe, 2015; Lusiana, 2015). The second traditional approach is (2) a top-down, land evaluation, pattern-oriented approach based on RS and census data (Geoghegan *et al*., 1998). More recent approaches encompass the coupling between biophysical and socio-economic models - for instance LUCIA and MP- MAS (Marohn *et al*., 2013). Many models have tried to be as close to the real world as possible by inserting and developing single processes of the system. Consequently, the models become more complex (Sohl and Claggett, 2013).

For the conditions of South East Asia and NW Vietnam, several modelling tools have been applied to assess LUC and its impacts. Table 1.1 shows a list of model tools that have been applied for assessing LUC and LUC impacts in Vietnam. Most of the models required either a large dataset or very specific data. For instance, Chieng Khoi watershed is described as a small watershed with various data of soil, land use, crop and farm household from previous studies for employing LUCIA and MP - MAS. However, there is still a lack of mid- to long-term data for evaluating the effects of soil conservation techniques (Marohn *et al*., 2013). Moreover, the models required a high-speed processor or free disk space due to simulation time step (daily), in-/output size (maps) and amount of in-/outputs (Mahron *et al*., 2013, Lippe *et al*., 2014; Sohl and Claggett, 2013). In the case of limited data, developing a new model could represent a simple and easy approach, as a simple model requires a smaller dataset. Potentially, the target information could be achieved by avoiding a more complex model that has higher labor requirements for collecting large data (Lippe, 2014).

1.4.3 Soil degradation dynamic at landscape level

Soil degradation is found worldwide and has become very serious under deforestation processes and intensified farming practices in developing countries such as Vietnam (Lal *et al*., 1989; Tuan *et al*., 2014; Lambin *et al*., 2001). Many regions in NW Vietnam are characterized by low soil fertility and a high risk of soil degradation because of their landscape structure and current farming practices (Yen *et al*., 2013; Clemens *et al*., 2010; Tuan *et al*., 2014, Vezina *et al*., 2006, Keil *et al*., 2013). The examination of soil degradation is often studied at plot level, therefore farmers often under-estimate the extent of soil degradation from plot to landscape level (Clemens *et al*., 2010). This could be the reason for the low adaptation of soil conservation techniques to mitigate soil erosion in NW Vietnam (Clemens *et al*., 2010; Tuan *et al*., 2014). The low adaptation of soil conservation techniques has encouraged continuous soil degradation continuously and spread widely in MNR of Vietnam.

Table 1.1 Required parameters of model to assess LUC and the impact at landscape level in Vietnam

No.	Name of model tool	Range of parameters	Type of parameters	Targets/Aims	Time step	Size/Level
1	CLUEs	>50	Biophysical (soil, climate, geology, etc) and social-economic (population, labor)	Land allocation	annual	Province (0.3.10^6 ha)
2	ERODEP	31	Biophysical of soil, hydrological (flow and rain), and landscape structure (slope, surface cover)	Erosion and sediment deposition	daily	Village (3.37 ha)
3	FALLOW	35	Biophysical (soil, plants), spatial (maps) and socio-economic (capital, labor, farm management, fertilizer price)	LUC and soil fertility development	annual	Village (558 ha)
4	LUCIA and MP MAS (individual and coupling)	>>50	Biophysical (soil, plants, climate), spatial (maps) and socio-economic (capital, labor, farm, distance to farm, etc of about 300 households)	Low cost soil conservation	daily	Commune (about 3100 ha)
5	LUPAS - Multiple goal linear programming	>50	Plant biophysical, social-economic, policy objectives, and spatial maps	Evaluate scenarios	annual	Province (0.3.10^6 ha)
6	MLR - Multivariate Logistic Regression	>50	Spatial of lithology, elevation, distance to road, settlements, distance to national road and ethnic group, and produced parameters	Land transition	period	Catchment (283 km^2)
7	RUSLE	54	Six factors from RUSLE equation for all land use types, climate, and spatial	Sediment load	annual	Basin (38 165 km^2)
8	SAMBA-GIS	39	Role playing game results and interviews	LUC decision	annual	Village level

Sources: Castella *et al*., 2005, 2007; Lippe *et al*., 2011, 2014; Marohn *et al*., 2013; Loi *et al*., 2016; Ranzi *et al*., 2012; Quang *et al*., 2014; Kim Chi *et al*., 2013.

To determine soil degradation distribution at landscape level, the spatial distribution of soil fertility could be assessed by the geostatistic method (Cobo *et al*., 2010), which requires an intensive lab analyses for a large dataset. Furthermore, Bui *et al*. (2017) introduced the fuzzy logic approach for predictive soil mapping in landscape area using slope-form under strong relief conditions. Both methods assessed the soil fertility and its distribution at landscape level. In case of assessing soil fertility development, the process required more work load, because the development includes minimum two measurements: initial and subsequent times. Another method was introduced by Goldshleger *et al*. (2010) using a remote sensing approach. This method used the remote sensing tools to assess the structure crust, salinity, and soil mineral deformation processes as well as alterations by fire. However, this method could only examine the soil surface within a large area or only soil salinization within a small area. Besides, Conforti *et al*. (2013) combined laboratory analyses with soil spectroscopy and geostatistics for assessing soil organic matter (SOM). However, this method could only present the relationship between soil fertility and water erosion.

Soil degradation is a complex process with multiple driving factors (Lal *et al*., 1989, Conforti *et al*., 2013; FAO, 2015). In this study region, farmers noticed that the soil degradation was occurring and expressed it through their observations: change of soil colour, or crop yield reduction (Nguyen, 2009). However, they still under-estimate the consequences at landscape level in the long-term and still focus on short-term cash income from current agricultural practices (Clemens *et al*., 2010; Tuan *et al*., 2014; Nguyen, 2009; Yen *et al*., 2013; Schad *et al*., 2012). Lal *et al*. (1989) stated that capturing and monitoring the completed processes of soil degradation is still processing in many regions; it is important to conserve the soil before it is too degraded and cannot recover. Therefore, raising awareness of soil degradation at landscape level in the long-term to farmers is very important. For that purpose, a simple spatial explicit model tool could be an option to identify the trends of soil degradation. Such findings could be transferred to local stakeholders and extension officers in raising awarenesswith farmers on landscape soil degradation. Many areas may require assistance to implement soil mitigation measures, especially in the sensitive and complex region of NMR Vietnam.

1.5 Objectives and hypotheses

The general objective of this study is to understand the causes and dynamic of LUC, and the impacts of LUC on natural resource management at landscape level to provide a scientific contribution to a more sustainable agricultural development on sloping land in NW Vietnam.

1.5.1 Objectives

The specific objects are:

- Understanding phenomena and causes of LUC; chapter 3 aims to classify and validate land use maps to achieve this objective.
- Developing an LUC model to simulate LUC for data-limited available watersheds. Thus, Chapter 4 aims to identify and analyze farmers' decision rules, and then develop a land use model.
- Assessing the impacts of LUC on soil properties at plot and landscape level. Chapter 5 aims to: (a) determine soil fertility conditions in farmer fields; and (b) develop a simple model to assess the development of soil nutrients under LUC.

1.5.2 Hypotheses

The study hypothesizes that:

- Land use patterns in NW Vietnam were transformed from 1954 to 2007 and land use maps can be derived by analyzing available RS data combined with government and farmer information.
- A newly developed model is constructed based on farmer rules and food requirements can be used to capture and model LUC.
- Soil fertility decreased during the long-term continuous mono-cropping. This development can be simulated using a simple model. This simple model is able to assess the reduction of soil fertility at the watershed level.

1.6 Conceptual framework of the study

This study is designed based on data-limited conditions within concept as an integrated approach. Following this general introduction, Chapter 2 presents the study site and the justification of site selection. Each core chapter briefly presents its specific objectives. Figure 1.5 illustrates the main targets, data sources, and the connection between the three major chapters in this study as the integrated approach. Chapter 3 presents materials, methods, and findings from the land use pattern changes from 1954 to 2007, as well as identifying key driving factors of LUC. Applying the output maps from Chapter 3, Chapter 4 develops a model to simulate the expansion of agricultural land in the watershed. This model used the initial map of 1954 combining census data, and farmer decision rules based on the food requirements from an increased population. The classified maps from Chapter are used as initial maps of the simulation and the validation maps for model exercises. Thereafter, Chapter 5 develops a simple model to simulate the dynamic of soil properties under LUC at the watershed level. For that purpose, the simulated maps of Chapter 4 are employed combining field soil sampling data and secondary data from other studies that were conducted in the same region. Furthermore, the general discussion (Chapter 6) discusses the findings in terms of the three main chapters, contributions of this study, and recommendations for further research. Finally, the publications within the framework of this study are listed as titles and abstracts.

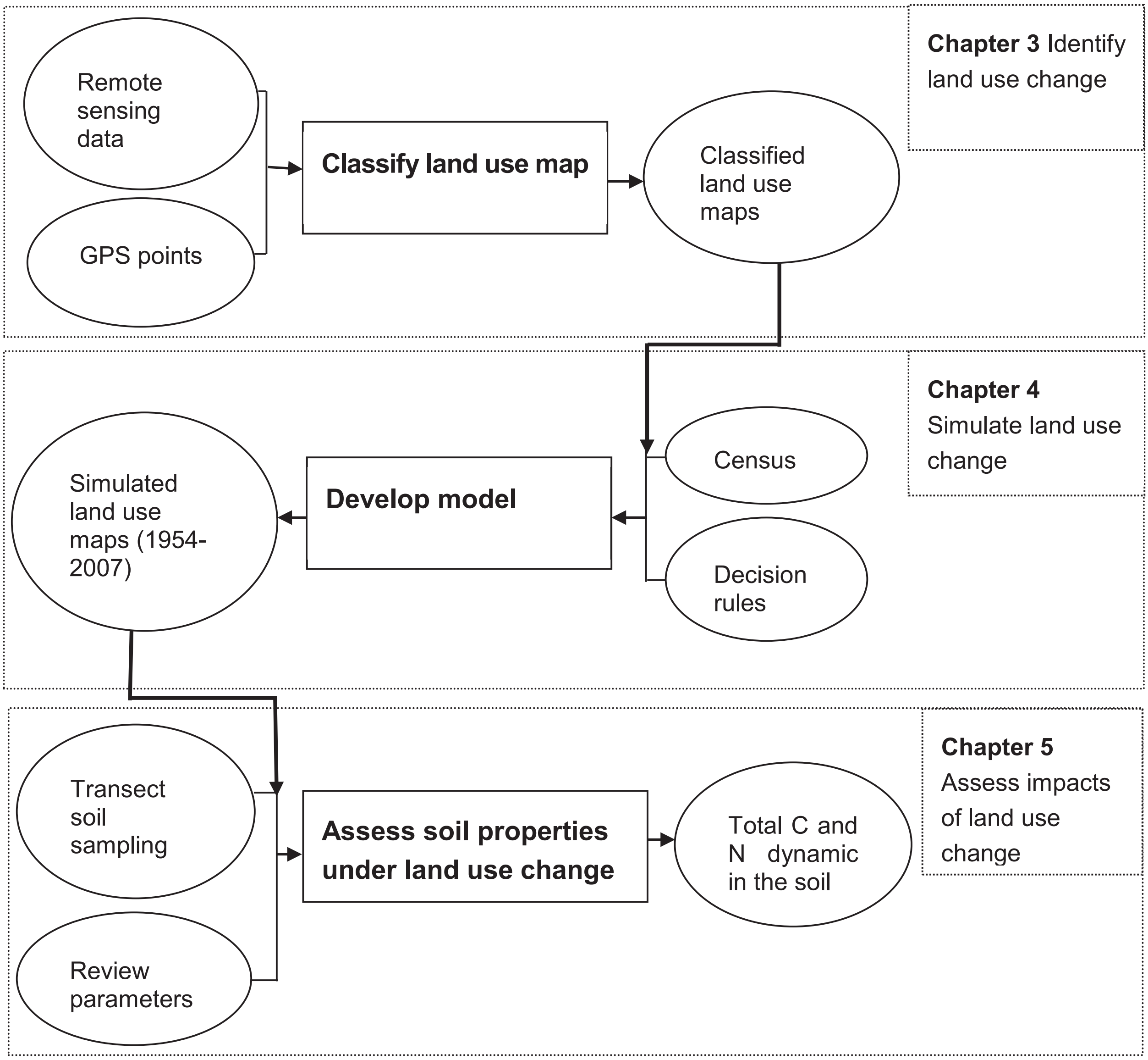


Figure 1.5 Conceptual framework and the connection between three main study chapters

Chapter 2. Study site

This chapter introduces the justification of the study site selection, and secondly the location, geographical information, as well as climate conditions of the site. Furthermore, an overview of soils and socio-economic conditions are described in the closing sections.

2.1 Justification of study site selection

Chieng Khoi commune represents general natural and socio-economic characteristics of the NMR in Vietnam and in Southeast Asia. In last decades, an enormous transformation of the agricultural system had occurred. On the one hand, this has improved living conditions of the local population and on the other hand, there is now immense pressure to maintain and preserve natural resources. Many studies have been conducted in these regions, especially in Chieng Khoi commune and Yen Chau district, to investigate the situation with the land and the reliant population. The present study was conducted within a framework of the DFG collaborative research centre - Sustainable Land Use and Rural Development in Mountainous Regions of Southeast Asia (SFB 564). This project operated from 2000 until 2014 with a total of four investigation phases and a final transfer phase. The overall objective was to investigate the limitations and potentials for sustainable agricultural development in sloping land across NMR in Vietnam and Thailand.

2.2 Study site description

2.2.1 Location and geography

The study was carried out in Chieng Khoi commune, which is one of 14 communes in Yen Chau district, Son La province. It is located five kilometers from national road 6, which links the centre central cities of the Red River Delta with the NMR (Figure 2.1). Elevation ranges from 400 m in the valleys to more than 1,000 m ALS (above sea level) of the high karst mountains in the Southeast catchment (Figure 2.1). Chieng Khoi commune size is about 3,100 ha and consists of five villages (Ngoang, Hiem, Put, Tum, and Na Dong).

2.2.2 Climate

Chieng Khoi commune is governed by a tropical monsoon climate with an average annual precipitation of around 1250 mm. The average temperature is 24° C, with hot summers from May to October and dry and cold winters from November to April (Yen Chau weather station, data collected 2009). Extreme weather conditions have been found more frequently in recent decades. For Chieng Khoi, Schad *et al*. (2012) reported a flooding event in 2008, Vu *et al*. (2014) showed high intensities of rainfall in 2010, and Nguyen (2009) reported a drought event in 2007. From farmer group discussions in 2011, extreme weather events have appeared more frequently from the 1990s. From 1990 to 2011, hail was reported in four events, flooding was reported in seven events, and a typhoon occurred three times. As shown in Table 2.1, extreme weather events occurred more frequently compared to the period of 1954 to 1990 (Table 2.1). Thus, climate change issues became an important topic for this region.

Table 2.1 Extreme events in Chieng Khoi since 1954

Events*	From 1954 to 1990 (number of events)	From 1990 to 2011 (number of events)
Hail	4	1
Flooding	7	3
Typhoon	3	2

* Field survey (2012). To avoid the phenomenon rose – tinted: ‘everything was better in the past’. The detail damage of each event was described, because people may only remember the really extreme events in the past, but also less strong recent events.

2.2.3 Soils

Soils in the study area mostly belong to the group of red and yellow soils in uplands and highland regions (Clemens *et al*., 2010; Bui *et al*., 1995). Schuler *et al*. (2007) and Clemens *et al*. (2010) classified soils into 11 types based local knowledge: Chieng Khoi commune consists of good black soil, sandy black soil, black soil mixing gravel, black soil mixing rock, red soil mixing rock, sandy red soil, poor red soil, red soil, yellow soil mixing gravel, poor yellow soil, sandy yellow soil, and black soil in the forest. These 11 soil types are mostly Alisols, Luvisols, Leptosols, and Anthrosols (Clemens *et al*., 2010).

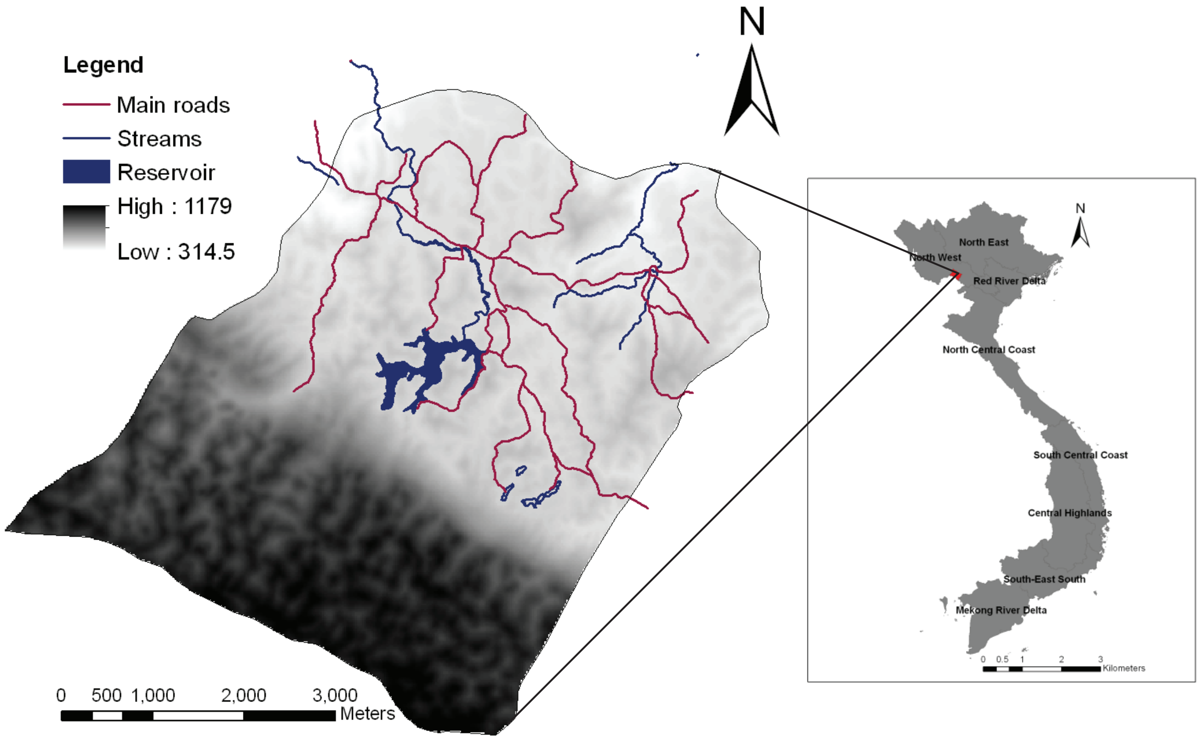


Figure 2.1 Location of Chieng Khoi commune in Yen Chau district, Son La province, Northwest Vietnam, showing topographic and infrastructure; the map on the right shows the location of Yen Chau district (red mark) in regional map of Vietnam.

2.2.4 Socio-economic conditions and agricultural systems

The resident Black Thai belongs to one of the largest ethnic minorities in Vietnam and have been living in this region for several hundred years (Lippe *et al.*, 2011; Schmitter *et al.*, 2011; farmer interviews, 2011). The main income comes from farming activities. Farmers often practice farming as at a smallholder size without machining; indeed, the first handle tractor was introduced in 2007. All households connect strongly with the extended family in the same village or commune. The education level has improved since the 1970s, however, only few have accessed colleges and universities (Richter, 2008; Beuchelt, 2008).

Currently, the main crops in Chieng Khoi are high yielding hybrid maize (*Zea mays)*, cassava (*Manihot esculenta*), and irrigated paddy rice (*Oryza sativa)*. Mango (*Mangifera indica*) plays an important role as an additional income source, but is cultivated extensively in a traditional method without fertilization or pruning.

Traditionally, farmers in Chieng Khoi practiced slash and burn in upland maize or cassava plots combined with paddy rice cultivation in the lowlands. Burning and hoetillage was traditionally used, and still is, to prepare maize from March to May before the rainy season begins (Wezel, 2000; Clemens *et al*., 2011). With long fallow periods from 7-12 years, this production system was defined as a composite swidden system (Rambo, 1998). In 1974, an artificial reservoir was established to supply water for irrigation and home consumption for the five villages in the Chieng Khoi commune. Paddy rice could then be cultivated twice per year. Since the 2000s, upland rice and local cassava varieties were replaced by high yielding hybrid maize and hybrid cassava grown monoculturally (Keil *et al*., 2008). Livestock, poultry, timber production, and aquaculture are common in small scales and provide a side income (Lippe *et al*, 2011).

Chapter 3. Challenges of assessing land use land cover change from 1954 to 2007 with varying remote sensing resolutions in Chieng Khoi commune, Northern Vietnam

This chapter presents a study to assess land use and LUC from 1954 to 2007. Output maps and decision rules with farmers' crop rotation practices in this chapter provides the dataset for the land use change model in Chapter four. This chapter presents a continuing work that conducted from a previous study. Therefore, sections of the land use land cover changes from 1993 to 2007 were adapted from previous results of Nguyen (2009).

3.1 Objectives

The overall goal of this chapter was to understand the causes and dynamics of land use change to provide information for decision making of natural resource management at watershed level. In rural mountainous regions, available data for natural resource management and socio-economic development are limited. In this context, the presented study aimed to develop a method to classify long-term land use maps with different resolutions by using historical datasets and local farmers' knowledge. Furthermore, those data also provided information about causes and consequences of farmer practices that have existed in history to develop conservation options towards a sustainable agricultural development in watershed areas with data-limited conditions. Specifically, this chapter presents a study aimed to (1) classify and validate land use maps, (2) assess the dynamics of land use changes from 1954 to 2007 in the Chieng Khoi commune in Northwest Vietnam.

The study hypothesized that: (1) long-term land use maps can be produced from classifying aerial photographs combined with historical farmer knowledge; and (2) land use dynamics from 1954 to 2007 can be assessed by using diverse remote sensing data sources and farmer decision rules with accepted accuracy levels.

3.2 Materials and Methodology

3.2.1 Data sources

3.2.1.1 Remote sensing data and ground truth points

With the purpose of using various remote sensing sources, Table 3.1 presents the remote sensing datasets employed for this study, namely aerial photographs, Landsat (Land-satellite) imagery, and LISS III (Linear Imaging and Self Scanning sensor). The aerial photograph of 1954 is a military aerial photograph taken by the French army and collected from the Data and Map Archive Center (Ministry of Resources and Environment). The Landsat Multi-Spectral Scanner - MSS 1973, the Thematic Mapper-TM 1993, and the Enhanced Thematic Mapper -ETM+1999 were further collected from the NASA Landsat Program (USGS - United States Geological Survey). The Indian Remote sensing - Linear Imaging and Self Scanning sensor - IRS LISS III 1C 2007 and a PAN (Panchromatic) images were obtained from the National Remote Sensing Agency (NRSA), India.

Table 3.1 Remote sensing data

Source	Aerial photograph 1954	Landsat MSS 1973	Landsat TM 1993	ETM+ 1999	IRS LISS III (and PAN) 2007
Pixel (m)	5	57	30	30	23.5 [1]
Date	na[2]	28/02/1973	1/2/1993	27/12/1999	4/3/2007
Season	na	dry	dry	dry	late dry season
Sensor	na	MSS	TM	ETM+	Self-scanning
Classification methods	Visualization	Hybrid classification	Hybrid classification	Hybrid classification	Hybrid classification
Target to classify	Observed visible ground pattern	Spectral ground pattern	Spectral ground pattern	Spectral ground pattern	Spectral ground pattern
Number of GPSs (Number of GPSs using for accuracy assessment)	Using historical training sets	66 (46)	81 (56)	102 (73)	150 (100)

[1] Sharpened with PAN to 5.8m;

[2] Not applicable

Associated with the remote sensing sources, 328 ground truth points were collected using the Global Positioning System - GPS Garmin CSX60 (Garmin Asian Corporation, Taiwan) to obtain the actual land cover types. After coding, the points were transferred into ArcGIS 9.3 (ESRI -Environmental Systems Research Institute, USA). The history ground truth points were digitalized from farmer interviews during transects walks and interviews about the plot history, (more detailed information to follow). From the total achieved points per year, one third were used for land use classification and two thirds were used for accuracy assessment from Landsat 1973, 1993,1999, and LISS III 2007, respectively (Nguyen, 2009; Leisz *et al.*, 2005).

3.2.1.2 Transect walks and plots history

In addition to the actual ground truth points that collected by GPS, the long-term history ground truth points (1954, 1973, 1993, and 1999) were collected during four transect walks with local stakeholders. Moreover, information on LULC history, and boundaries of different types in the past were also obtained from these transects. Two to five elder farmers were involved in the transect walks. Elders were approached for this study who grown up in the study region, were more than 60 years old, and had been recommended as knowledgeable by the village headmen. Thus, they were invited to determine information from 1954 up to date. The routes of the transects were jointly designed with the farmers before going to the field and longer routes were designed through the villages (average 6 km) and the surroundings of the Chieng Khoi reservoir (approximate 10 km) to cross check the retrieved information. Farmers discussed and agreed among their group to answer questions provided from a check list containing information such as crop history, field boundaries, important events, and causes and consequences considering crop choice decisions (Appendix 3.1, 3.2). The precise locations and tracks were obtained by GPS and later processed using ArcGIS 9.3.

Additionally, general household information was collected during the dry season from March to May 2012. Twenty-two households were selected to conduct semi-structured interviews with farmers who can be described as the fixed residence from one of six villages and managing the upland plots surrounding the Chieng Khoi reservoir during the survey period. These farmers were selected because the construction of the reservoir was one of most important events in Chieng Khoi history (Richter, 2007). In addition to general information about education, occupations and agricultural activities, all plots belonging to these farmers were assessed for plot crop history and the plot-related cropping decisions. Firstly, their house locations, main roads, and land marks were defined by interviewers together with farmers using a colour printed Google Earth image of Yen Chau District 21^0 02' 45.86" N and 104^0 18' 03.19" E in 2006 (accessed: 18.09.2010). Secondly, locations, size, and current crops of each plot were determined and crop types of previous years were investigated into the past using 2011 as the initial year (interview period) and 1954 as the final year, with the latter referring to the oldest available remote sensing data source. Famers were further asked to describe which factors influenced plot level crop decisions. The information was cross checked and consolidated with farmers' decision rules data obtained from the focus group discussions (more information to follow) (Appendix 3.1, 3.2). Land use history information from transects and plots were used as ground truth points in the past to identify land cover types and verify the accuracy of land cover classification in 1973, 1993, and 1999 (Leisz *et al*., 2005).

3.2.1.2 Farmers' decision rules on crop choices and crop rotation

To enhance the possibility to classify long-term history images, farmers from three out of six villages in Chieng Khoi commune were invited to focus group discussions to determine decision processes on crop choice and crop rotations. For this purpose, the villages Ban Ngoang, Ban Me and Ban Hiem were chosen because they are regarded representative for the characteristics and conditions of the commune as recommended by the head of the Chieng Khoi commune. The validity of the recommendation was confirmed by the Statistics Office in Yen Chau district and Steinbronn (2009).

In each village, 7-10 famers joined the focus group discussions. They were divided into a young group with participants aged less than 50 years and an older group with participants aged above 50 years. Hagel (2011) reported the importance of the division of farmers by age to reveal knowledge flows within the villages and capture their development and impacts. It was further assumed that older farmers would remember their own original traditional cultivation systems without having transferred this knowledge to younger generations. Furthermore, dividing farmers into two groups may reduce the influence of cultural factors such as respect as younger farmers do not want to disagree with older or respected farmers, as noted by Hagel (2011). A number of cross checking stages were conducted to repeat questions to ensure that participants were 'on-track' and to reduce the influence of dominant participants (Lippe *et al*., 2012).

In each village, three group discussions about farmers' decisions on crop choice and crop rotation practices were conducted, starting with old groups, followed by young groups and ending with the old and young farmers in one common discussion. The agreements that were reached in the mixed group were considered as final results. The issues and decisions that differed between both groups were considered as past decisions (from old groups) or current decisions (from young groups). Pair wise ranking method was chosen to construct scenarios in the past during the group discussion (Bechstedt, 2003), while matrix tables were created for preference crops (PLA, 2001). Table 3.2 presents an example of a crop choice matrix, where the farmers were requested to choose one crop from every pair. All criteria were considered under the assumption of 'if the farmers have only one plot to cultivate, which crop they will choose from every pair'. The ranking exercise was conducted to cross-check their decisions, where the farmers named and gave more points to the crops they preferred. The ranking number depended on the number of crops in each period and in each village. Subsequently, with low yielding local varieties, and without chemical fertilizer, farmers needed a large cultivation area to meet the demand of local food consumption.

Table 3.2 shows an example of a crop choice matrix for Ban Ngoang, Chieng Khoi commune in 2010. The pair wise choice matrix applies a ranking between two crops to indicate the importance of each crop in terms of food security. Farmers listed the crops that existed in the past, and chose one from two choices in the matrix. The written abbreviation name of crops in the cell indicates the choice taken. The highest number (6) corresponds to the highest-ranking crop. Results of crop ranking differed in each village and between young and old farmer groups in 1954, 1999, and 2010, which are listed in Appendix 3.3.

Table 3.2 Example of a crop choice matrix for Ban Ngoang, Chieng Khoi commune in 2010

2010	Paddy Rice	New Maize	N. Cassava	Old Cassava	Soybean	Vegetable	**Rank**[1]
Paddy Rice	X	PR	PR	PR	PR	PR	**6**
New Maize		X	NM	NM	NM	NM	**5**
New Cassava			X	NC	NC	NC	**4**
Old Cassava				X	SB	V	**1**
Soybean/Peanut					X	V	**2**
Vegetable						X	**3**

[1] *With value by 6 referring to the most preferred, and 1 to the lowest preferred crop by farmers*

Description of abbreviations: PR: Paddy rice, NM: New Maize, NC: New Cassava, OC: Old Cassava, SB: Soybean, V: Vegetable

Note: Hybrid varieties were referred to as 'new' and the local variety was referred to as 'old' cassava during focus group discussions

3.2.2 Image processing

Remote sensing data (Table 3.1) were pre-processed before using them for LULC classification. Kadmon and Harari (1999) indicated that pre-processing steps, such as mosaicking, are necessary for aerial photographs. The aerial photograph dataset of 1954 employed for this study required six pictures in two sequences to cover the study site. In one sequence, each picture covered 50% of successive picture. Two sequences comprised of 25% of the common areas. A mosaic was produced by fitting images of individual scenes into a single composite. The position of each picture was predetermined by flight lines of aerial photos. Two to three common Region of Interests (ROIs) were visualized in each picture to determine the common area of neighboring photos. The mosaic was constructed using a pixel base method in ENVI 4.3 (Environment for Visualizing Images, ITTVIS, USA) software (Figure 3.1). ENVI software uses the common areas of two photos as the pixel indicator to place images in the mosaic, like the feature-base-method mentioned by Korpela (2006). Land marks such as main rivers (e.g. Black River), national roads and high peaks were used to tie images to the chosen ground, the mosaic image was registered to standard projection WGS84 (World Geodetic System), datum UTM (Universal Transverse Mercator), at 48 North using georeferencing process. The rectification of the aerial photograph was done using tracks taken during the transect walks through the commune, and Google Earth images of Yen Chau District (Appendix 3.4). This process applied Geometric correction random distortions as described in Lillesand and Kiefer (2000). The received composite image then was cropped based on the polygon area, which refers to the study site.

Furthermore, Landsat 1973, 1993, and 1999 were also rectified and then cropped with similar methods as mentioned above. The images were corrected by radian and geometric corrections and then registered to the standard unified WGS84 coordinate system. In case of image LISS III 2007 with 23.5x23.5 m, Saraf (1999) confirmed that mapping capacity of LISS III is more effective when its resolution is enhanced with high resolution panchromatic (PAN) data. A PAN is a single band image that is sensitive to light of all wavelength invisible spectrums and often displayed as shades of grey with high resolution while LISS III contains more spectral as multispectral image, thus, sharpen a multispectral image means to increase spatial resolution of a multispectral. In this sense, the fusion technique has been applied to merge two images to produce a pan sharpened image that contains high spectral resolution (four bands) and higher spatial resolution (5.8x5.8 m) (Saraf, 1999). The pan sharpened image was cropped based on the study site boundary.

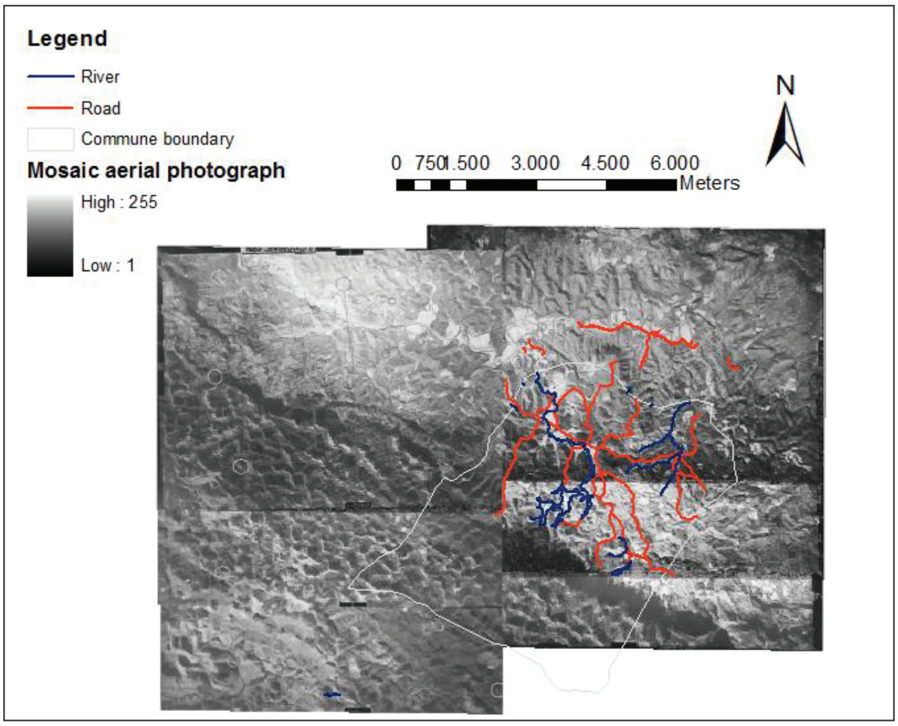


Figure 3.1 The mosaic aerial photograph 1954 from six pictures before georeferencing processes

3.2.3 Classification methods

Manual classification and automatic classification approaches are commonly used to classify LULC (Lillesand & Kiefer, 1999; Koperla, 2006). However, in case of the varying remote sensing data sources used in this study, a mixture of different classification methods was deemed more appropriate (Yang and Lo, 2002).

Table 3.3 presents five LU classes in Chieng Khoi commune. In 1954, the forest was dominant. Except for a long-term LULC map of 1954, the residential area was used instead of tree class because pattern texture of tree class was mixed in with the mosaic image. In general, LULC maps (1954, 1973, 1993, 1999 and 2007) were classified in a first step using five classes. At second step, the classified map of 1954 and 2007 were further use to identify the location of upland crops as crop level classification. This step was conducted using farmer decision rules obtained during focus group discussions (see 3.2.1 for further information). The resolutions of the satellite image in 1973 (57 m x 57 m), 1993 (30 m x 30 m), and 1999 (30 m x 30 m) were rather low which would result in a spectral confusion as one-pixel size was larger than the average field size in the commune (about 500 m^2). Therefore, detailed classification of crop distribution over these three years was a poor application. Similar issues were also reported by Dewan and Yamaguchi (2009), Yang and Lo (2002) and Viet and Phuong (1993).

Table 3.3 Common LULC types for all considered periods in Chieng Khoi commune

No	LULC type	Description
1	Forest	Dense primary forest and dense secondary forest, fallow* about 7 years and longer with medium and large trees (≥ 10 m)
2	Tree/ or Residential area	Mixed small tree, bush, fruit tree, planted forest as less dense vegetation /location of farmers' houses**
3	Paddy rice	Low elevation and flat areas where water level is low and drying out during dry season
4	Water body	Lake or big ponds larger than 2,500 m^2 (excluding small streams and rivers of ≤ 10 m width)
5	Upland cultivation	Crop areas cultivated in low and high land with slopes larger than 5°, elevation>300m above sea level, also young fallows (about 1-6 years), with grass and bushes.

* *Fallow term in this study refers to a natural fallow period (FAO, 2013)*

** *The residential area consisted of small houses and dense orchard home gardens with in the villages.*

Multi-temporal datasets based on varying satellite sources often challenge land use classification processes (Nurminen *et al*., 2015; Kadmon and Harari-Kremer, 1999). Hence, the next sections present suitable classification methods according to time period and satellite image types as presented section in 3.2.3.1. Crop level classification in 1954 and 2007 will follow in section 3.2.3.2.

3.2.3.1 Land cover classification

Mapping in1954

The LULC map 1954 was classified over two steps (Figure 3.2). The first step aimed to classify the land use map with five main classes using a visualization classification method, whereas the second step focused on a determination of the upland crop distribution using historical soil, farmer crop decision data combined with GIS methodology (see the next section).

Training sets were identified from Giang's (2002) dataset referring to LULC types in aerial photographs of selected communes in Yen Chau District. The manual interpretation process is based on texture, patterns, lightness and darkness based on the given features of aerial photo pictures (Nurminen et al., 2015; Kadmon and Harari-Kremer, 1999; Korpela 2006). The resulting land use map was first classified into five LU classes (forest, residential areas, water body, paddy rice, and upland cultivation) as described above (Table 3.3).

Mapping in 1973

The distinction between LULC classes was checked before the classification processes began using ENVI 4.3. A separability analysis of the five classes was applied using Transformed Divergence (TD) and Bhattacharya Distance (BD) statistic parameters (Saha et al., 2005). These statistic approaches measure how well the chosen land use classes can be separated during classification. ENVI 4.3 software calculates TD and BD directly using the following formula:

The Transformed Divergence (**TD**):

$$\mathrm{TD}(i,j) = 2\left[1 - \exp\left(\frac{-\mathrm{D(i,j)}}{8}\right)\right] \tag{3.1}$$

where TD(i,j) = Transformed Divergence between classes i and j
D(i,j) = Divergence between classes i and j

$$\begin{aligned}\mathrm{D}(i,j) = {} & 0.5\mathrm{T}\,[\mathrm{M(i)} - \mathrm{M(j)}] \times [\mathrm{InvS(i)} + \mathrm{InvS(j)}] \times [\mathrm{M(i)} - \mathrm{M(j)}] \\ & + 0.5\mathrm{Trace}[\mathrm{InvS(i)} \times \mathrm{S(j)} + \mathrm{InvS(j)} \times \mathrm{S(i)} - 2\mathrm{I}]\end{aligned}$$

where M(i) = mean vector of class i, where the vector has N channel elements (N channel is the number of channels used)
S(i) = covariance matrix for class i, which has N channel by N channel elements
InvS(i) = inverse of matrix S(i)
Trace[] = trace of matrix (sum of diagonal elements)
T[] = transpose of matrix
I = identity matrix

The Bhattacharrya (or Jeffries-Mastusuta) Distance was calculated as:

$$\mathrm{BD}(i,j) = 2\left[1 - \exp\left(-\mathrm{a(i,j)}\right)\right] \qquad (3.2)$$

where BD(i,j) = Bhattacharrya Distance between class i and j
a(i,j) was calculated as:

$$\mathrm{a}(i,j) = 0.125\mathrm{T}\ [\mathrm{M(i)} - \mathrm{M(j)}] \times \mathrm{Inv}[\mathrm{A(i,j)}] \times [\mathrm{M(i)} - \mathrm{M(j)}] + 0.5\ln\left\{\det\left(\mathrm{A(i,j)}\right)/\mathrm{SQRT}[\det(\mathrm{S(i)}) \times \det(\mathrm{S(j)})]\right\}$$

where M(i) = mean vector of class i, where the vector has N channel elements (N channel is the number of channels used)
S(i) = covariance matrix for class i, which has N channel by N channel elements
Inv[] = inverse of matrix
T[] = transpose of matrix
A(i,j) = 0.5*[S(i)+S(j)]
det() = determinant of a matrix
ln{} = natural logarithm of scalar value
SQRT[] = square root of scalar value

The TD and BD values of 1.8 to 2.0 indicate complete separation between two classes, whereas values from 1.4 to 1.8 indicate that the signature generated from training sets was not separable from other classes (Saha *et al*., 2005). Then, the LU map of 1973 was classified by a maximum likelihood supervised classification method. This classification assumed that the statistics for each class in each band were normally distributed and calculated the probability that a given pixel belongs to a specific class. Each pixel was assigned to the class with the highest probability based on both the variances and covariances of the class signatures from training areas (Campbell, 1996). Comparing with unsupervised classification methods, which were based on clusters of pixels into sets of classes, this method is more common and sufficient to classify LULC as well as vegetation dynamics (Leisz *et al*., 2005; Kadmon and Harari-Kremer, 1999; Ashraf *et al.*, 2009).

Mapping in 1993, 1999 and 2007

Similar to the processes with mapping in 1973, the separability analyses were conducted for 1993, 1999 and 2007 first, then the training samples were defined and evaluated based on the class histogram and statistics. After validating training sets, a maximum likelihood procedure was applied to determine the shape of the spatial distribution of five classes. Two subclasses of forest were used to avoid shade and slope effects in high rugged terrain in the northwest of the study site, and after the classification, they were merged in one forest class.

3.2.3.2 Development crop level classification methods

After the classification of LULC map 1973, 1993, and 1999, a further detailed classification step was conducted to distinguish upland crop locations. However, those Landsat images above had relatively low resolution (30 x 30 m). Even resolution in Landsat TM 1993 and ETM 1999 was higher than Landsat MSS 1973, but the upland plots were small, ranging from 200 to 1500 m^2. Moreover, plots of more than 1,000 m^2 used to be divided into several subplots for different purposes, such as cassava intercropped with upland rice and cassava intercropped with maize for home consumption, in some cases, a small plot of maize or cassava were found in the fruit trees areas during the 1990s. One pixel in a Landsat image consisted of the spectra information that represented a common refection of all crops. Therefore, the statistic parameters analysis of separability for upland crops gave a TD/BD value ranging from 0.32 – 1.03 in both years (still lower than the range of separability of two classes, which should be from 1.8-2.0). Additionally, no soil map of Chieng Khoi in 1993 and 1999 existed and farmers were not able to adequately identify GTPs during the interviews. This lack of information made it impossible to distinguish the different annual upland crops for periods: 1973, 1993, and 1999.

Therefore, LULC maps in 1954 and 2007 were used for crop level classifications. In the case of LULC 1954, the specific location and area of the main upland crops were determined. In this region, upland rice, cassava, and maize were the staple crops to supply basic home consumption. For this purpose, elder farmers were asked to define the proportion of preference crops to fulfill food security for a household in 1954, using upland cultivation area from the 1st stage of classification process to define each crop type (maize, cassava, upland rice) accordingly. Additionally, historical soil maps, slope map and distance map were created to support the 2nd stage of the LU classification procedure.

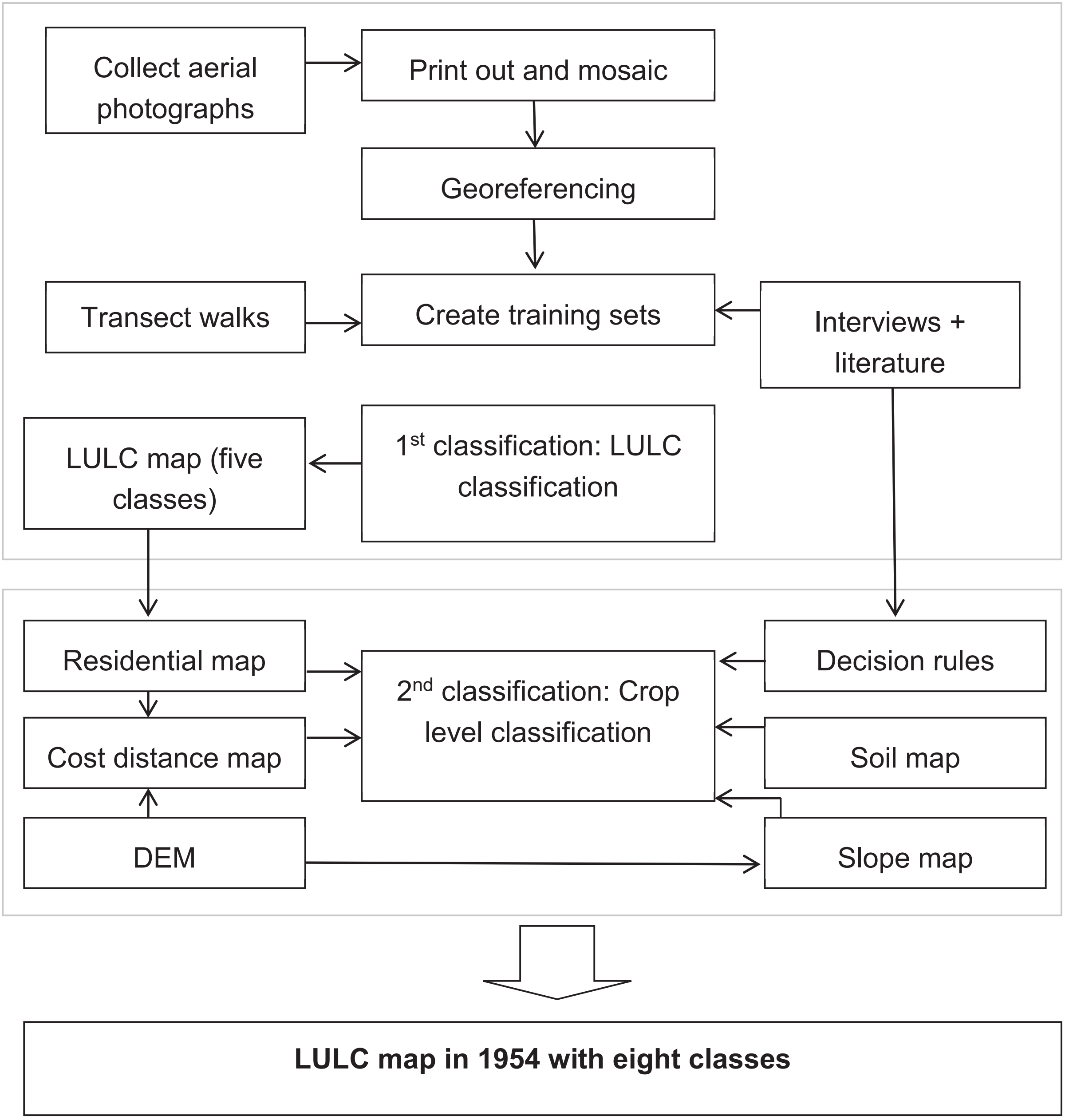
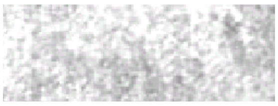
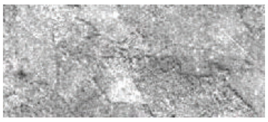
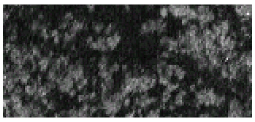
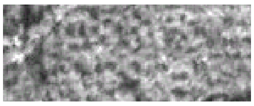
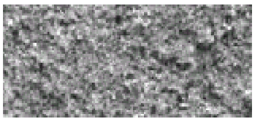
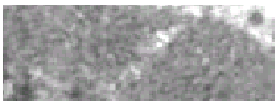
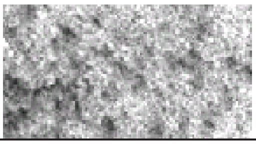
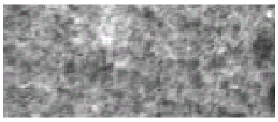
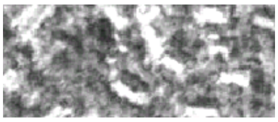
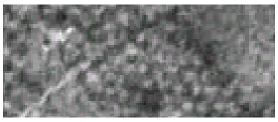


Figure 3.2 Two steps to classify LULC 1954 map at crop level classification from aerial photograph combined with historical information from farmers

Table 3.4 Training sets for aerial photograph visualization classification (adapted from Giang, 2002)

No	Land cover	Colour	Patterns	Position	***Samples***
1	Paddy rice	Grey White	Very smooth	Close to resident area	
2	Upland cultivation area	Grey bright	Very smooth/fine	Moderate slope	
3	Natural forest	Dark black	Very rough/coarse	Higher elevation	
4	Plantation forest	Black	Very Coarse/rough	Surrounding natural forest	
5	Bamboo forest	Dark Grey	rough		
6	Water body	Grey	Very smooth		
7	Nonuse land	Light black	Rough	Close to forest, close to street or river	
8	Secondary forest	Dark black	Rough	Close to natural forest	
9	Residents area	Grey with white spots	Rough	Where residents' areas are, close to streams, road, lowland	
10	Fruit tree	Black	Rough	Close to villages, have the rows	

Historical soil maps

The soil maps of 1954 were modified from an existing local soil map of Clemens *et al*. (2010) referring to the year 2010. The local soil map represented 12 soil classes and was derived from local farmer knowledge combined with soil profile information. Building on the outcomes of the focus group discussion, the original 12 soil classes were simplified to a historical ‘black and non-black soil’ and a ‘stony soil’ map. Therefore, soil classes with common characteristics such as all soils with a black colour were grouped into one class and so forth. Subsequently, a ‘black and non-black soil’ map was created containing two classes: black soil and non-black soil; a ‘stony soil’ map was created referring to the four classes: black soil non-stony, sandy soil, poor soil, and a combination of red and yellow soil (Figure 3.3). These classes followed farmers’ descriptions based on their decisions on crop choice and crop allocation concerning soil types (see further in Figure 3.6).

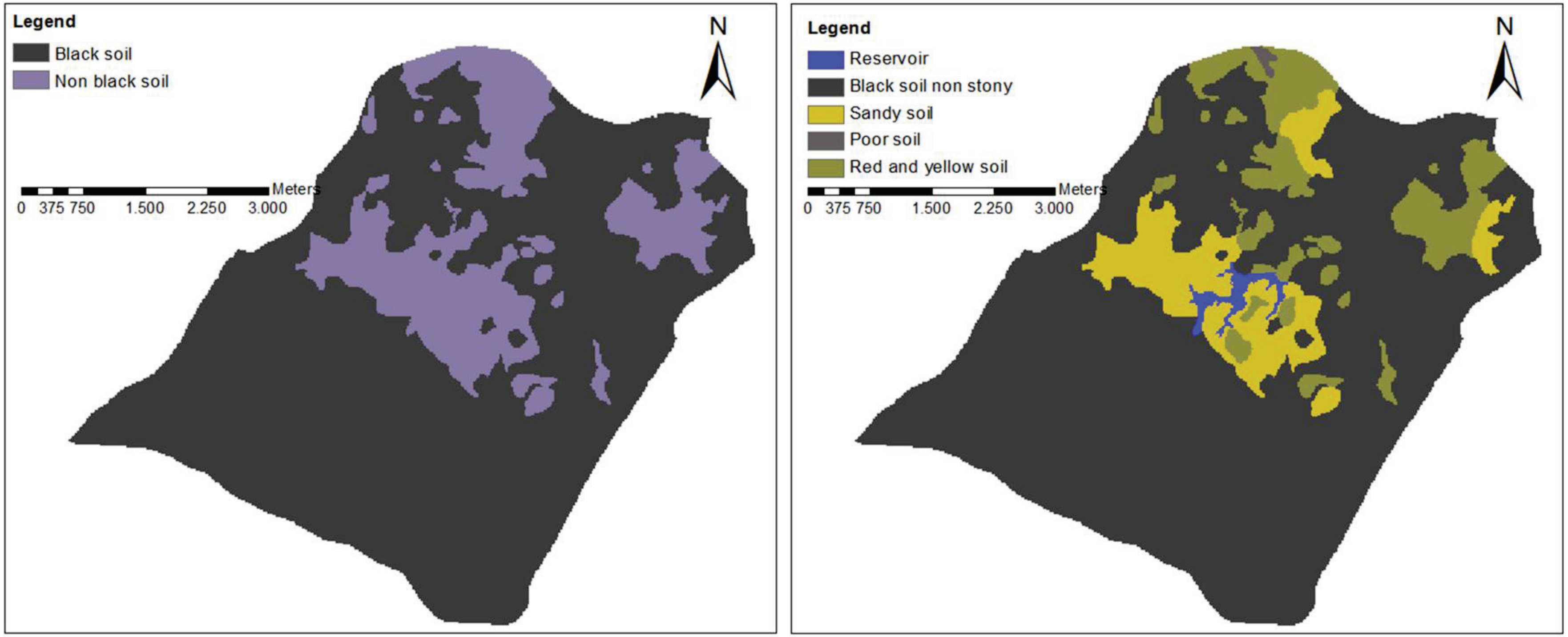


Figure 3.3 Soil map in 1954 in Chieng Khoi commune, modification from a local soil map in Clemens *et al*. (2010). The left image presents the black and non-black soil map, the right map represents a detailed soil map with stony properties (sandy, poor, red and yellow soils) and black soil non-stony.

Slope and distance maps

The slope map was created from a Digital Elevation Model (DEM – derived from contour lines from Geodatabase, Data and Map Archive Center – Ministry of Resources and Environment). The distance map was produced by a Cost Distance function in Spatial Analyst tool in ArcGIS 9.3. Cost distance tools calculate the least accumulative cost for each cell to specified source locations (residential areas) over a cost surface (slope map). Cost distance is the prerequisite for finding the least cost path or corridor (ArcGIS Desktop, 2007). In this case, the distance from homestead to all locations in Chieng Khoi commune was calculated.

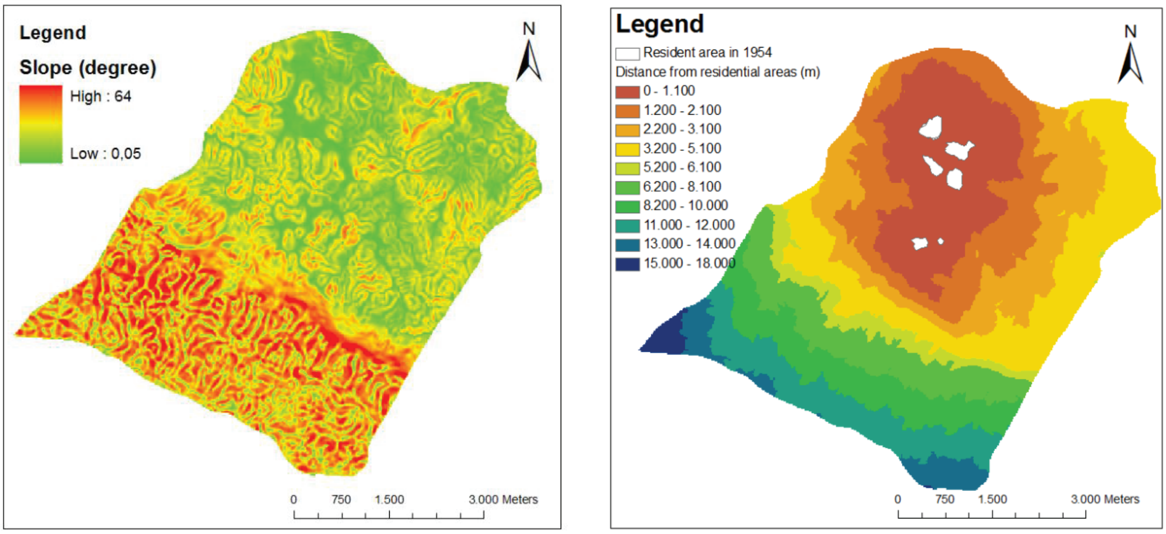


Figure 3.4 Slope map and distance map in Chieng Khoi commune

In a next step, the first choice of farmer crop location was adjusted by increasing the distance from resident areas on appreciated soil types and slopes. The increasing distance adjustments were stopped once the defined areas of the first choice-crop were reached. The same procedure was applied for the remaining crops. All adjustment processes were conducted using ArcGIS 9.3 and PCRaster (PCRaster Team, 2011). Figure 3.5 shows the adjustment processes in ArcGIS and PCRaster softwares, with a first distance area calculated to determine the upland area characterized by the distance less than the minimum distance as defined by farmers. The distance area was subtracted from upland areas and then overlaid with the historical soil maps and the slope map to extract approximated areas for the first crop choice as a potential crop area. Then the potential crop area was compared with the area of first choice crop which was defined by crop rotation. If the potential crop area equaled the defined area of the first crop choice, then the first crop choice area was deemed a potential crop area, otherwise increasing the distance from residential areas to upland fields by every 100 m was tested until potential crop areas were reached the defined as the first crop choice. The following choice of crop was adjusted with similar processes, but excluding the area of previous crop choice selection.

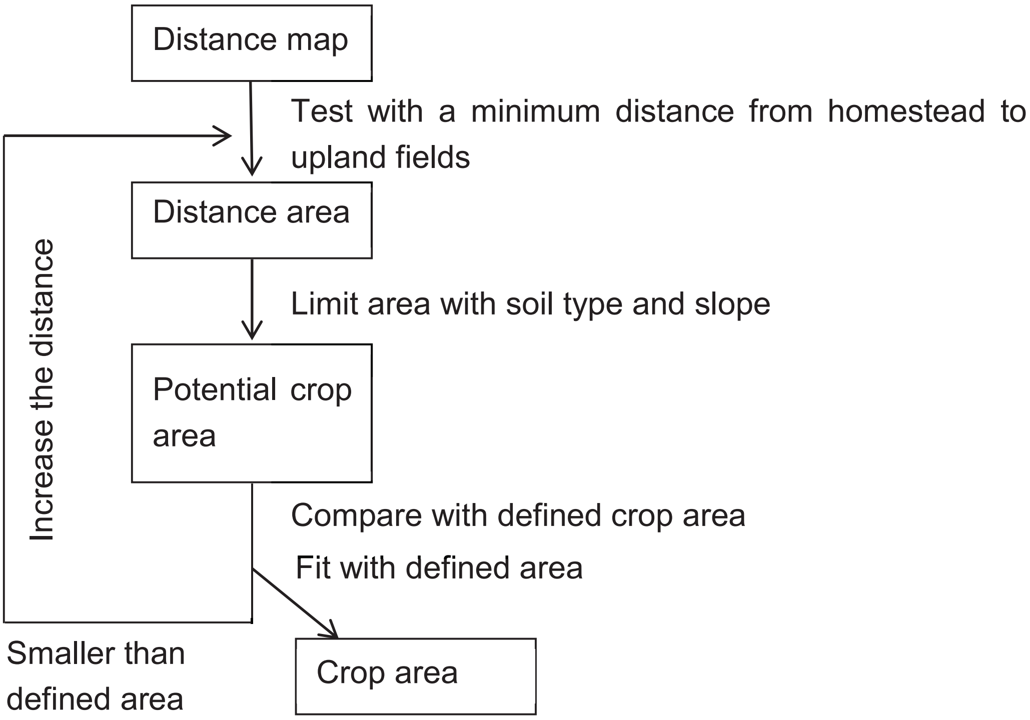


Figure 3.5 Adjustment processes

The LU map of 2007 was classified to distinguish locations of upland crops. The harvesting calendar (Appendix 3.5 - from Upland Program database), modification of local soil maps (Clemens *et al*., 2010), and a farmer decision tree (from farmer interviews) were used to distinguish common upland crops in 2007.

Upland areas as classified in the LULC map of 2007 were first converted into vector files. This vector was used to mask and extract upland crop areas from the LISS III images as regions of interest (ROI) for further crop level classification. The detail classification steps were:

- Firstly, a supervised maximum likelihood procedure was applied. Training sets were created based on the repeated evaluation of class histograms and statistical parameters of each class.

- Secondly, the output was overlaid with the local soil map using ENVI 4.3 and ArcGIS 9.3. Suitability of land for each crop was used as the indicator to assign the crop by implementing the decision-tree.

3.2.4 Accuracy assessment

The LULC map 1954 was validated by the additional farmer interviews, cross-checked by presenting these maps to the farmers who had not participated in previous interviews. A re-allocation of LU types was based on their agreements. The paddy rice class was received by combining information of current paddy rice areas in 2010 (Upland Program database, 2010) and historical paddy rice areas as received from farmer interviews. The historical paddy rice area existed until 1968, thereafter was replaced by an artificial lake. Finally, a detailed LULC map for 1954 was validated using the results from the farmers' group discussion. The percentage of farmers agreeing with the map was used to assess the accuracy due to the lack of other independent information. Moreover, the comparison between calculated and defined areas was used as a quasi-validation (Rounsevell *et al.*, 2003).

For the case of the maps in 1973, 1993, 1999, and 2007, an accuracy assessment was conducted using a confusion matrix table with Kappa coefficient. The confusion matrix table was created by comparing error values for each LU class that was classified with respective value in the ground truth data. The table has the same number of columns and rows that equal the number of classes. The land cover classes in the ground-truth image head the rows, while the same classes for the classified image head the columns (Wilkie and Finn, 1996). The Kappa coefficient was used because it considers all elements in the confusion matrix rather than only the diagonal elements (Rosenfield and Fitzpatrick-Lins, 1986). It is calculated as follows:

$$\hat{k} = \frac{N\sum_{i=1}^{r} X_{ii} - \sum_{i=1}^{r} X_{i+}X_{+i}}{N^2 - \sum_{i=1}^{r} X_{i+}X_{+i}} \qquad (3.3)$$

where r: = Number of row in confusion matrix

Xii = Number of row *i* and column *i*

Xi+ and X+i = Total of row *i* and column *i*

N = Number of observations

The Kappa coefficient measures the agreement between classification and ground truth points ranging from 0-1 with 1 referring to perfect agreement, and 0 to no agreement, a value of >0.8 is recommended, however, greater than 0.4 is acceptable (Trodd, 1995; Scepen, 1999; Froddy, 2002).

3.2.5 Post classification analysis and change detection

After the classification processes, the maps often showed salt and pepper effects caused by random pixels throughout the image. Hence, individual pixels were classified differently from their neighbors that made classified images appear speckled (Lillesand & Kiefer, 1999, Gong *et al*. 2006). Thus, the classification maps were smoothed by the Majority function in ENVI to replace the class value in the centre of a kernel by the majority class of that kernel, this procedure is a common step in LU classification (Lillesand & Kiefer, 1999; Tottrup and Rasmussen, 2004; Tottrup, 2004, 2007; Saha *et al*., 2005). The size of a kernel was 3x3 meaning that a kernel consisted of 3x3 pixels equaling nine pixels of a classification map. During the majority process, the center pixel class was replaced by a majority class in a kernel. The residential polygon was extracted from Giang (2002) and overlaid to separate secondary forest class and residential class. The area of residential class was checked by census data from the office of statistics in Yen Chau and its location was proved by farmer mapping in the villages. Change detection was conducted using cross tabulation analysis to determine the quantity of conversions between different land cover classes.

The final post classification step was the harmonization of spatial resolution of all classified LU maps. The minimum field size in study regions was 500 m^2 (Statistic book Chieng Khoi commune, 2011). Subsequently a resolution of 20 x 20 m was chosen as a common resolution for all classified maps. The LU maps in a raster format were re-sampled in two ways:

- Harmonization from the lower resolution: Maps 1973, 1993, and 1999 showed lower resolutions than the common resolution of 20x20 m, thus their map pixels were split to increase resolution.
- Harmonization from the higher resolution: In case of the maps of 1954 and 2007 which showed higher resolutions, meaning pixel sizes were smaller than the common resolution, the pixels were merged.

In both approaches, the LU class in a mixed pixel was assigned by the class of the nearest neighbour cell; this method uses the most suitable method to retain the information for discrete data such as the classes of land use maps (Esri, 2015).

3.3 Results

3.3.1 Decision rules and crop rotation

History of crop developments and farmers' decision rules on crop choices

This section presents the history of crops and the farmers' crop decisions resulting from group discussions. During the 1950s to 1960s, varieties of the most common crops (upland rice, cassava, maize) had lower productivity compared with modern hybrid and fertilized crops, therefore, farmers gave high priority to staple crops (Table 3.5). For example, the highest priority was given to upland rice and paddy rice, followed by three years cassava which was introduced during the Indo China War. From 1954 onwards, cassava became an important staple crop with the cropping area further expanding in the 1960s. Vegetable and flavour crops - such as herb and medicinal plants - were only used for home consumption. Thus, these crops were planted in home gardens or intercropped with main crops (Table 3.5). Based on the results from the pair wise ranking of crop choice, which is presented in Appendix 3.3, upland and paddy rice were ranked with higher scores than cassava and maize. Only common crops were considered, while crops with less than one ha in the total watershed area were excluded from the list for pair wise ranking. In addition, several crops that were planted only for a short period of up to two years were excluded, such as cotton, mulberry, and potato.

Paddy rice requires a consistent and large water supply, thus this crop was planted close to water sources (rivers, springs) or terraced upon sloping lands, while rain-fed crops such as upland rice, maize, and cassava were planted on hills surrounding the villages. Therefore, there was no competition concerning the location of planting areas between paddy rice and upland rice, as well as other upland crops, with paddy rice being the most important crop for food security from the 1950s to the 1970s. Paddy rice was planted mainly on flat lands many hundreds of years in Chieng Khoi commune, while a few terrain paddy rice plots were found in Ban Hiem village. Due to the specific requirements of being able to regulate water levels during the vegetation period, manure application was done annually in between cropping periods to maintain productivity. Total area and location of paddy rice production plots were almost constant until 1973, when the artificial reservoir was established and irrigation management improved. Since then, the paddy rice fields originally used for one crop per year were converted to double cropping – rain-fed and irrigated paddy rice. The spring of the main river in Chieng Khoi flows in a south – north direction through the commune, and from higher to lower elevations of the Karst mountains. Therefore, paddy rice was distributed from the southern to the northern part of the commune, surrounding the spring and along the river, with the largest areas in flat land in the lower north-west of the commune.

Table 3.5 General farmers' ranking on crop choice from the 1950s to the 1990s based on focus group discussion, carried out in Chieng Khoi commune, Yen Chau district, Son La province, Northwest Vietnam

Ranking order	Name of crops[*]	Reasons
1st	Paddy rice and upland rice	Staple crop, both paddy rice and upland rice were the first choice as they had no area competition. While paddy rice was planted on flat land and upland rice was planted on upland fields.
2nd	Three years cassava[**]	Staple crop was not common before the 1950s but more common and important after 1954 to the 1990s. Crops acted as one of most important starch source in the household.
3rd	Sticky maize[***]	Additional food for home consumption with quite low crop yields (> 0.5 Mg per ha), grown in upland fields following upland rice and often used for livestock feed
4th	Peanut	Additional food source and acted as a flavour for household meals

[*] *Names of crops were different and were included many names based on farmer definitions. In some villages, farmers used the characteristics of crops to name them*

[**] Crop was named as local cassava or high cassava.

[***] Crop was named as local maize or white maize.

In contrast to paddy rice, the location of upland crops was determined using several criteria depending on the period. During the assessment stage between 1950s and 1990s, the criteria was as followes: importance of crop, distance to transport products from the fields to houses, the convenience of harvesting, weeding and soil management, slope, and soil properties (soil colour and texture). In the past, shifting cultivation required new areas annually, and these areas replaced forest or fallow land; 'New Areas', and the previously cultivated land was named as 'Old Areas'. As a priority crop for upland fields, upland rice was chosen to plant in 'New Areas' (Figure 3.6). 'Old Areas' were divided into upland rice for second year and maize or cassava. With a short distance (< 1 hour walking, as defined in farmer groups) to residential area and good soil (indicated by black colour), non-stony soil was selected for three years cassava while maize was located in stony areas. Areas where land was cultivated for two to three years, soil colour became grey, reddish or yellowish (as described by farmers); these areas were left to fallow. In case of a long distance to the residential area and of good soil, non-stony soil was used for maize and cassava intercropping, whereas stony soil was used for maize and 'bad' soils (also name as non-black soils in the local soil map) were left fallow (Figure 3.6). Although expanded upland cultivation areas were not recorded by the statistics office in Yen Chau, farmers who had fields near the forest boundary expanded their cultivation areas into secondary or primary forest, about 5 - 10 m every one or two years. During the field work in 2011, the same situation was observed with a smaller width and length of 3 - 5 m encroachment, bi-annually during the dry season.

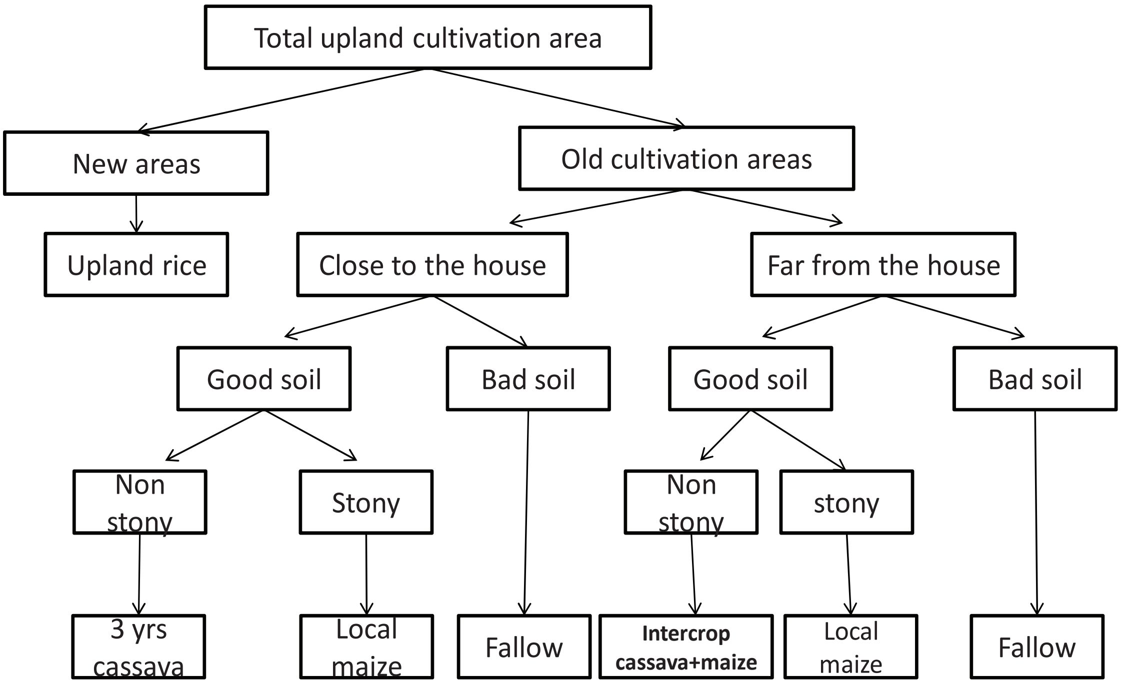


Figure 3.6 Farmers' decision tree on the location of crops between 1960s and 1990s in Chieng Khoi commune (Adapted from Nguyen, 2009)

In the later assessment stage of 2007, farmer decisions were different, and cultivation expansion to natural forest areas was officially banned and infrastructure had improved. In addition, access to further distant upland plots was easier due to the availability of motorbikes, thus the distance from homesteads to fields became a less important criterion for selecting the location for important crops. Farmers stated that good soil could be used for all crops while poor soil was considered suitable for cassava only. In case of soils with intermediate fertility level, maize could only be cultivated with fertilizer input, often unaffordable to the farming community. Therefore, farmers preferred to grow cassava or to use an intercrop. Early harvesting maize led to longer periods of bare soil exposure, while cassava or intercrops still covered the ground. In the case of stone contents, farmers planted maize, and *vice versa*, intercropped maize with cassava. Observed changes in soil colour (still black or becoming brownish) gave further indications in deciding which crop to be planted. The results showed the strong existing relationship between soil quality, cropping calendar, soil characteristics, and crop cover. These farmer decision rules are summarized below:

- Maize was planted in upland areas with fertile soil and bare soil in the dry season.
- Cassava was planted in upland areas with fertile soil with ground cover in the dry season, in brownish soil or upland areas with intermediate soil quality, with stones in the soil, or in upland areas with poor soil.

Intercrops were planted in upland areas with fertile soil with ground cover in the dry season, in black soil or upland areas with intermediate soil, without stone.

Crop rotations

Beside farmers' decision rules on crop choices, historical crop rotations were investigated during group discussions and key informant interviews in Chieng Khoi commune, Yen Chau district. Farmers determined crop rotations in different time periods. In this region, composite swidden cultivation systems were common and popular until the 1990s, as mentioned in section 2.1. A composite swidden system consists of integrated upland rotating crop/fallow plots and downstream permanent paddy rice fields. Paddy rice was planted once or twice per year, mostly closer to water sources during the first season mid February to June and the second season from July to November. The cropping period strongly depended on the specific weather of the year. Manure was applied annually to compensate nutrient export and to enhance the soil properties. Home livestock production provided manure for paddy rice. Pest and weed control were conducted manually. In the upland areas, crops were rain-fed. Farmers slashed and burned fields after harvesting and planted their rain-fed crops at the beginning of the rainy season.

The original good soils were described as black coloured soils. These soils were used for planting for a longer period (one to three years longer than the soils were nonblack colour) before fallowing for about 7 to 14 years. The lower quality soils were described as gray or black with stones and cropped for 2 to 3 years continuously. Crop rotations were grouped into 3 periods:

- 1954 to 1973: due to the complete establishment of the artificial lake in 1974 (establishment started in 1968, completed in 1974) and availability of remote sensing data (Landsat in 1973).

- 1973 to 1993: because Land Law allowed long-term land use rights starting in 1993.
- 1993 to 2007: the third stage was further sub-grouped into as follows:
    - (3a) 1993 to 1999: the right of land title for agricultural land (also known as the 'Red Book') was applied in 1999 in Chieng Khoi commune.
    - (3b) 1999 to 2007 due to available remote sensing data (LISS III).

In the first period (1954 to 1973), upland rice was planted first for two years after slashing the plants in the forest (or in the older fallow areas), in few areas with low productivity, then upland rice was planted only one year. Intercropped maize and three-year cassava followed in the rotation because cassava was introduced at the beginning of the 1950s and commonly planted after 1954 while maize has been always used by farmers. Excluding the rotation in small areas, the general crop rotation from 1954 to 1973 is shown in Table 3.6.

Table 3.6 General crop rotation in Chieng Khoi commune, Yen Chau district from 1954 to 2007

1999-2007	Forest	Hybrid maize					
1993-1999	Forest	Upland rice	Upland rice	Maize/ Cassava	Maize/ Cassava	2 yr. fallow	
1973-1993	Forest	Upland rice	Upland rice	Maize/ Cassava	Maize/ Cassava	3 to 4xfallow	
1954-1973	Forest	Upland rice	Upland rice	Maize/ Cassava	Maize/ Cassava	5 to 7xFallow	(average 6 years)

During the second period (1973 - 1993), the fallow period was shortened from seven to three or four years. Maize and cassava intercrop followed two years of upland rice. Then the fallow period followed for three to four years. The last period of study, from 1993 to 1999, the fallow period lasted for two years then the next crop of hybrid maize rotation started again. However, after the issuance of land ownership, farmers increased their investment for plots, intensified and abandoned fallows from crop rotations. The cropping systems then had no rotation and were solely cropped with two main crops; hybrid maize, and hybrid cassava intercropped with hybrid maize. Fallow and secondary forest areas were replaced completely after the slash and burn or were slowly replaced by maize intercropped as agroforestry, with timber plantation using teak (*Tectona grandis*) or Lat hoa (*Chukrasia tabularis)*. From 1999 to 2007, hybrid maize was the dominant crop and replaced the fields of other crops, even expanding into all remaining areas except those with very poor soil conditions (Table 3.6).

3.3.2 LULC maps from 1954 to 2007

LULC maps and their classification accuracy are shown in this section. Post classification of the aerial photograph for 1954 derived five classes: Residential area, water body, forest, paddy rice, and upland cultivation area (Figure 3.7, left). A total of 80% of older farmers (total 10 farmers) agreed with the final classified map during the validation discussion. The water body was visible in the image and differed from the paddy rice, whereas upland fields and young fallow areas were not distinguishable using the image. The same situation occurred with the location of crop types. In this case, maize, cassava, and upland rice were mixed and appeared with the same background pattern in aerial photographs before and after mosaicking the images. Therefore, further classification was undertaken using farmer decision rules with the results of further classification and will be presented below.

LULC map of 1973 of Chieng Khoi commune achieved an overall accuracy of 50% (23/46) and Kappa coefficient of 0.39. Separability of land cover classes ranged from 1.8 to 2. As shown in Table 3.7, the values were acceptable for the hybrid classification except for paddy rice and water body (1.4). These classes were mixed because the image was taken during the dry season, thus the shadow shallow areas in water body showed a similar spectral pattern as paddy rice, which were dry areas during the dry season. The low value of separation between paddy rice and water body was corrected based on farmers' knowledge of the location of water body and stable location of paddy rice in post-classification processes. At the end, seven classes were derived from the supervised classification LULC map 1973 (Figure 3.7): residential, water body, forest, paddy rice, upland cultivation area, secondary forest, and 'unknown'. The 'unknown' class represented the boundary area to fit the coordinate system.

Table 3.7 Example of separability of land cover classes derived from Landsat MSS 1973 of Chieng Khoi commune. The minimum of Transformed Divergence -TD and Bhattacharrya Distance - BD values were calculated using ENVI 4.3. Further results of 1993, 1999, and 2007, see in Appendix 3.6

Name of classes	No of points	Upland cultivation	Paddy rice	Water body	Forest
Group class[*]	55	1.9	1.9	1.9	2.0
Upland cultivation	8	x	1.8	1.9	1.9
Paddy rice	16	x	x	1.4[**]	2.0
Water body	11	x	x	x	2.0
Forest	25	x	x	x	X

[*] TD and BD value for residential areas were 1.2 (with paddy rice), 1.4 (with water body), 1.6 (with upland cultivation), so residential area was grouped in group class and separated with known polygon from Giang (2002).

[**] The low value of separation between paddy rice and water body is corrected based on known location of water body and stable location of paddy rice in post-classification processes.

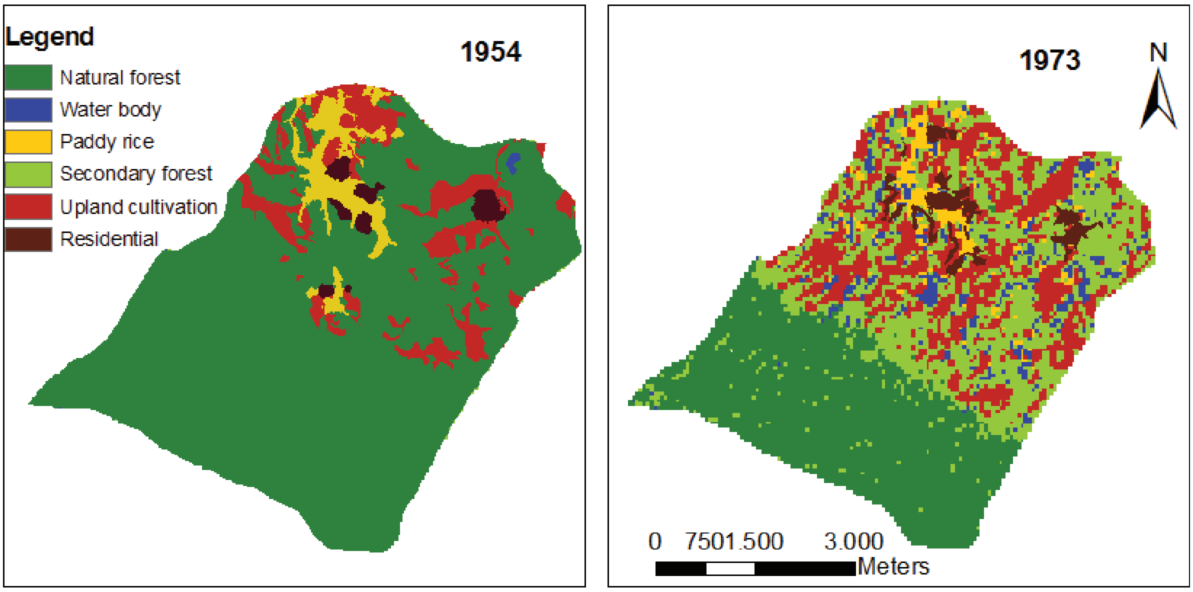


Figure 3.7 LULC maps in Chieng Khoi, derived from aerial photograph 1954 and Landsat MSS 1973

LULC maps in 1993, 1999, and 2007 were classified by five groups: forest, tree, water body, upland, and paddy rice (Figure 3.8) with overall accuracy values of 81.1%, 98.5%, and 82.5% respectively. Kappa coefficients were 0.68, 0.98, and 0.74 respectively. Water body class in these years represented the artificial lake in Chieng

Khoi commune; it was concreted in 1974 within a fixed area (40 ha). Similar to water body class, the paddy rice area was also fixed as it is the main staple crop, and has been for hundreds years (99 ha in 1959 and 79 ha in 2011 - Statistics Department Yen Chau, 2012). After the completion of the artificial lake in 1974, few areas were transformed from one crop per year to two crops per year due to an enhanced available water supply. However, in these years, water body and paddy rice classes were partly misclassified due to:

- Date of data source: Landsat image 1993 was the taken in late dry season in February 1993 while the Landsat image 1999 was taken in middle of dry season in December 1999. Dry shallow water body areas were classified as paddy rice or upland class.
- Season effect: Similar results of misclassification occurred in 2007 during a drought when much of the lake dry.
- Resolution effect: The resolution of the Landsat 1993 and 1999 images (30x30 m) was more than five times lower than the resolution of LISS III 2007 sharpened with PAN (5.8x5.8 m). Each pixel represented either an area size of 600 m^2 or 34 m^3, consequently, the mixed pixels in the lake margins could be misclassified, especially in the case of the classification process of the Landsat images. The highest error occurred with the Landsat 1973 with resolution 57x57 m (mostly from water body to paddy rice).

Table 3.8 shows the statistics of LULC types from 1954 to 2007, the misclassification was shown while water body and paddy rice classes were both dynamic with unexpected increases and decreases in area during the 53 years. In Table 3.8, residential and secondary forest classes in 1973 were summed as one class ‘Residential/tree’, because tree class is also included secondary forest in the LULC maps 1993, 1999, and 2007 (mentioned earlier in Table 3.3). This class increased until 1993 and then decreased up until 2007. Forest area dropped from 83.4% of total area in 1954 to 29.7% in 2007 which is associated to the increase in upland cultivation area from 10.1% in 1954 to 22.7% in 2007 and residential/tree area from 1.8% to 43.6%. Upland cultivation area increased from 1954 to 1973 (+130 ha) and then decreased in 1993 (337 ha). This misclassification with the residential/tree class could be mainly attributed to cultivation history. During the 1970s, the long fallow period was still prevailing in the commune and after second year of fallow, pixels with bush and small trees show similar spectral than secondary forests.

Table 3.8 Statistic LULC type areas in Chieng Khoi commune from 1954 to 2007

No	LULC types	Area in 1954 (ha)	Area in 1973 (ha)	Area in 1993 (ha)	Area in 1999 (ha)	Area in 2007 (ha)
1	Forest	2595	2068	1146	1303	929
2	Residential/tree	55	95	1572	1283	1361
3	Paddy rice	140	105	83	92	110
4	Water body	4	169	18	26	17
5	Upland cultivation	315	645	308	423	708
6	Unknown	0	14	0	0	0
	Total*	**3109**	**3096**	**3127**	**3127**	**3125**

**The total areas were different because of resolution issues; LULC map in 1954 (20x20 m), in 1973 (57x57 m), 1993 and 1999 (30x30 m) and 2007 (5.8x5.8 m)*

Besides the aspect of misclassification, the overall trend of increasing upland cultivation and decreasing forest area (including both natural and secondary forest) were consistent during the period of 1954 to 2007 (Figure 3.9).

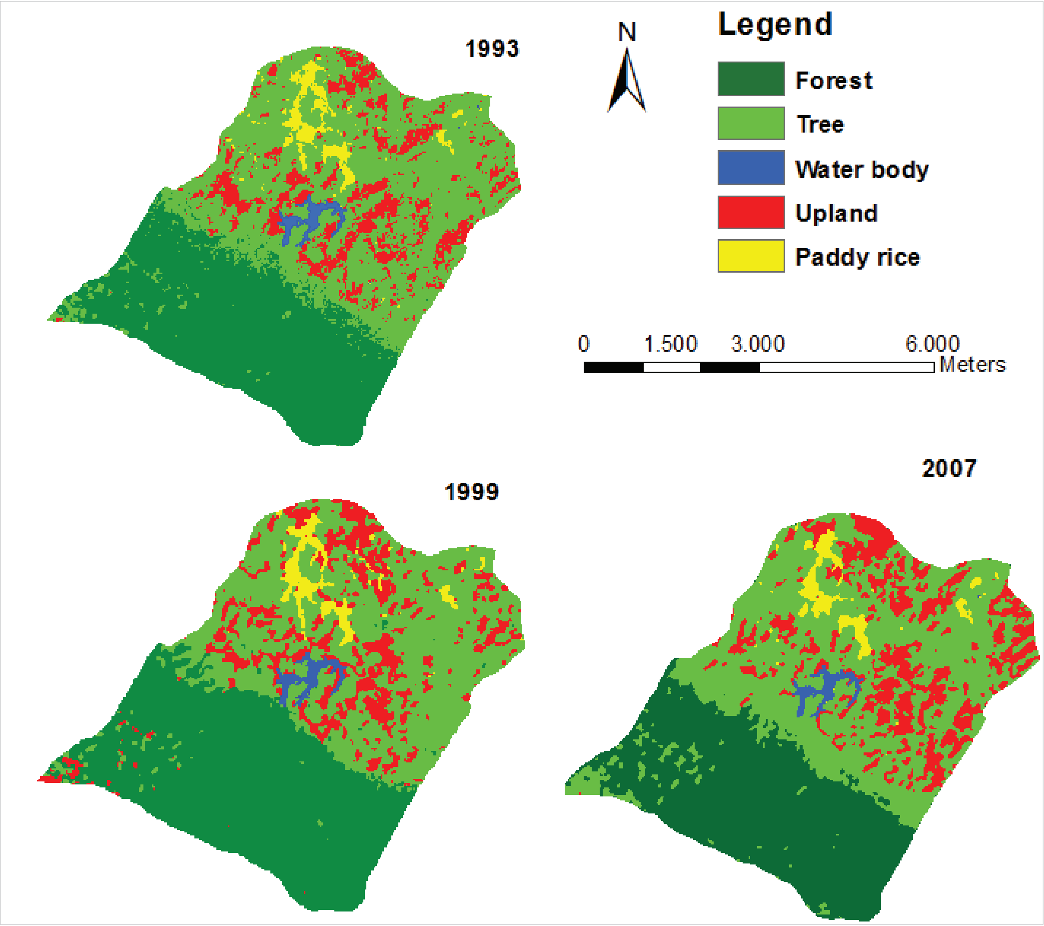


Figure 3.8 LULC map 1993, 1999 and 2007 classified using supervised classification method (Nguyen, 2009)

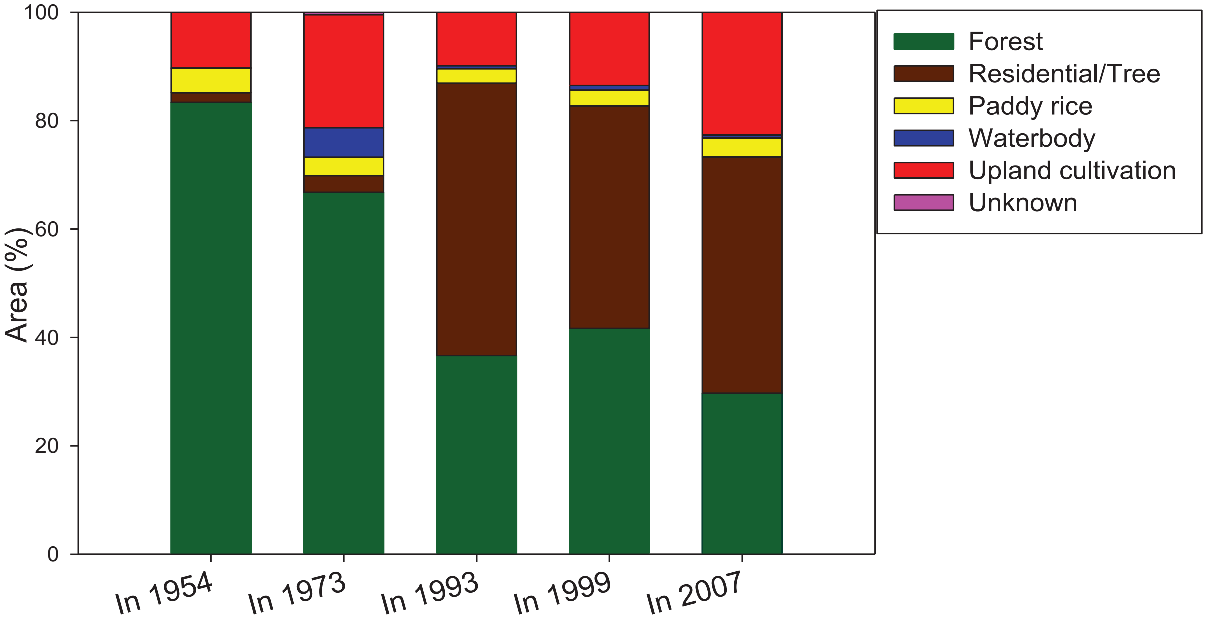


Figure 3.9 Area occupied by different LULC types from 1954 to 2007

3.3.3 Crop level classification in 1954 and 2007

The previous sections presented the first results following fieldwork and the first step of LULC map classifications. The subsequently more detailed classification methods were developed to determine the upland crop distribution in the LULC maps 1954 and 2007, which was impossible by classical methods with available remote sensing data in a small watershed such as the case of Chieng Khoi commune. In 1954, the historical time mark that was remembered by elder farmers was the victory in the Indo China War, thus farmers could recall the farming situation during this year very well. In case of 2007, besides the better memory of a recent year, remote sensing data (LISS III) had a high resolution (5.8 x 5.8 m) and Google Earth imaging was available. All this support allowed further classification. Therefore, the detailed classification method processed only two LULC classified maps which entailed high accuracy at the first classification and also referred to more precise inputs compared to 1973, 1993, and 1999.

Detailed LULC map 1954

After the first classification step of LULC map 1954, the resulting output was used for detailed classification. For this purpose, crop rotation in 1954 (as shown in Table 3.6), farmer decision rules (Figure 3.6), and farmer choices (Table 3.5) were used for a spatial adjustment process. From historical crop rotation, total upland cultivated area was divided into 10 groups (2x upland rice, 2x maize and cassava, and 6x fallows) to determine a ‘defined area’ value. Thus, the adjustment process was conducted 9 times, twice for upland rice, twice for maize and cassava, 5x fallow, and then fallow in year six was the remainder of total area; these values were named as the ‘calculated area’ values. Table 3.9 shows the results of the adjustment processes; all calculated areas were adjusted with close values of defined areas. The calculation of the sixth year fallow area received the largest different area with defined value - minus 0.78 ha, the smallest different areas were the calculation for the second year of fallow, fifth year fallow (plus 0.02 ha), and second year maize and cassava (minus 0.02 ha). Figure 3.10 shows the maps of single calculated area locations and assigned crops after the adjustment process. While increasing the distance to reach defined areas, upland rice crop (in first and second year) had the closest distance to residential areas (1.1 km) and fallow (at all ages) revealed the longest distance to residential areas (2.14km) The area resulting from all calculations slightly differed with defined areas (Table 3.11). Four of six famers agreed with the result maps, one farmer disagreed, and one farmer partly agreed (this farmer mentioned that he gave the grade 5/10 for the result). The final detailed LULC map 1954 was produced after merging the produced maps with classified LULC maps of the initial classification step (Figure 3.11, left).

Detailed LULC map 2007

Like the detailed classification of the LULC map 1954, the LULC map in 2007 was produced using the initially classified map as shown in Figure 3.8 combined with farmer decision rules. In this case, a detailed classification was conducted to receive land use types at crop-level, mainly maize, cassava, and intercrop (maize and cassava), which were not possible to distinguish based on remote sensing data only. At the time, the maize hybrid variety was the dominant mono-crop planted without fallow periods (similar findings are also shown in historical crop rotation, Table 3.6), although cassava and intercrop fields were still detected because there was almost no production of maize on poor soil areas. Maize, cassava, and intercrop were distinguished with high overall accuracy values (84.4%) and an acceptable Kappa coefficient (0.74). A detailed LULC map 2007 was produced with seven classes including the additional three classes of maize (282 ha), cassava (283 ha), intercrop maize and cassava (163 ha) (Figure 3.11, right).

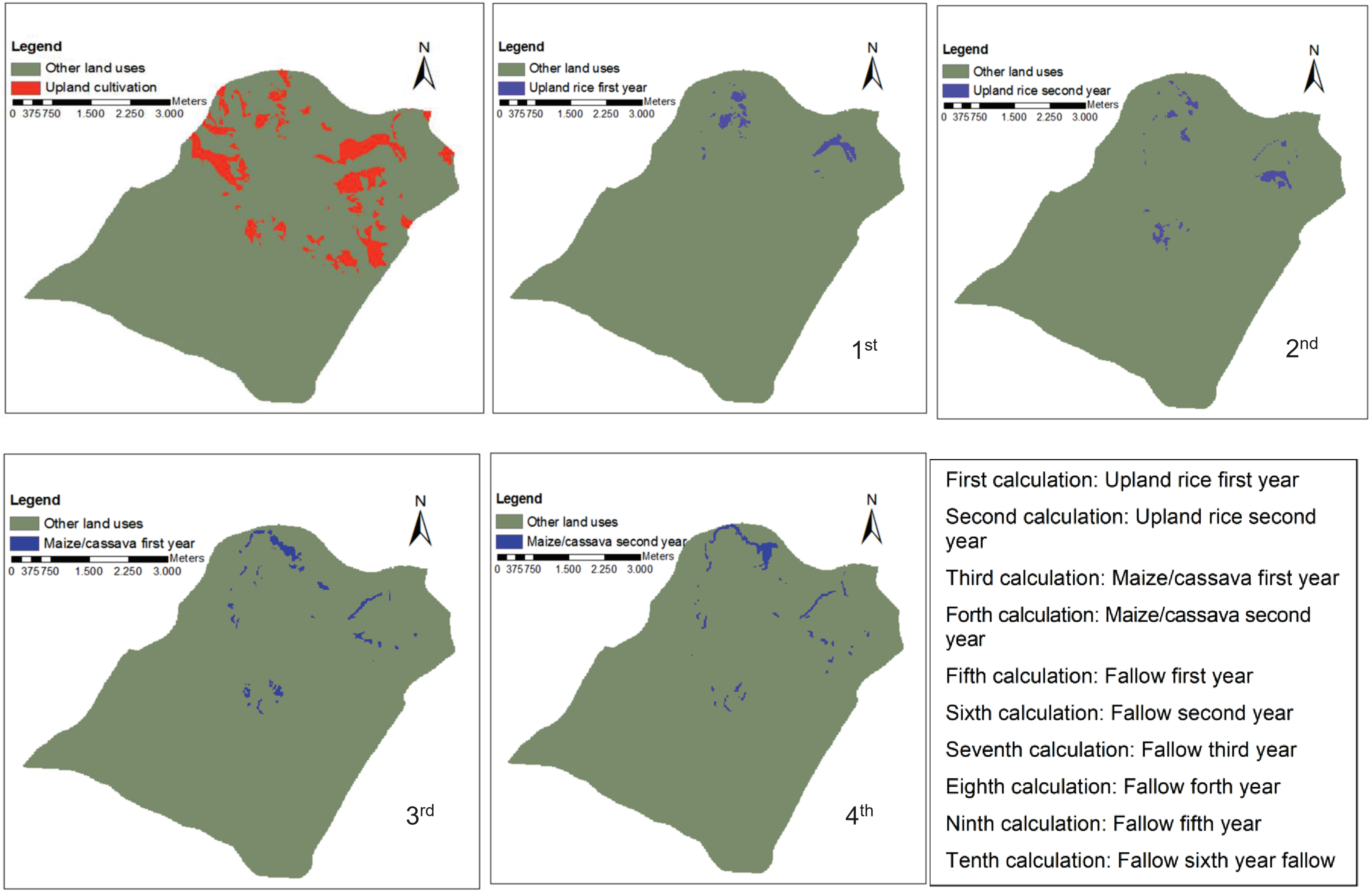
Table 3.9 Comparison of identifying areas after the adjustment process with defined areas. Positive values indicate the areas higher than the defined area*, minus values indicate areas lower than defined values

Order of calculation	Target upland crops to calculate in order	Calculated area** (ha)	Defined area (ha)	Difference with defined area* (ha)
1st	Upland rice first year	31.64	31.5	-0.14
2nd	Upland rice second year	31.40	31.5	+0.10
3rd	Maize/cassava first year	31.84	31.5	-0.34
4th	Maize/cassava second year	31.52	31.5	-0.02
5th	Fallow first year	31.12	31.5	+0.38
6th	Fallow second year	31.48	31.5	+0.02
7th	Fallow third year	31.36	31.5	+0.14
8th	Fallow forth year	31.60	31.5	-0.10
9th	Fallow fifth year	31.48	31.5	+0.02
10th	Fallow sixth year	32.28	31.5	-0.78

** Defined area equal to a value derived from the total upland area divided into 10 (crops)*

*** Calculated area - the values resulting from adjustment processes*

**** Difference area less than 1 ha was accepted at commune level (Statistic Department Yen Chau district, 2012*



First calculation: Upland rice first year

Second calculation: Upland rice second year

Third calculation: Maize/cassava first year

Forth calculation: Maize/cassava second year

Fifth calculation: Fallow first year

Sixth calculation: Fallow second year

Seventh calculation: Fallow third year

Eighth calculation: Fallow forth year

Ninth calculation: Fallow fifth year

Tenth calculation: Fallow sixth year fallow

Figure 3.10 Crop maps after 10 adjustment processes to identify suitable location to fulfill defined area for upland crop based on farmer decisions

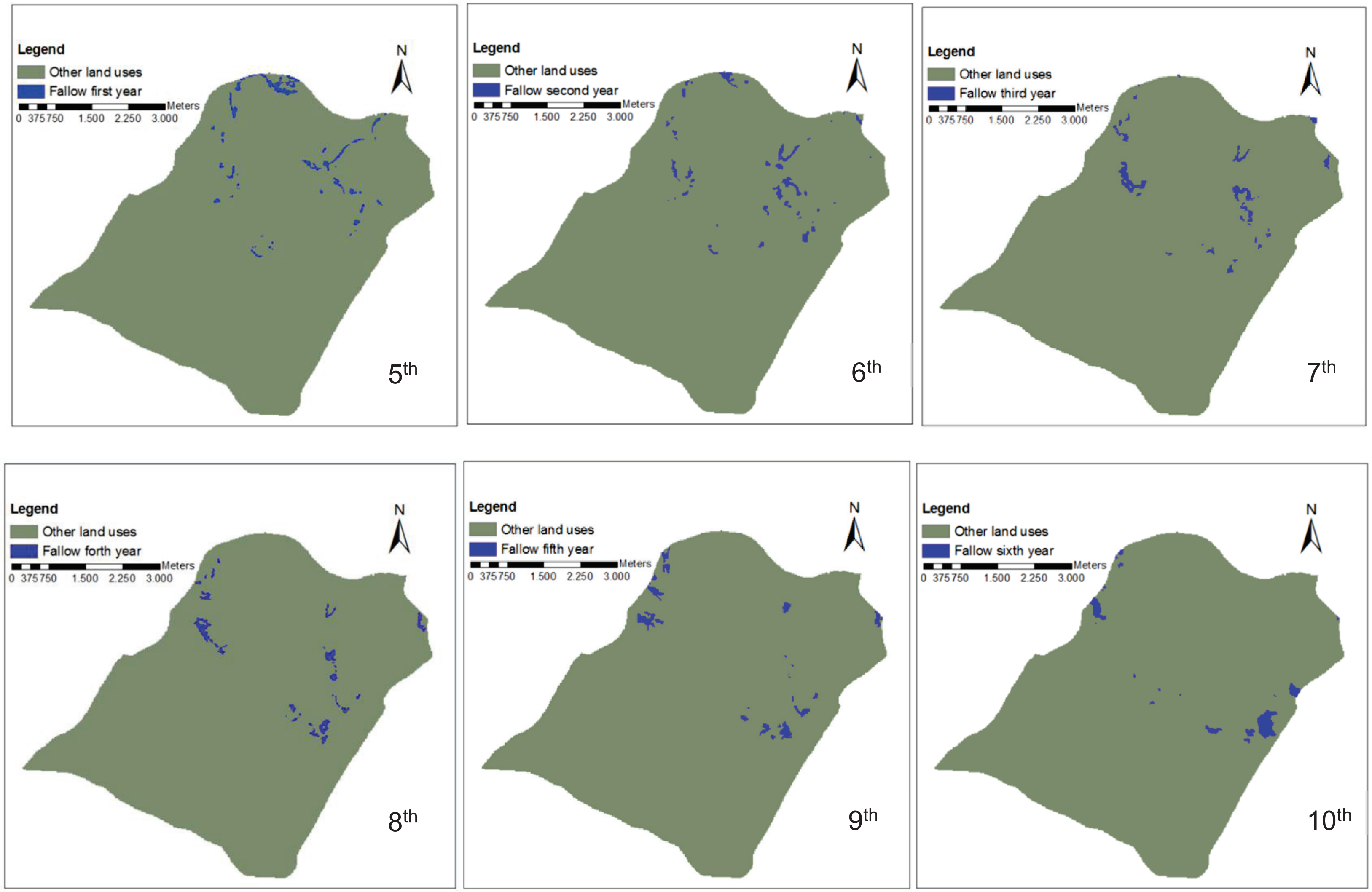


Figure 3.10 (Continue) Crop maps after adjustment process to identify suitable location to fulfill defined area for upland crop based on farmer decisions

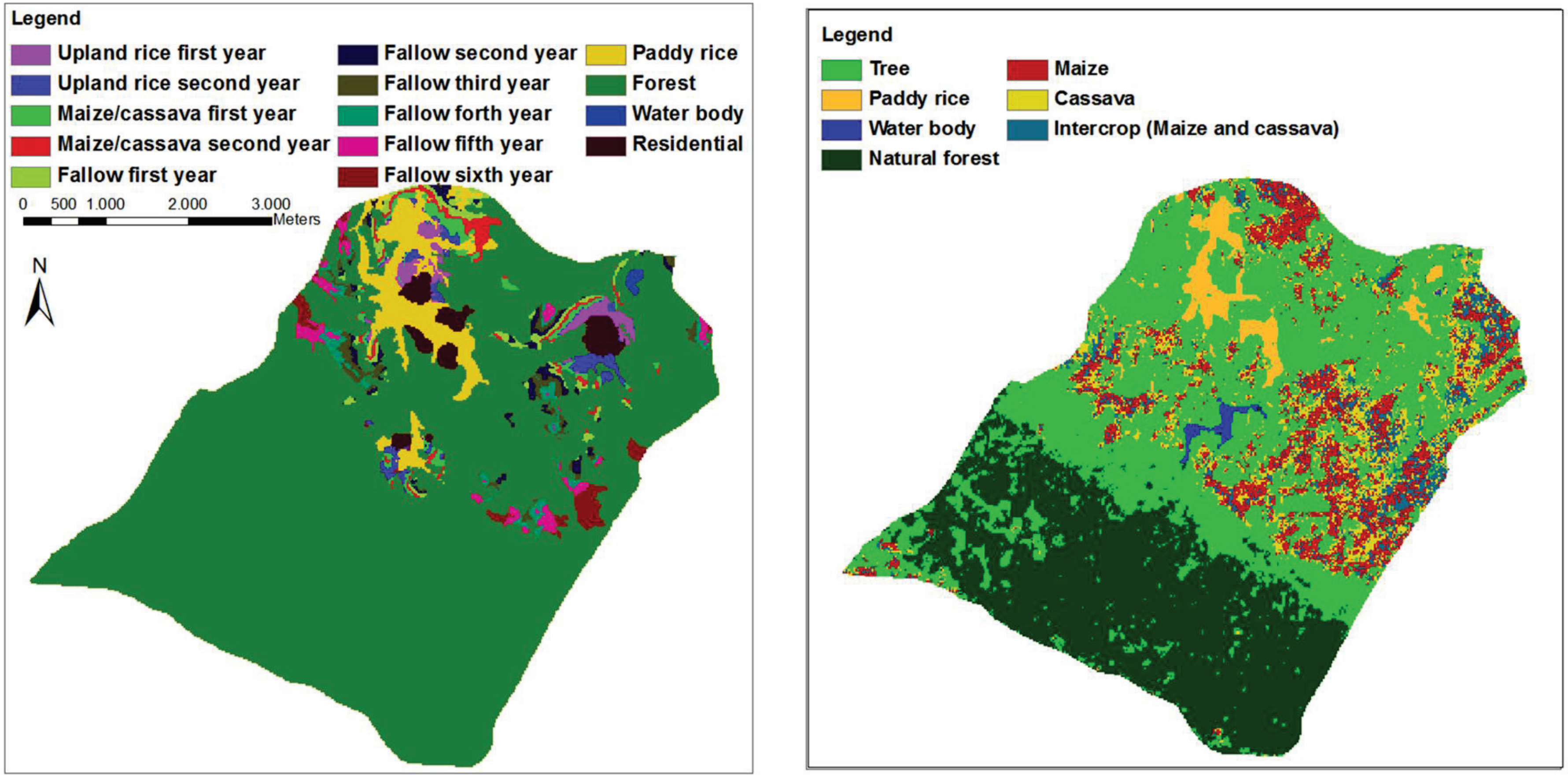


Figure 3.11 LULC maps of 1954 (left) and 2007 (right) after detailed classification using farmer decision rules and GIS tools

Table 3.10 Maximum distances of upland crops to homestead in Chieng Khoi commune in 1954, used during the adjustment processes using farmer decision rules on upland crop distribution

Crops	Maximum distance to residential (m)	Other addition criteria	Area (ha)
Upland rice	1100	Good soil, non-stony, first consideration of area with slope ≤ 50% then to slope ≤ 100% before increasing distance.	63
Maize and cassava	1600	Good soil, non-stony soil, slope ≤ 100%, excluding upland rice areas.	64
Fallow	2140	In upland cultivation area, slope ≤ 100%, excluding areas which were planted upland rice, maize and cassava.	188
Total			315

Harmonization of map resolution

The produced five LULC maps were computed to a common resolution of 20 m x 20 m. Detailed classified maps of 1954 and 2007 were also exported to LULC maps using the same resolution. Harmonization processes produced maps with homogeneous spatial resolution that also allowed further detection processes. Due to misclassification issues, were mentioned above, this section focused on the change detection between detailed LULC maps in 1954 and 2007. Figure 3.12 demonstrates LUC detection

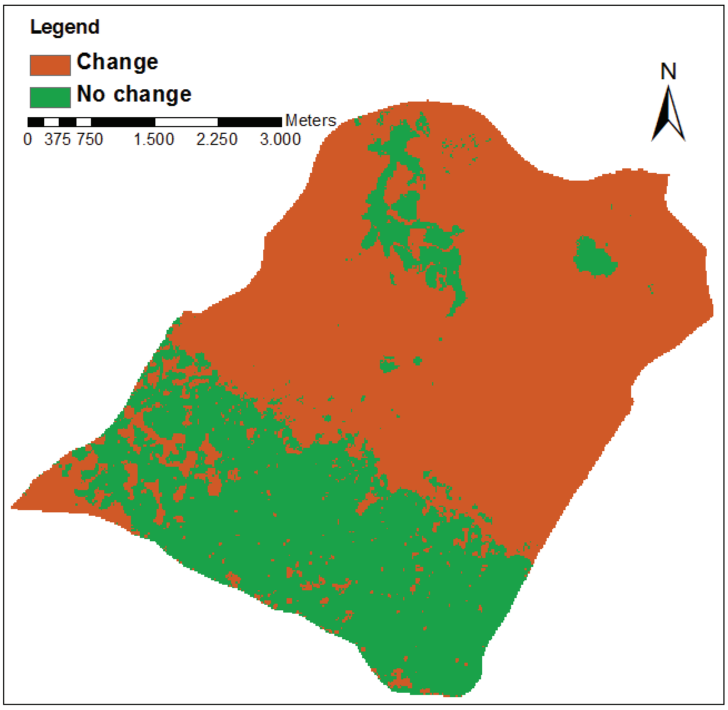


Figure 3.12 Land use change detection map between 2007 and 1954 in Chieng Khoi commune

after the map harmonization process. A total of 34% consists of natural forest in the southwest, paddy rice, and some village areas showed no change after 53 years (or they were switched back to the same land use types as before). Other classes were occupied by 66% especially upland crop classes and large areas of natural forest that were replaced by different classes, from the center and towards the northern parts of the watershed (Figure 3.11).

3.3.4 Agricultural expansion and modified farming practices affect natural resources in Chieng Khoi watershed

Results mentioned above reveal an enormous increase of upland agricultural areas in the 53-year assessment period (from 315 ha in 1954 to 708 ha in 2007). Comparing two maps in Figure 3.10, these upland cultivation areas have mostly expanded surrounding original cultivation areas into forest areas since 1954. The large upland areas in 2007 were shown from the centre to eastern and northeastern areas of the commune, whereas the smaller areas were located at the western watershed area. The expansion also took place towards the southeast of the watershed, which is associated with higher elevation (Chapter 2.1). A similar result was also found during field observations in 2010. Figure 3.13 shows an example of cultivation fields extending to the upper slope in Chieng Khoi commune, where a new maize field was established consisting of a part on the lower slope cleared in 2008 and an extension to the upper hill cleared in 2010.

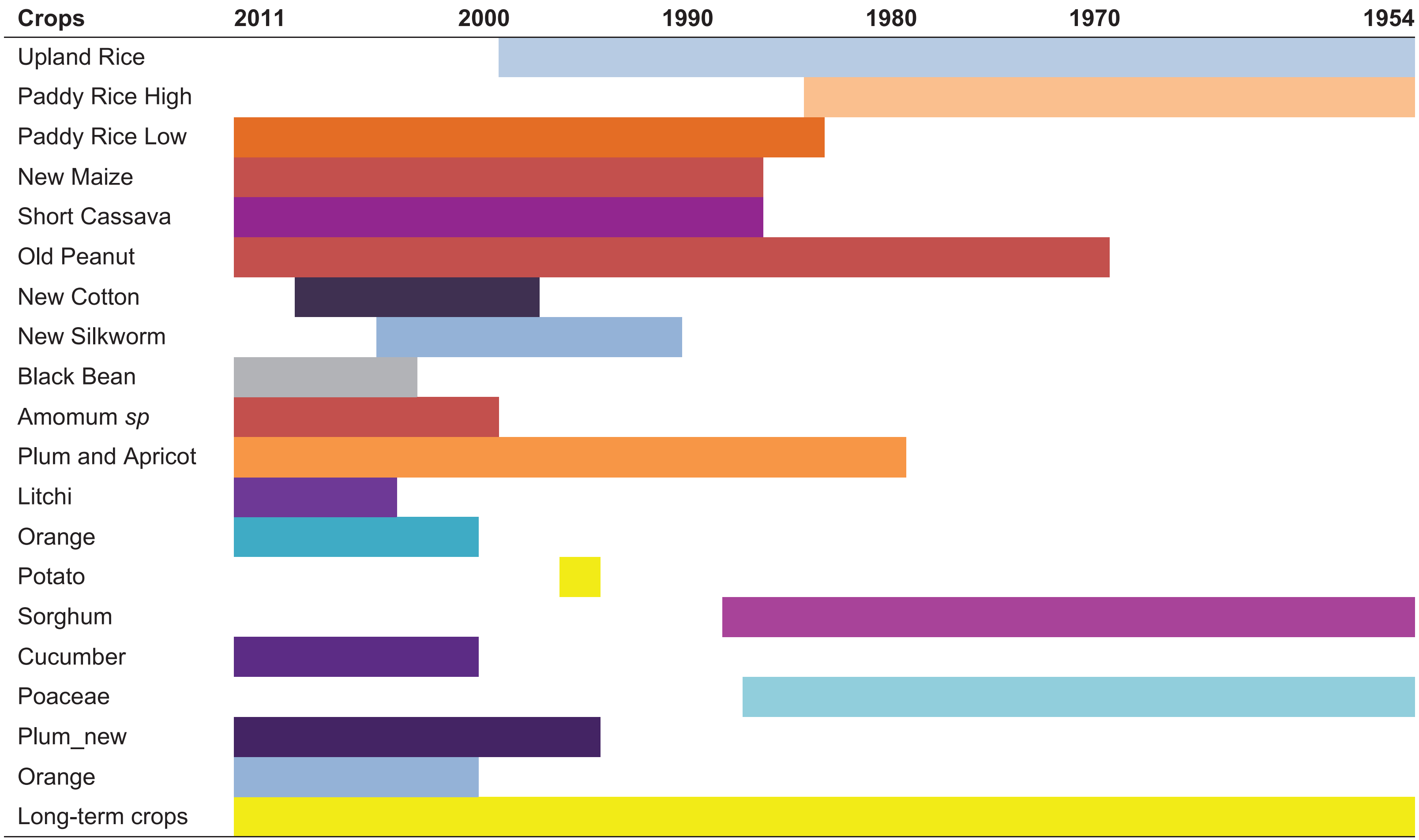
Figure 3.13 New plot in Chieng Khoi commune (Source: own picture, taken in 2010)

Besides the expansion of agriculture into the uplands, farmers modified their management practices in all cultivated lands. Before the 1990s, farmers used hoes, and slashed and burnt the field to prepare land for cropping. In this period, intercropping, crop rotation with long fallow periods and various local varieties were mentioned by farmers. Since the 1990s, farmers planted many new crops compared crops existed only for short periods (potatoes - *Solanum tuberosum* L., new cotton - *Gossypium hirsutum*, and new mulberry - *Morus indica* L.) or are/were planted on small areas for home consumption (beans, fruit plants, and vegetables). Moreover, hybrid paddy rice (short paddy rice); hybrid maize (new maize), and hybrid cassava (short cassava) were adopted well by farmers. These crops not only became dominant crops by providing high household incomes (in cash and productivity), but they also were planted intensively and continuously in a mono cropping system supported by chemical fertilizer and tillage.

The expansion of agricultural land to forest areas, especially to upper slopes, combined with modified farming practices led to high risks for natural resources (Figure 3.13). Forest cover was reduced by more than 50% (Figure 3.9). An associated reduction of carbon stock resulted from deforestation and because of removal of plants during crop harvesting. Moreover, tillage in sloping land favored water erosion leading to reduction of soil fertility. Figure 3.14 shows the brighter soil colour after two years of cultivation compared to the darker soil colour in newly opened areas. Further impacts of LULC changes on soil fertility will be discussed in chapter 5 with detailed analyses of soil samples.

Figure 3.14 The expansion of agricultural land to upper slopes in 2011 (left) and water erosion in maize plot (right) 2009)

Table 3.11 List of crops and their history since 1954 until 2011 based on farmers' focus group discussion



* Crops were named by farmers using order of time appearance and plant characteristics (except Amomum *sp* and Poaceae)

** Long-term crops are those that were planted by farmers from 1954 and are planted currently: sticky maize, three year cassava, peanut, sweet potatoes, Bon plant, Cotton, Mulberry for Silk worm, dye plant, soybean, sesame, green vegetable, banana, mango, longan, jackfruit, pineapple, taro, pumpkin, squash, ginger, tamarind, sugar cane, melon, climbing bean, non-climbing bean, eggplant, old plum, pomelo, lemon, and chili (scientific names of all crops are listed in Appendix 3.7).

3.4 Discussion

3.4.1 The effects of map classification methods and data source quality on LULC changes at watershed level

The LULC classification results show a reduction of forest area by 53.7% and an increase of upland cultivation by 12.6% in 53 years in the Chieng Khoi watershed. The reduction of forest areas was associated with an increase of upland cultivation areas with most of the forest areas in 1954 being replaced by tree class; tree plantation, secondary forest and plantation forest areas in 2007. Chi (2007) showed a similar finding in a larger study site in the same province. The classification land use map in a catchment area covered that 284 km^2 in Suoi Moi, Son La Province, also showed the reduction of forest class by 4.4% (equal 3 098 ha including both closed and open canopy forest) from 16.7% in 1954 to 10.3% in 1999), whereas upland field areas added 12.4% ha from 1954 (24.1%) to 1999 (36.5%).

Besides the contrary trend of forest and upland cultivation classes, the classification showed the unexpected dynamic of other land use types without a necessary relationship to surface patterns. This issue could be explained by the date the images were taken, season and spatial resolution effects (as also mentioned in 3.3.2). For example, Table 3.8 and Figure 3.9 show the decrease of water body and paddy rice classes from 1973 to 1993, however, it was not only a decrease by land use change, but also caused by the differences in pixel size between Landsat MSS in 1973 (57 m) and Landsat TM 1993 (30 m). Each pixel being almost double the size; each class in 1973 could be classified less precisely compared to 1993.

The data sources were not the only factor that influenced the results; the classification methodology also contributed a high impact to the unexpected coutcomes. This study used two methods to classify land use change: visualization based on visual ground patterns from images (to classify aerial photographs) and hybrid classification based on spectral bands reflected from ground patterns (to classify Landsat MSS, TM, and LISS III). The use of an individual method was necessary because in the case of historical aerial photographs for Chieng Khoi watershed, the image quality was low and composited by six pictures, thus the automatic hybrid classification was an unsuitable method due to the noise from boundaries between pictures after mosaicking process and the variability of the brightness of six pictures. In the case of Landsat images, the visualization method was highly labour intensive because Landsat images present the spectral reflection of ground patterns and the interpretation of spectral reflection in Landsat images could be influenced by personal optics. Several methods such as object-oriented segmentation classification and the pixel based method were also commonly used for small to medium scale with a high accuracy of classification

(Kefyalaw, 2015; Yu, 2006; Nagabhatla *et al.*, 2014). Chieng Khoi commune is a small watershed but characterized by highly heterogeneous surface covers. Hence, the hybrid classification and visualization methods combined with local farmer decision rules were sufficient to achieve a classification accuracy range from 50% to 98%.

When focusing mainly on the development trend of forest and upland cultivation classes, the misclassification occurring in other classes can be considered as an error of classification processes, rather than land use changes.

Table 3.12 Land use changes in Suoi Moi, Son La province, land use type classified from aerial photographs and satellite imagery from 1954 to 2000, adapted from Chi (2007). Grey columns represent the year that land use maps were classified from aerial photographs

Year Land use	1954	1973	1988	1993	1996	1999	2000
Closed canopy forest (ha)	1146	825	800	627	582	445	660
Open canopy forest (ha)	3581	4003	1997	1508	1251	1174	2280
Shrub (ha)	13616	12139	13701	13345	12881	11610	12049
Grassland (ha)	1874	1439	1415	1671	1691	1499	1442
Upland field (ha)	6825	8856	9322	10189	10423	10932	10382
Paddy rice (ha)	1210	1151	1175	1069	1582	1456	1597
Residential (ha)	123	na	na	na	na	1246	na
Water body (ha)	na*	na	na	na	na	3	na
Total (ha)	28375	28413	28410	28409	28410	28365	28410

* *na - unknown or unclassified*

Table 3.12 shows the land use changes from 1954 to 2000 in Suoi Moi, Son La province using the different sources of images with various pixel sizes obviously resulting in different total areas within the same study. Upland field class from 1996, 1999 and 2000 were 10423 ha, 10932 ha, and 10382 ha, respectively. However, upland field areas in 1999 were larger than in 2000, and smaller than in 1996. This could be caused by an interpretation of ground pattern and resolution between satellite images (1996 - a SPOT image and 2000-Landsat ETM) and aerial photographs (1999). Similar misclassifications were reported by Chi (2007) while using two sources of images.

Hence, the previously stated hypothesis that the land use dynamic from 1954 to 2007 can be assessed using diverse remote sensing data sources and farmer decision rules, can be only partly accepted, as the dynamic of land use was basically assessed between the forest and upland cultivation classes. However, the dynamic of other land use types was ambiguous due to the misclassification problems mentioned above.

3.4.2 Role of farmer decision rules to classify historical LULC maps

As described above, local knowledge of farmers and villagers supported the LULC classification processes. Without this contribution of historical ground truth points and farmer decision rules, the single method approaches such as supervised or unsupervised automatic classifications would be insufficient to classify the historical LULC maps, and especially to investigate the crop distribution in the upland areas of the case study area. In Kefyalaw *et al*. (2015), a multi-temporal approach to improve LULC classification in agricultural crops over 41 years in South Central Ethiopia (from 1972 to 2013) was used, however even in this case, remote sensing data were available, but the local knowledge was still a useful input for mapping and successfully improving misclassification by 18% in the examined study period. In this study, local knowledge was not only used for the LULC classification at crop level, but also implemented to validate the historical land use map. This information provided a significant value for LULC classifications because through farm management activities, farmers directly influence the ground patterns, especially to the agricultural areas or relevant land use types. Therefore, farmers have played an important role in land use changes in the past, present, and will continue to in the future (Castella *et al*., 2005; Castella *et al*., 2007; Lippe *et al*., 2013).

Moreover, the farmer knowledge also compensated for the limitation of data sources in rural areas. At watershed level, historical remote sensing data are often limited or low quality. In case of Chieng Khoi commune, the mapping unit storage capacity is weak considering both available labor and technology of the local commune office. All land use data were kept on open shelves or cupboards with the mapping information on paper printed forms or hand written. Under the tropical humid weather conditions, however, most of the printed information disappeared after three to four years. Additionally, the responsible person was replaced every second year and working on data storage as a side responsibility without necessary professional skills. Remote sensing such as Landsat, SPOT, LISS III images were available but the spatial resolution is relatively ranged from average to low. Thus, combining local knowledge with remote sensing data was the suitable approach to assess historical LULC in this small watershed with limited data. This combination supported the first hypothesis that long-term historical land use maps could be classified by long-term historical remote sensing incorporating farmer knowledge. Cousins (2001) used historical data including non-geometric cadastral maps and aerial photographs from 1945 to 1981 to analyze the LULC changes in south east Sweden. The author concluded that using the corrected processing methods, historical data are very useful in determining LULC changes and general trends over 300 years. Acquiring historical ground pattern information by using the historical aerial photographs, Maltlack (2009) determined the stand age of second-growth forest, then this information integrated with the soil sampling to illustrate the development of the physical and chemical consistency of the soils over 100 years in northern Delaware and south east Pennsylvania, USA. The author concluded that the present environmental conditions were still well reflected by the analyzed LULC history.

3.4.3 Implication historical LULC information

In this study, a long-term historical dataset was used for understanding LULC dynamics and assessing the impact on nature resources and agricultural activities in rural areas. The historical data represented the source to explain the present situation and can be used to simulate potential scenarios to mitigate actual situations (Cousins, 2001; Crawley, 1990). Such as, natural resources were reported with negative impacts: the low water quality, soil degradation, reduction of carbon stock (Schmitter *et al*., 2010; Clemens *et al*., 2010; Schad *et al*., 2012; Wezel *et al*., 2002a, b). Agricultural production was also reported as unsustainable in this study region (Keil, 2008; Tuan *et al*., 2014). Against this back ground, this study proposes to use the long-term historical LULC information as inputs for:

- Assessing the impacts of LULC changes on natural resources by looking at the history, which may explain the present conditions and describe a potentially better future.
- Simulating the consequences of the new alternative systems to agricultural production and natural resources in the future using modelling tools.
- Testing conservation methods to mitigate the current problems such as erosion, flooding, and soil degradation using modelling tools.

Chapter 4 and 5 will present examples of the above uses. Chapter 4 uses the LULC maps to develop a model to simulate the expansion of agricultural land in Chieng Khoi commune. In Chapter 5, historical LULC maps are used as the inputs for a model to assess the impact of LUC on soil fertility in the same region.

3.4.4 Lessons learned

This section details the pros and cons through the lessons learned.

Cons: This chapter demonstrated the development of the classification methods to understand the LULC changes from 1954 to 2007. Besides the success of identifying the main dynamic trends, the long-term historical aerial photograph in 1954 revealed only a small amount of the information, which was caused by the limitation of the spectral; a manual interpretation method and the complex available data source for this study site. Kadmon and Harari (1999) also indicated that the manual classification is time-consuming and with low efficacy in analyzing the ground patterns. Together with the low to moderate resolution Landsat images, the results of the classification show an overall moderate accuracy - 78.4% in all periods (1954:80%; 1973: 50%; 1993: 81.1%; 1999: 98.5%; 2007: 82.5%) and consisted of some misclassification.

From the findings, the suggestions for further studies using limited datasets at watershed level are: (1) the study should use two watersheds that contain similar locations, social, economic and historical conditions to determine parallel LULC information, this parallel approach could support the conclusion on the accuracy of the classification, especially on crop level classification, which the validation procedure proved limited because the long-term historical information derived from the interviews. Next, (2) expert interviews and deep focus group discussions are recommended to derive more precise historical information; and lastly, (3) a larger sample size (more than 20 farmers) is also recommended to improve the validation procedure. This approach could be named as the ‘twin watersheds’ approach which could improve upon the limitations of the present study.

Pros: Kadmon and Harari (1999) and Cousins (2001) concluded that historical aerial photographs are powerful sources for detection, quantification and analysis of ground patterns to address the question of LUC over historical period. Moreover, a mosaic consisting of six aerial photograph pictures since 1954 still expressed the main trends of forest and agricultural areas in the Chieng Khoi watershed. Additionally, the open access and freely available data has been a point of interest, e.g. Google Earth is increasingly used to understand surface features in a given landscape (Kefyalew *et al*., 2015; Nagabhatla, *et al*., 2014). Especially the combination of remote sensing and farmer interviews is a cost-effective method for studies in a small watershed area, further characterized by its remote location and low data availability. The use of farmer decision rules to classify LU maps is the most important issue obtaining during this study, because the farmers were involved with the map classification and validation processes, which could give them a clear overview of LUC, providing the first warning signals to farmers about the current negative situation and assist them to imagine and take actions towards to sustainable agriculture.

3.5 Conclusion

The results indicate that the diverse spatial resolution remote sensing data can derive valuable information of LULC in the Chieng Khoi watershed. Herein, the appropriate method is highly recommended to satisfy the quality of remote sensing data. Besides, the identification of agricultural land expansion and replacement of forest areas from 1954 to 2007 are important results that explain the high increase of cultivation in sloping land. Moreover, the employed harmonization processes allow the change detection processes to bring heterogeneous remote data to homogenous map results. This supports the potential uses of historical data to determine and develop suitable approaches to retain sustainable agricultural development both economically and ecologically in data limited and remote small watershed regions.

Chapter 4. Developing a land use change model for data-limited watersheds

This Chapter presents the chosen method to simulate land use change from 1954 to 2007 for data-limited watersheds surrounding Chieng Khoi commune. Required input information such as historical LULC maps, decision rules, and crop rotations were derived from the previous Chapter to construct and validate developed modelling procedures.

4.1 Objectives

Building on the results of Chapter 3, this Chapter aims to investigate the main factors that drive LULC changes at the watershed level of Chieng Khoi commune by using a newly developed LUC modelling approach. Although a variety of LUC models are currently available such as CLUEs (Catchment Land Use for Environmental Sustainability), FALLOW (Forest, Agroforest, Low value Landscape Or Wasteland?), and MP- MAS (Mathematical Programming –based Multi-Agent Systems), most of these require rather large datasets, which are often not available for rural areas or are only available at a high cost of labor, time and financial resources. Therefore, this Chapter focuses on the development of a ‘land use land cover changes’ model or short term ‘LUC’ model (use in this Chapter) that builds on minimum data input and mathematical algorithms to simulate LUC patterns in this tropical watershed. In case of this study, a minimum dataset refers to datasets that are often available at watershed level such as population growth, farmer knowledge and literature reviews. The specific objectives of this Chapter are as follows: (1) identify; and (2) analyze the main driving factors leading LUC since 1954 at that watershed scale of Chieng Khoi; (3) develop a model to simulate annual LUC from 1954 to 2007 based on the main factors identified; and, (4) validate the outcomes of the LUC model.

Subsequently, the guiding hypotheses are: (1) a mathematical algorithm can be built from farmers’ decision rules and (2) the LUC from1954 to 2007 can be modeled using a minimum dataset.

4.2 Overview of model concept development

In principle, other existing models simulate the changes of land use and land cover using variables that represent case study-specific LULC driving factors. For example, the CLUEs model integrates socio-economic and biophysical driving factors at watershed scale. This model simulates LUC by using a set of variables that convert actual LU type to others (Verburg *et al*., 2002). Similarly, the core modules of the

FALLOW model also use both socio-economic and biophysical processes, but these processes are connected through a dynamic loop that is supported by additional modules focusing on the transition from a shifting cultivation to more intensive land use systems, as well as impact modules that assess the consequences of LUC. In case of FALLOW, the model simulates LUC using soil fertility at plot-scale as the principal driving factor (Lusiana *et al*., 2012; Mulia *et al*., 2013).In contrast, while developed with similar components, MP-MAS model combines an economic model of farm household decision-making and a biophysical model of crop yield based on expected yields under different water supplies and changes in soil nutrients (Berger and Schreinemachers, 2012). However, in case of data-limited watersheds, such models often need to be built from a small dataset. Therefore, the core of developing an LUC model could be the determination of the most suitable driving factors of LUC for a data-limited watershed.

The concept of the newly developed LUC model was constructed based on the main driving factors of the study site. Castella *et al*. (2005) confirmed that data derived from a participatory approach could be used for predicting LUC. Therefore, Lippe *et al*. (2011) used the participatory approach to build a qualitative dataset to simulate LUC for a data poor environment. In case of LUC, food security (or food demand) is a key factor that is often related to LULC patterns (Verburg *et al*., 1999a, b, 2013). For instance, the FALLOW model was developed by the World Agroforestry Centre comprising five core processes, where two of these processes are related to food security concerns and farmer decisions at village level (Lusiana *et al*., 2012; Mulia *et al*., 2013). In the case of Chieng Khoi watershed, local food demand is largely satisfied by agricultural activities that are mostly originate from local crop production systems. Therefore, combining support from market factors, crop rotations, and farmer decision rules, using the food requirement of this watershed is a promising approach to assess the LUC in rural areas where access to data is limited and food self-sufficiency is important.

Food demand is closely associated with the population from the household to global levels (FAO, 2011a; Hazell and Wood, 2008; Buringh and Dudal, 1987). Thus, when food demand increases it also accords to an increase in the population. In this study, the term ‘food demand’ solely focuses on available food quantity, but not the increase of food preference, that could be also attributed as ‘food preference’ and ‘food quality’ that indicates an increase in a high standard of food. This was done because the simulation exercise began in 1954 when scarcity of food was reported as the most crucial factor to be considered for land use planning from the government (Minh, 2010). An increased food supply can be achieved by an (1) expansion of agricultural cultivation areas; (2) transformation of land use types to agricultural purposes such as the transformation from another land use type to an area for storing agricultural products; or, (3) an intensification in the agricultural sectors such as using high-yielding varieties, chemical fertilizers, and pesticides (Hazell and Wood, 2008; Buringh and Dudal, 1987). Herein, the LUC model was developed based on the food demand from the population growth of the watershed. The previous Chapter developed a comprehensive understanding of the increase in upland cultivation at the expense of forest areas. This dataset provided the input and validation data for constructing the newly developed LUC model. Therefore 'LUC' in this Chapter refers to the changes in agricultural and forest areas of Chieng Khoi commune.

The LUC model was constructed based on two main components. The first component identifies the amount of conversion areas; in this case, the expansion of agricultural land equals the conversion areas. The amount of expansion land was determined by food, commercial orientation, policy and preference requirements (Figure 4.1) based on:

Food requirement was selected because this term determines how much area is needed to satisfy the food demand for an increasing population (FAO, 2011a).

Market demand requirement was selected because this term determines which crops were considered of high priority because of high market demands (Keil *et al*., 2008, Vu *et al*., 2014; Minh *et al*., 2011).

Policy requirement was selected, because this term determines which crops were promoted by government policy. This element was matched with commercial and food requirements in this study (Lentz *et al*., 2011; Nguyen, 2012; Saint-Macary *et al*., 2010).

Preference requirement was selected because this term determines which local crops farmers preferred to plant for their own (subsistence) consumption (based on author's survey data).

The second component was the location of conversion areas. In this study, the second component distinguished suitable locations for the required expansion areas as well as areas that were cultivated before, but became unsuitable to continue with the current cropping systems based on local soil conditions. This component was specified by the farmers' decisions and crop rotations (see Chapter 3).

Farmers' decision: The farmers decided the locations to extend for the cultivation based on their own current resources such as labor availability and crop specific needs. For example, in the study region, fresh cassava tube needs instruments for harvesting and transporting to the house.

Crop rotations: Farmers practiced crop rotations to increase land use efficiency. At a specific area, crop rotation determined the replacement crops or other land use types annually. In this study, the crop repetitions or more suitable crops or fallow areas were rotated in upland fields.

The two components consisted of six elements. All elements were considered as driving factors, but because they were dissimilar/or changing over longer-term periods, therefore the LUC model was assessed and simulated during three contrasting periods:

(1) 1954-1973: driven by population growth, food requirements and swidden agriculture (Minh *et al*., 2011)
(2) 1973-1993: driven by population growth and the establishment of an irrigation lake (Richter, 2007)
(3) 1993-2007: driven by population growth and a shift towards market commercialisation (Keil *et al*., 2008; Minh *et al*., 2011)

Model simulations focused on individual periods because in each period, the LUC model needed to be modified according to the main driving factors. Therefore, the next sections will not only describe the input data for the LUC model, but also the adaptation of input data for the appropriate period of simulation.

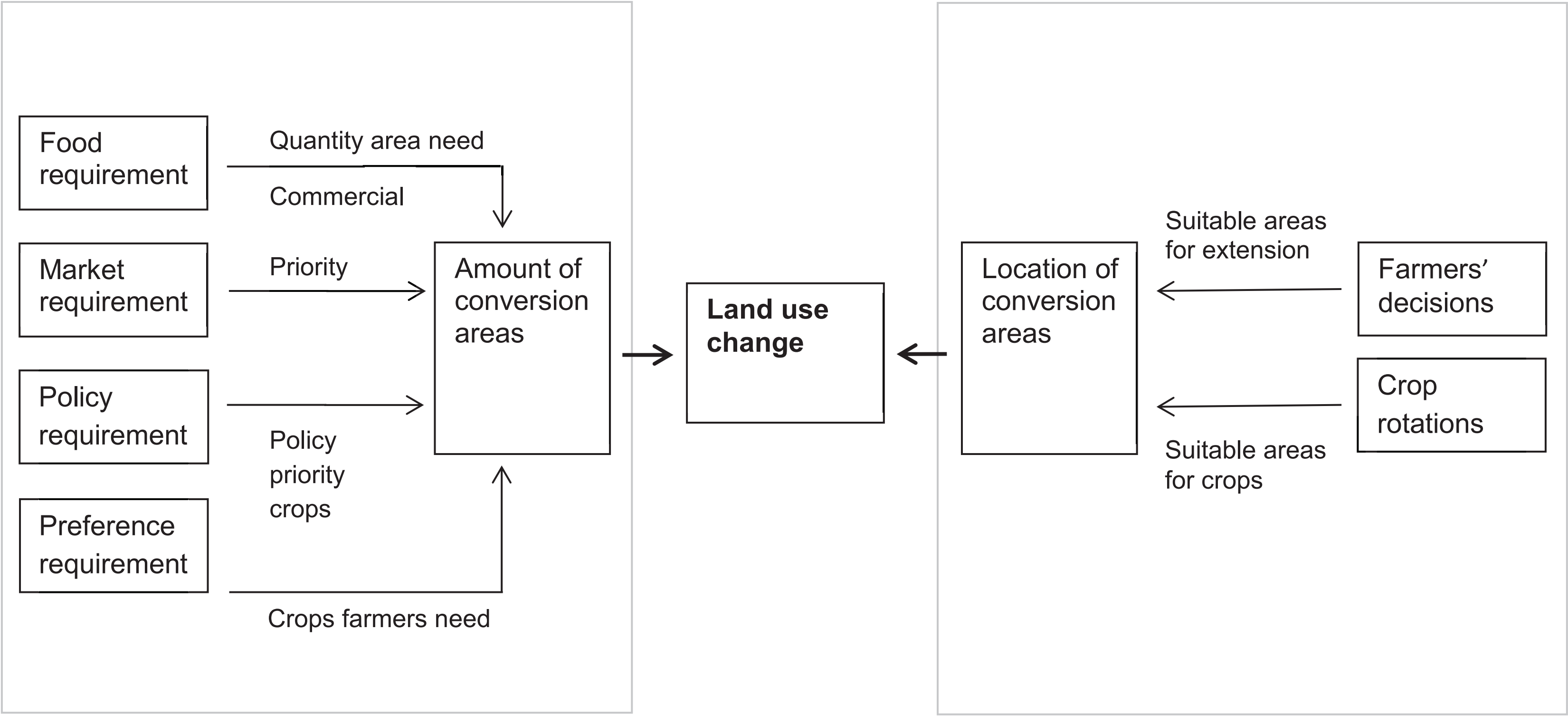


Figure 4.1 Scheme of LUC model structure

4.3 Input data

The previous Chapter provided most of the input data for developing the LUC model. Figure 4.2 illustrates the necessary data for constructing and validating the LUC model for the Chieng Khoi watershed. This section focuses on the processing of input data for model construction and parameterization, which is presented in Figure 4.2a, whereas section 4.4 will concentrate further on the validation data and its procedures which are presented in Figure 4.2b.

4.2.2 Crop rotations

Crop rotation and decision rules were assessed in Chapter 3 and will be used for LUC simulations. Section 3.3.1presented the results according to three study periods. As a result in Section 3.3.2, the change in length of fallow period from 1954 to 2007 is shown. The fallow period was shortened from seven to three (or four) years after 1973. Since 1999, the fallow period disappeared in the crop rotations in Chieng Khoi watershed. Figure 3.6 determined the first crop after new agricultural land was converted from other land use types. In this study, upland rice was the pioneer crop that was sown in the opened land after clearing the forest. The following crops were regulated using crop rotations as shown in Table 3.6. Until 1999, the crops rotated with similar cycles; upland rice was planted for two years and the intercrop of maize/cassava followed for two years, then fallow periods took place for two to six years. Table 4.1summarizes the crop rotation patterns as described in Chapter 3 for the assessment period of 1954 to 1973 as:

- example of an idealized crop rotation per plot during a period of 20 years
- example the crops distributed and rotated per idealized household for a period of 20 years

The LUC model used the crop rotation to determine the following crops planted in one plot annually. The appropriate fallow length was employed according to three simulation periods (1954-1973, 1973-1993, and 1993 -2007).

4.3.2 Map inputs and farmer decision rules

The initial input map for the LUC model builds on the detailed land use map of 1954 presented in Figure 3.11 (Chapter 3). The spatial resolution was 20 x 20 m, comprising14 land use classes: upland rice first year, upland rice second year, maize/cassava first year, maize/cassava second year, six fallow classes (from first year to sixth year), paddy rice, forest, water body and residential area. The land use map of 1954 was used as initial map for the LUC model; this map was created using the distance from homestead to the outmost location of the watershed as the indicator for crop level classification. Even though the map validation reached 76.7%, the map still showed some artificial effects. Marchini (2011) and Adriaenssens *et al*. (2004) discussed similar issues in that the imprecise, diverse and complex data with expert knowledge were complicated to model. Combining this with site-specific conditions, several problems of uncertainty may arise. Therefore, a ‘fuzzy logic’ approach was recommended to avoid artificial precision when using uncertain information or data (such as linguistic and vague knowledge as derived from the participatory focus group discussions). Hence, the crop types in the map were randomly distributed using this rather vague approach first. For this purpose, the crop types were weighted using fuzzy membership values as the representative crop types. Zhu *et al*. (2001, 2010) recommended this method to predict detailed spatial variation of soil properties. The upland crop classes were registered for membership values using PCRaster software. The membership values ranged from 0-1. The gradual transition from 0-1 represented all pixels of upland crops class. This process also aimed to arbitrarily distribute the pixels using the random function in PCRaster to produce a normally distributed random upland crop map. Afterward, each crop registered for its criteria following the farmers’ decision rules mentioned in Chapter 3 (crop level classification - Section 3.2.3.2), and the adjustment process (Figure 3.5) was repeated for the random upland crop map to produce ten randomly distributed crop maps from crop and fallow areas. These crop maps were then merged with the other remaining land use classes in the LU map of 1954 to create an initial input map for LUC model simulations.

As mentioned above, the model was built to simulate LUC during three distinct periods. The first simulation stage started in 1954 and the two following stages entailed the modification of initial maps before employing the model because in collaboration with the major driving factors (Section 4.2.1), the appearance of new classes also needed to be considered such as:

- 1973-1993: Land use map included a lake class after the establishment of an artificial irrigation lake in Chieng Khoi watershed. Therefore, the input map of this simulation period meant adding an **artificial lake class** as a new LU class in case of the input map of 1973.
- 1993-2007: Natural and secondary forests were distinguished based on the classified LU map of 1993. Thus, the simulation period after 1993 further included a secondary forest class. On that account, **the secondary forest class** was added in the LU map of 1993 before the next simulation was run.

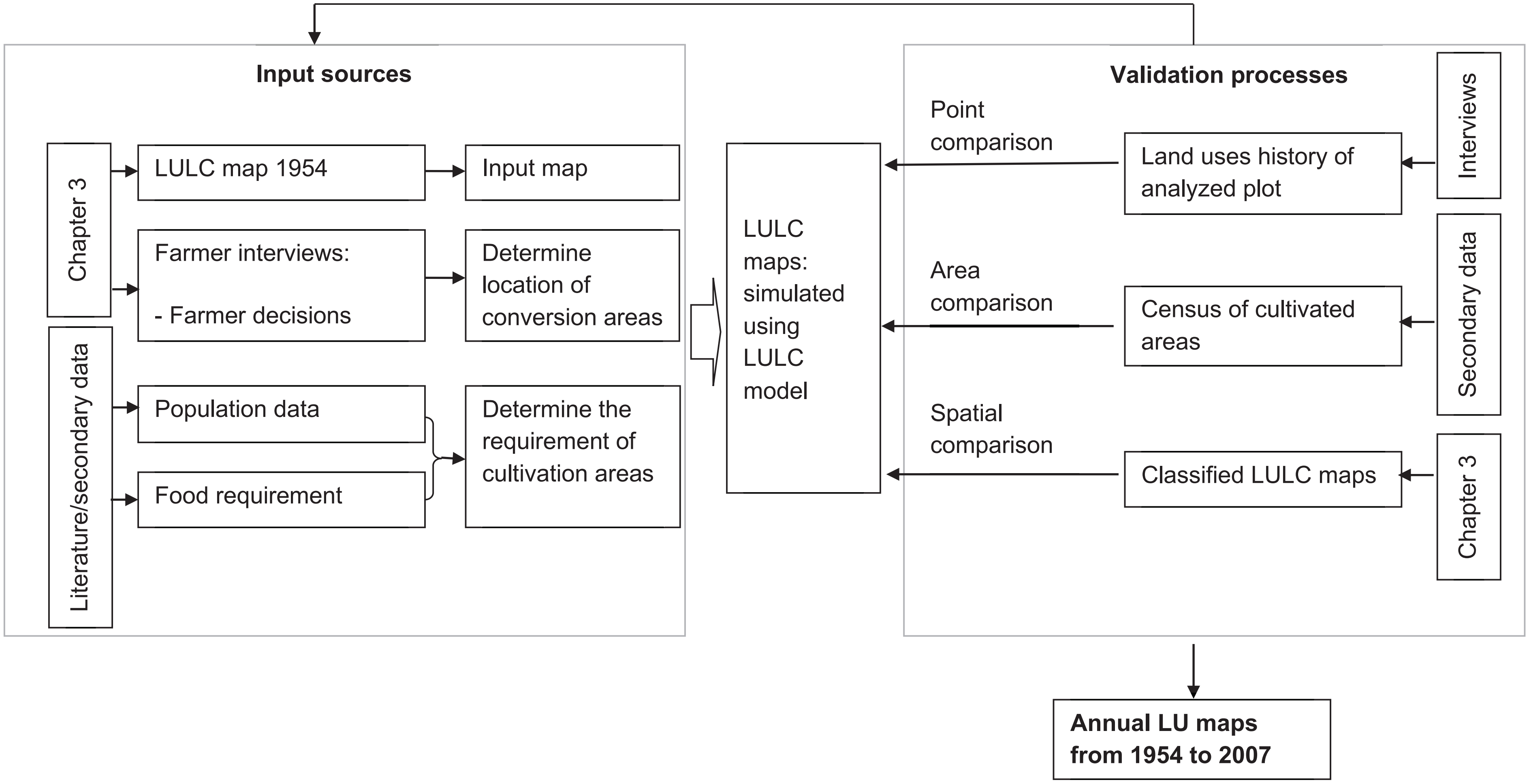


Figure 4.2 Overview of data input in the frame work for LUC model construction and validation

Table 4.1 Crop rotation matrix scheme in Chieng Khoi commune for an ‘idealized’ example household with 10 crops in 10 plots, with the area first starting with Crop 1 and repeated for one year then followed with Crop 2 to Crop 10. A plot presents the unit area for a crop. This table represents rotation in one plot (following horizontally) and in all plots in one household (vertically from left to right).

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 19	Year 20
Plot1	Crop1	Crop2	Crop3	Crop4	Crop5	Crop6	Crop7	Crop8	Crop9	Crop10	Crop1	Crop9	Crop10
Plot2	Crop2	Crop3	Crop4	Crop5	Crop6	Crop7	Crop8	Crop9	Crop10	Crop1	Crop2	Crop10	Crop1
Plot3	Crop3	Crop4	Crop5	Crop6	Crop7	Crop8	Crop9	Crop10	Crop1	Crop2	Crop3	Crop1	Crop2
Plot4	Crop4	Crop5	Crop6	Crop7	Crop8	Crop9	Crop10	Crop1	Crop2	Crop3	Crop4	Crop2	Crop3
Plot5	Crop5	Crop6	Crop7	Crop8	Crop9	Crop10	Crop1	Crop2	Crop3	Crop4	Crop5	Crop3	Crop4
Plot6	Crop6	Crop7	Crop8	Crop9	Crop10	Crop1	Crop2	Crop3	Crop4	Crop5	Crop6	Crop4	Crop5
Plot7	Crop7	Crop8	Crop9	Crop10	Crop1	Crop2	Crop3	Crop4	Crop5	Crop6	Crop7	Crop5	Crop6
Plot8	Crop8	Crop9	Crop10	Crop1	Crop2	Crop3	Crop4	Crop5	Crop6	Crop7	Crop8	Crop6	Crop7
Plot9	Crop9	Crop10	Crop1	Crop2	Crop3	Crop4	Crop5	Crop6	Crop7	Crop8	Crop9	Crop7	Crop8
Plot10	Crop10	Crop1	Crop2	Crop3	Crop4	Crop5	Crop6	Crop7	Crop8	Crop9	Crop10	Crop8	Crop9

The new classes appeared after 1973 when the first simulation period ended. Therefore, only the land use map of 1973 and 1993 needed to be revised prior to the next simulation processes for the two other simulation periods (1973 -1993 and 1993 -2007). The simulated maps of 1973 and 1993 were used to add new classes. Map modifications are presented in the results Chapter for of period 1973-1993 and 1993-2007 as necessary map correction processes.

4.3.3 Census data

Kerr and Cihlar (2003) confirmed that census data can be used to derive LU information; therefore, census data were collected at the district level. The Statistics Department in Yen Chau owns detailed statistical information collected from 1958 at the village level. Starting in 1958, the data were collected from all village reports, summarized at commune level and submitted to the office of statistics in the district committee. During the full agrarian reform from 1953 to 1956, farm activities were managed with higher human capacity and regulated by local government (Lenzt *et al*., 2011; Minh *et al*., 2011), more homogenous rules and most of the data recorded during that period were field measurements taken directly on the ground (Statistics Department Yen Chau district, 2012).

After collecting from the Statistics Department, the local area and yield units were converted into standard units. Afterwards, the printed and hand-written data before 1990 were entered and merged in electronic form with existing data after 1990. In this study, the population and crop yield data were considered to calculate the annual required cultivation areas to produce enough food for annual incremental population growth in the LUC model; detailed calculation and relation of these variables will be presented in the results Chapter. The upland cultivation data were used for the validation of the LUC model with the validation described in further detail in Section 4.4.

4.3.4 Food requirement

At the core of the LUC model was the demand of basic food to satisfy the growing population. Therefore, the energy requirements from food intake were calculated from available literature. The data from publications in the same region were first considered (Bui *et al*., 2011; Wezel *et al*., 2002a). Further data such as energy content in basic starch sources were collected from various sources (Table 4.2). Maize, cassava and upland rice were the main starch sources provided from upland fields in Chieng Khoi watershed (Chapter 2). The paddy rice crop provided staple starch food sources;

however, paddy rice areas were treated as fixed and had regulated irrigation since 1954 (see Section 3.3.2). Therefore, the food contribution of paddy rice was identified by farmers during group discussions with elder farmers (Chapter 3) and then deducted in the LUC model. The Pearson correlation coefficient was measured to determine if there was a significant correlation between population and upland cultivation areas from census data. If the value ranges from -1 to +1; at 0, there is no correlation, at -1, there is a maximum negative correlation and at +1 there is a maximum positive correlation (Rounsevell *et al*., 2003).

Table 4.2 List of input parameters retrieved from the literature

No	Input parameters	Unit	Sources
1	Annual calorie requirement per person	kcal/person/year	Bui *et al*., 2011
2	Population in Chieng Khoi	person	Statistics Department Yen Chau district, 2012
3	Calories per 1 kg of upland rice	kcal/kg	FAO, 2003
4	Average upland rice yield	kg/ha	Wezel *et al*., 2002a
5	Calories per1 kg of maize	kcal/kg	Hertrampf and Piedad-Pascual (2000)
6	Average upland maize yield	kg/ha	Wezel *et al*., 2002a and farmers information
7	Calories per 1 kg of cassava	kcal/kg	Bradburry and Holloway, 1988
8	Average upland cassava yield	kg/ha	Wezel *et al*., 2002a
9	Calories produced from 1 kg of other crops	kcal/kg	FAO, 2003

4.4 Model validation

After calibration/parameterization, the model was validated using an independent dataset. The basic validation process of a land use model is the comparison between the model outcomes and independent data, such as real-world observations (Parker *et al*., 2003). Kok *et al*. (2001) stated that land use models often lack a proper validation because of data problems. Therefore, Rounsevell *et al*. (2003) used a quasi-validation process to compare observed and simulated data in agricultural land use distribution at the regional scale. **A quasi-validation** in this case statistically compares the model results with annual census data as the observed dataset. A visual comparison of the observed and modeled maps was also considered as an approach for validating a LUC model, for example as a **qualitative comparison** of hot-spots of change (Verburg *et al*., 2002; Kok *et al*., 2001, Rounsevell *et al*., 2003). Furthermore, **a multiple resolution** approach was recommended to validate LUC models to quantify the degree of similarity between simulated and observed spatial patterns (Costanza, 1989; Rounsevell *et al*., 2003; Ahmed *et al*., 2013; Pontius *et al*., 2008; Castella and Verburg, 2007).

In this study, three levels of validation were used: (1) **Point validation** - a qualitative comparison by calculating the percentage match of classified points in the simulated maps; (2) **Area validation** - a quasi-validation by statistically comparing the land use type areas from model simulation with information from census data; and; (3) **Spatial-explicit landscape validation** - a multiple resolution approach using the goodness-of-fit method of Pontius *et al*. (2008).

Overall, a model simulation was rejected when the fit at the three levels was lower than a 50% match between observed and simulated maps. Figure 4.2 on the left shows the input data and the three levels of validation processes. The following sections will describe detailed methods and data inputs for different validation level procedures.

4.4.1 Point validation

The ground truth points (GTPs) required for point validation processes were collected from transect walks and household interviews as described in Section 3.2.1.2. GTPs were derived from farmer interviews, which were conducted in farmers' upland fields while recording GPS location to indicate the LU history of the plots. This data was used as a **qualitative validation**. The ground truth points were then overlaid on the simulated maps. The accuracy level was calculated:

$$Accuracy\ (\%) = \frac{\mathrm{Pfit}}{\mathrm{Ptotal}} \times 100 \qquad (4.1)$$

Where P_{fit} = number of historical points that presented the same land use type fit in simulated location

P_{total} = total historical points

Costanza (1989) concluded that if a landscape model performed at least 32.5 % correctly it could be fairly accepted. In this study, the accuracy of all subsequent years was checked if the accuracy of model performance reached 50% using the one sample t-test. The level of accuracy was considered as a first stage of model behavior, but the acceptance and rejection processes also needed to consider area validation and spatial validation results respectively.

4.4.2 Area validation

The area validation was found by comparing the area of each class in the simulated map with the classified map. For this quasi-validation t-test was used to determine the probability difference between simulated and measured values from classified maps, for example, the probability of 0.001 means that the chance of no difference is 0.1% (Rounsevell *et al*., 2003). This study used upland cultivation and forest classes for the area validation procedure because other classes consisted of uncertain issues caused by the diversity of resolutions from remote sensing data sources, such as water body class (as mentioned in Chapter 3). In case of crop LU class, the simulated values were also compared with available data from the census. In case of the forest class, the information was unavailable at commune level from 1954 to 2007. The Pearson correlation coefficient was used to determine the association between the development of area between simulated values and actual values from census data and classified maps. Pearson value ranges from -1 to +1 as mentioned in Section 4.3.4.; at 0, there is no correlation; at -1, there is a maximum negative correlation and at +1 there is a maximum positive correlation between simulated values with actual values.

4.4.3 Landscape validation: Goodness-of-fit method

The spatial landscape validation followed the goodness-of-fit method (Costanza, 1989) comparing the simulated maps with those classified from satellite imagery. This study quantified the agreement between the simulated and classified maps at multiple resolutions as described in Pontius *et al*. (2011). Costanza (1989) stated that quantitatively evaluating the goodness of fit of an ecological simulation model is difficult. With complex patterns, measuring the similarity of the patterns was a suitable and necessary method to evaluate the performance of complex ecological models. Therefore, Pontius *et al*. (2008) and Castella and Verburg (2007) used this method to prove the ability of LUC models to simulate LUC.

Herein, the LU map of 1954 represents the reference map at the initial time, classified LU maps represent the reference maps at subsequent times, and simulated LU maps represented the results required to be validated at subsequent time steps. The agreement between simulated maps and reference maps at subsequent times indicates the level of model accuracy to simulate the LUC. A 'Goodness-of-fit' (GOF) was calculated from sampling window size by the equation below - the higher the proportions of agreement, the closer the two maps.

$$Fw = \frac{\sum_{s=1}^{t_w} \left[1 - \frac{\sum_{i=1}^{p} |a_{1i} - a_{2i}|}{2w^2} \right]_s}{t_w} \tag{4.2}$$

Where F_w = fit for sampling window size w

w = dimension of one side of the (square) sampling window

a_{ki} = number of cells of category i in scene k in the sampling window

p = number of categories (i.e. LU types) in the sampling windows

s = sampling window of dimension w by w which slides through the scene one cell at a time

t_w = total number of sampling windows in the scene for window size w (Costanza, 1989)

A weighted average determines the fit at different window sizes. This value summarizes the overall fit that is weighted higher in the small window sizes but not ignoring the larger window sizes (Castella and Verburg, 2007). The weighted average of the fits (F_t) was calculated as:

$$Ft = \frac{\sum_{w=1}^{n} F_w e^{-k(w-1)}}{\sum_{w=1}^{n} e^{-k(w-1)}} \tag{4.3}$$

Where F_t =weighted average of the fits over all window sizes

F_w = fit for sampling windows of linear dimension w

k = weight given to small versus large sampling windows - $k = 0.1$ (Costanza, 1989)

Additionally, the figure of merit was also recommended at spatial level with multiple resolutions to check the dynamic trend of LUC (Lusiana *et al*., 2012 and Pontius *et al*., 2011). The figure of merit determined overall correspondence between actual and simulated changes considering two comparisons:

- The initial LU map was overlaid with reference maps to derive actual changes
- The initial LU map was overlaid with simulated maps to derive simulated changes.

The intersection and union of actual changes and simulated changes were measured. The figure of merit is the ratio between the intersections divided by the union of changes. This ratio ranges from 0 to 1 - where 0 refers to no intersection changes, 1 refers to a perfect intersection between actual and simulated changes, which indicates that the model is perfectly good at simulating LUC. Figure of Merit (FOM) was calculated as:

$$\mathrm{FOM} = \left(\frac{A \cap B}{A \cup B}\right) \times 100\% \qquad (4.4)$$

Where A = actual changes (ha)

B = simulated changes (ha)

The FOM derived important insights of actual and simulated LUC processes which also evaluated the behaviour of the LUC model. The detailed steps are described in Appendix 4.1. PCRaster and ArcGIS software were utilised to implement the processes to calculate Fw, Ft and FOM respectively.

4.5 Results

4.5.1 Background (or basis principle) of LUC model development

4.5.1.1 Food self-sufficiency in rural mountainous areas

The World Food Summit (1996) defined that ‘Food security exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life’. Comparing with above definition, Jamieson *et al*. (1998) agreed that many mountain communities around the world, especially in Vietnam, suffer from food shortage and nutritional deficiencies; these areas rely on agricultural activities. In the early 1950s, the shifting cultivation system was a common farming practice in the mountainous regions of Southeast Asia to provide food for their population, where farmers first cleared the forest and let farming plots lie fallow when fertility decreased; described as a swidden composite system (Rambo, 1998). In this case, crop fields were cleared by slash and burn in the uplands combined with paddy rice cultivation in the lowland areas using local crop varieties.

In case of Vietnam, more than 75% of Vietnam's total area is mountainous or made up of sloping land. Also, 70% of the total population lives in rural areas and 48% depend on agricultural activities. Shifting cultivation leads to land degradation (Schmidt-Vogt *et al*., 2009). However, Mertz (2009b) revised several studies on shifting cultivation systems and found that, in retaining the fallow period, a range of environment services are kept in balance (hydrology, biodiversity, and carbon storage). Unfortunately, shifting cultivators are often relatively poor farmers, who are opportunistic in nature and would convert to any crops with maximum areas for maximum profit. Rural mountainous regions in Vietnam are often related to subsistence needs and were connected with shifting cultivation during the early 1950s.

4.5.1.2 Increasing population and food demand

The population increased by 300% from 1960 to 1984 in the mountainous regions (Sikor, 1995; Jamieson, 1998); this led the requirement of significantly more food. Thus, agricultural areas expanded to non-cultivation areas. Natural forest was the only arable land where cultivation could be expanded; a reduction of natural forest cover decreased from 93% (1943) to 17% (1991) in total areas of Son La province, NW Vietnam (Sikor, 1995; Jamieson, 1998). In Yen Chau district, the population rose by 50% at a growth rate of 2.4% annually from 1988 to 2006 (Saint Macary *et al*., 2010), resulting in an explosion of cash crops with high profits which led to an expansion of cultivation to steep slopes in NMR, legally as well as illegally.

During the early 1950s, the shifting and swidden cultivation practice has produced low yield, therefore, required cultivation area in this system was higher than requirement areas in the high yielding systems to ensure food demand (Castella *et al.,* 2005a). After 1954, the cooperative policies were implemented with an enforcement of land reform between 1955 and 1957; the farmland was distributed equally to all farmers (Minh, 2010). Therefore, the LUC model considered the area need per capita for simulating the LUC.

After the 1990s, intensive cash crop production replaced traditional agricultural systems (Keil *et al*., 2008). New technologies were the used, alongside chemical fertilizer, hybrid varieties and new farming management practices (such as tillage and irrigation) (Wezel *et al*., 2002*a*; Clemens *et al*., 2010; Schmitter *et al*., 2010). Due to changing production methods, crop productivity increased under intensive mono cropping (Wezel *et al*., 2002). Consequently, land use systems rapidly transformed during recent decades. A well-known change in agriculture was from shifting traditional cultivation to intensive systems. For example, cash crops replaced shifting cultivation vastly in Southeast Asia (Ziegler *et al*., 2011; Mertz *et al*. 2009*a*; Fox *et al*., 2009). In this period, agricultural production development drove by many factors (see further). Food demand became less important than previous periods. Therefore, to achieve the purpose of using a limited dataset, the LUC model employed the production of major cash crop as the factor to simulate the expansion of cultivation areas.

4.5.1.3 Major focus in the case study

The LUC model was built with the core is ‘food demand’ as the basis for expanding agricultural land, which is suitable for a data-limited watershed. The commune in this study was described as remote in mountainous regions in NW Vietnam. After the Indo China War in 1954, food scarcity was reported as the main constraint to rural development (Lentz *et al*., 2011; Minh *et al*., 2011; Richter, 2007). Therefore, the LUC model builds on sufficient food demand of the watershed population as a key variable to simulate LUC. Hence, the dynamic changes of upland crop areas were the focus in this study, because apart from paddy rice, upland rice, maize, and cassava have always provided main starch sources for the household consumption in Chieng Khoi commune. Paddy rice was the set as first choice crop (Chapter 3); however, it provided insufficient yield to meet the food demand of the commune population, as irrigation areas were limited and local crop varieties only produce a low yield. Therefore, paddy rice has not fully support communal food demand since 1954. Hence, upland crops were used as an additional starch source. Upland crop areas were more dynamic because these were planted with rainfed crops (upland rice, maize, and cassava). This model excluded the food contribution from water body base because the contribution of food from aquaculture was small.

4.5.2 LUC model concepts

Figure 4.3 illustrates the division of model simulations into three assessment periods, where the population growth increased linearly, while upland cultivation areas fluctuated on a yearly basis. The un-regularly developed areas were caused by the food demand of different periods (Section 4.2). Therefore, the LUC model simulated the quantity of area expansions and crop distributions in three distinct periods:

Period 1: A self-sufficient period from 1954-1973 when LUC were driven by:

- Population growth and food requirements determining the quantity of area expansion.
- Swidden agriculture practice determined crop distribution.

Period 2: An improved self-sufficient period from 1973-1993 when LUC were driven by:

- Population growth and food requirements determined quantity of area expansions.
- Construction of an irrigation lake in Chieng Khoi commune that led to shorter fallow periods thus determining crop distributions. Additionally, the construction of the lake increased the accessibility to upland fields.

Period 3: A commercialization period from 1993-2007 when LUC were driven by:

- Population growth, food requirements and the influence of market commercialization, which determined quantity of area expansions.
- Monoculture of cash crops determined crop distributions

The following sections first describe the calculation of area expansions, and then the identification of crop distribution according to each simulation period.

4.5.1.1 Period 1: A self-sufficient period from 1954-1973

The clear correlation between population and upland cultivation areas from 1958 to 2007 was proven with a Pearson correlation coefficient attained at 0.82, indicating that population was a suitable variable to simulate the need of areas to fulfill local food requirements (Figure 4.3), whereas paddy rice provided the starch food intake source with a constant area of 40 ha (Section 3.3.2 and 4.3.4). Therefore, due to the rain-fed system with local varieties, the farmers determined that paddy rice contributed 30% of food intake in the period of 1954 to 1993. Although the artificial lake was established in 1974, low yielding varieties of paddy rice kept a constant share of paddy rice in total home consumption until high-yielding hybrid paddy rice varieties were introduced in the 1990s. Moreover, after that, the hybrid upland crops combined with the application of chemical fertilizer also led to an increase in the household income, associated with a population increase. Thus, farmers still defined the same share of paddy rice to food intake sources as in previous periods. Consequently, upland crops continuously contributed 70% of the food intake.

The total upland area required annually, which could fulfill the demand for energy requirements of the population at watershed level, was determined as:

$$Area = 0.7 \times \frac{P \times Ca}{En \times Yc} \tag{4.5}$$

Where Area = requires total upland area to satisfy the need of the population (ha)

P = population (person)

En = average energy content of food intake (kcal/kg)

Yc = average crop yield upland crops (kg/ha)

Ca = calories needed per capita per year (kcal/person)

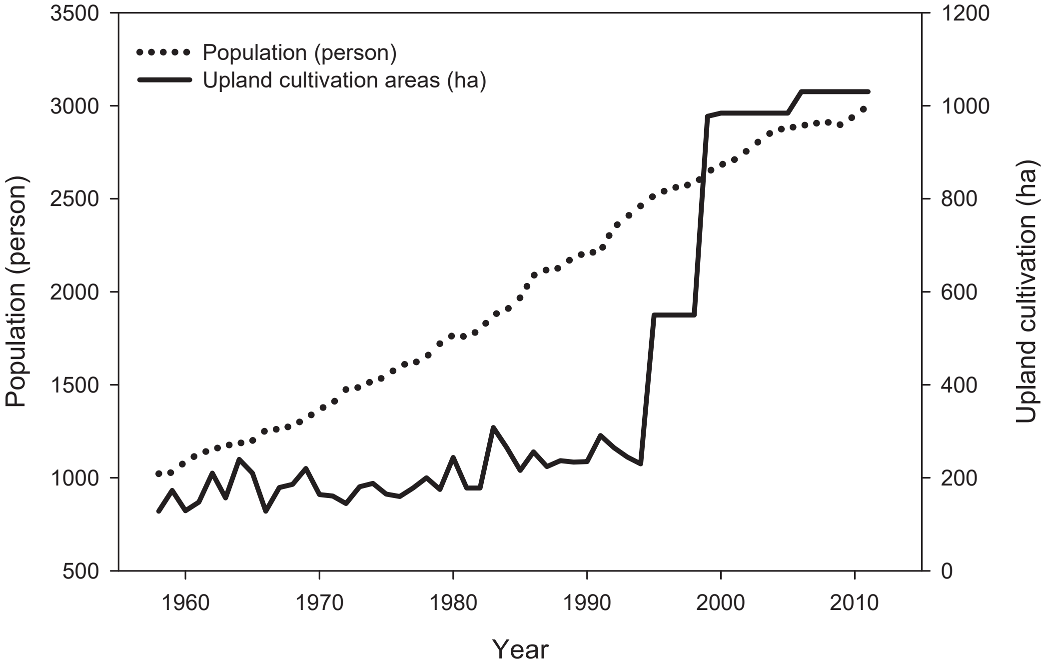


Figure 4.3 Development of population and cultivation upland areas (Statistics Department in Yen Chau District, 2012)

The process of determining this formula was developed from a stepwise procedure to define the energy required at watershed level. Firstly, the demand energy requirement was defined by using population and calorie variables per year in the watershed as:

$$\mathrm{D}EnRe = P \times \mathrm{Ca} \tag{4.6}$$

Where D*EnRe* = the total energy demand of the watershed in a day (kcal)

Secondly, the energy requirement was defined by potential supply using the energy content of food intake produced from crops. Therefore, energy requirement was calculated as:

$$SEnRe = En \times Yc \times Area \tag{4.7}$$

Where S*EnRe* = the total energy supply of the watershed in a day (kcal)

Herein, the average energy content of food intake (En) was calculated using the three major starch crops planted in the upland areas of the Chieng Khoi watershed. The average crop yields (Yc) were calculated from yields of upland rice, maize, and cassava with the assumptions that three crops were equivalent in terms of food intake for the basic home consumption, and all upland crops were harvested once per year (as upland crops were cultivated in a rainfed system). When the energy supply satisfied the energy demand, the required area was determined. Thus, the formula (4.5) was derived while S*EnRe* equaled D*EnRe.*

After the defined quantity of land expansion, the suitable crop was selected for these areas using the farmers' decision rules described in Chapter 3. Besides the expanded areas, other areas were also rotated using more suitable crops when the previous crops became less suitable in the following years.

Upland rice was chosen as the first-choice crop for new opened areas (Figure 3.6c), after the second year of cropping, intercropping maize and cassava was selected twice in two years. After that, the fallow class repeated next six years before the fallow areas were rotated to the upland rice class (Table 3.6). The crop rotation presented in Table 4.1 was employed to register the following crops in existing cropping areas in the LU map. In this period, fallow period was repeated in six years, on average.

4.5.1.2 Period 2: An improved self-sufficient period from 1973-1993

In this period, the amount of expansion areas was determined similarly to the previous period. Equation 4.5 was employed to identify the amount of required upland areas to satisfy the food requirements of an increasing population. Compared to the previous period, upland crop areas were not only expanded surrounding the residential areas, but also next to the water body areas, especially surrounding the artificial lake, completed during 1973-1974. Increased water availability for irrigation increased with the presence of the artificial lake. Thus, the possibilities to cultivate paddy rice increased in some areas, while increased water availability contributed an alternative impact on the wider and better distributed upland cultivation areas. Consequences occurred in upland areas for two reasons:

(1) Improvement of infrastructure to access the upland fields during the construction of the lake.
(2) Upland crops were mainly rainfed crops; a small water application increased the chance of successful seed germination. In the past, farmers either carried the water to the fields or waited for rain to start seeding. Due to the establishment of the lake, more areas were available for cropping nearby.

Concerning the location of crops, upland rice was also the first choice crop which was selected for opened areas from other classes. However, the fallow period was shortened to four years because farmers required more cultivation space (Chapter 3). Therefore, the following crop was identified similarly with the previous simulation period - annually with four repetitions of the fallow class instead of six years fallow periods.

4.5.1.3 Period 3: A commercialization period from 1993-2007

Figure 4.3 illustrates an irregularly large rise of upland cultivation areas compared to the described periods. Again, equation 4.5 was employed to determine the self-sufficient amount of expansion areas, while the influence of commercialization was considered as an additional factor causing a major increase in upland cultivation areas. After 1999, cash crops (maize) were introduced to finally become dominant in the study region (Chapter 3). Consequently, farmers modified crop rotations practice to maximize production. Thus, for LUC modelling, two further sub-periods were distinguished.

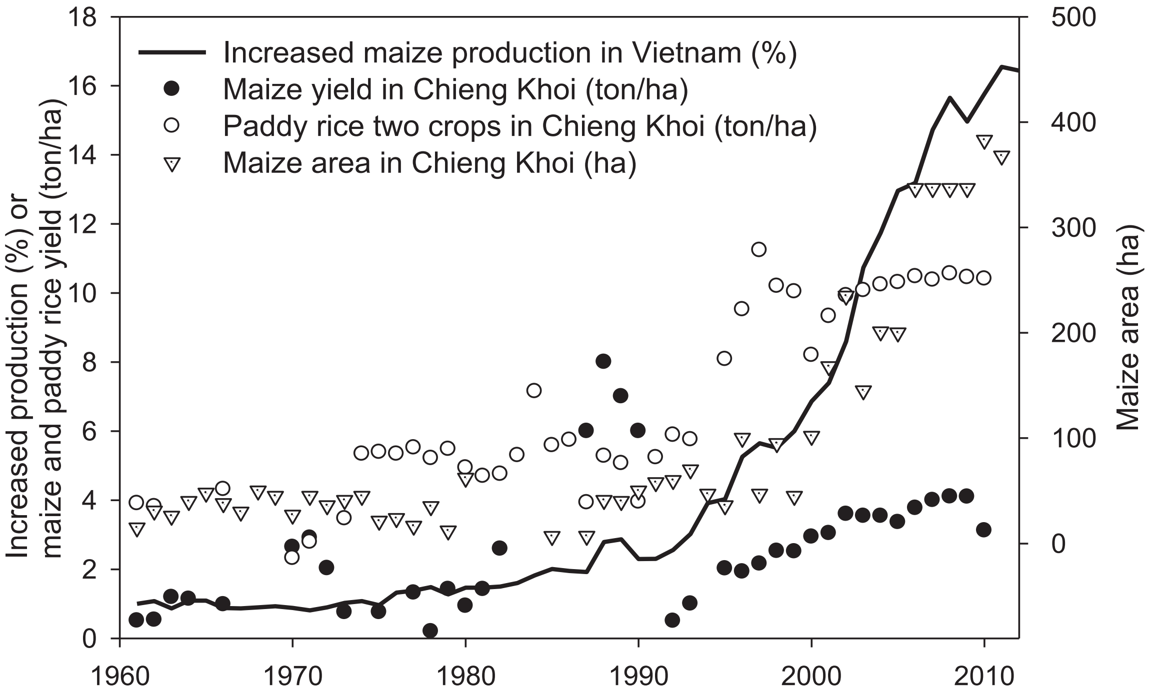


Figure 4.4 Maize yield and area in Chieng Khoi commune and increases maize production in Vietnam (Statistics Department in Yen Chau District, 2012, General Statistic Office of Vietnam, 2011, and FAOSTAT, 2013)

(1) Period from 1993 to 1999: The basic expansion was calculated like the previous periods using equation 4.5 with two-year repetitions of fallow. In this period, maize provided, not only the food intake, but it also created the cash income. This proportion was excluded from the household energy consumption. Figure 4.4 shows the development of maize production at the national level in relation with the development of maize cultivation at commune level. The Pearson correlation coefficient was 0.95, which indicates that the area of maize at commune level was highly correlated with the production of maize at national level, although maize yield fluctuated. The high correlation resulted in the assumptions that: (1) the increased crop production was related to the increase of cultivation areas; and, (2) the increase of crop yield was excluded (Section 4.5.1). Therefore, the influence of commercialization was determined by multiplying the self-sufficient expansion with a factor calculated by equation 4.8.

$$Factor = \frac{Pro\ (n)}{Pro\ (1)} \qquad (4.8)$$

Where Pro (1) = maize production at first year of the simulation (Mg)

Pro (n) = maize production at year n (Mg)

Figure 4.4 also shows an increase in the production of paddy rice. This additional production resulted from the well water supply from the establishment of the artificial lake in 1974 and the wide application of chemical fertilizer, pesticides and improved varieties in the 1990s. However, according farmers’ interviews, the extra production only improved the food shortage need, but did not satisfy the need of population. However, the increase in paddy rice production meant that farmers needed less maize for food intake and sold is for cash income.

(2) Period from 1999 to 2007: The amount of area expansion was continuously following the period from 1993 to 1999 using equation 4.5 and 4.8. Concerning crop distribution, the fallow period disappeared. Furthermore, continuous mono cropping replaced crop rotations and, from 1999 to 2000, fallow areas were registered for maize as the principle cash crop. The previous intercropping and even new opened areas were also used for maize. Although farmers opened the new areas illegally, they are considered in this study.

4.5.1.4 Input parameters

Secondary data were collected through the literature review. The data from publications in the same regions were considered first. Additional data were collected from various sources as listed in Table 4.3. These values were employed for Equation 4.5; the population data were used as the variable input annually during the three simulation periods. The factor mentioned in equation 4.8 was also employed as annual input for simulation in modelling period three.

Table 4.3 Input parameters used for LU in Chieng Khoi commune, Yen Chau district.

No	Parameters	Value	Unit	Convert from	Sources
1	Total calorie requirement for 1 person per year	1434450	kcal/ person/ year	3930kcal*365 days	Bui *et al*., 2011
2	Population in 1958	1022	person	-	Statistics Department in Yen Chau district, 2012. Other years are listed in Appendix 4.2
3	Calories produced by upland rice	4160	kcal/kg	-	FAO, 2003 FAO, 2002a
4	Average upland rice yield	700	kg/ha	700 kg/ha in 1993 and 500 kg/ha in 1998	Wezel *et al*., 2002a
5	Calories produced by maize	4015	kcal/kg	-	Hertrampf and Piedad-Pascual (2000)
6	Average upland maize yield	1000	kg/ha	-	Wezel *et al*., 2002a and farmers information
7	Calories produced by cassava	1386	kcal/kg	580 KJ per 100 grams =1386kcal/kg fresh	Bradburry and Holloway, 1988
8	Average upland cassava yield	4800	kg/ha	8000kg/ha in 1993 convert to dry 60%	Wezel *et al*, 2002a and farmers information

4.5.3 The performance of LUC model

4.5.3.1 Statistics of simulating expansion areas

Figure 4.5 statistically presents the increase of upland cultivation areas based on three model simulations. The first model exercise simulated the required upland cultivation areas under self-food sufficient from 1954 to 2007. Figure 4.5 (a) illustrates a slight increase of required upland cultivation from 9.32 ha (in 1955) to 27.6 ha (in 2007). The second model exercise simulated the required upland cultivation areas using self-food sufficiency combined with the cash crop factor. In the second exercise, simulation began from 1973 using the input map which was edited (Section 4.3.2), the simulation ran continuously to 2007. Figure 4.5b shows the development of required areas from 69.56 ha (in 1973) to 131.64 ha (in 2007). On average, using the single self-sufficient in food, required upland areas increased 0.35 ha per year, while the self-sufficient combined with cash crop factor, required upland areas needed at 1.88 ha per year, more than five times single self-food sufficient approach.

The third model exercise simulated the required upland areas using three distinct periods. In each period, the input maps were edited before each simulation exercise. The upland cultivation areas increased slightly during the three periods according to the increased population, however, the required upland cultivation areas increased to large areas (253.28 ha in 2007) because the input map was edited. Figure 4.6 shows the comparison of required upland areas during distinguished period simulations. The peak of the first and last year of simulations were considered as the stabilization of simula-tions when the input maps were corrected. Combining existing are-as, total upland culti-vation increased from 315 ha in 1954 to 687 ha in 2007.

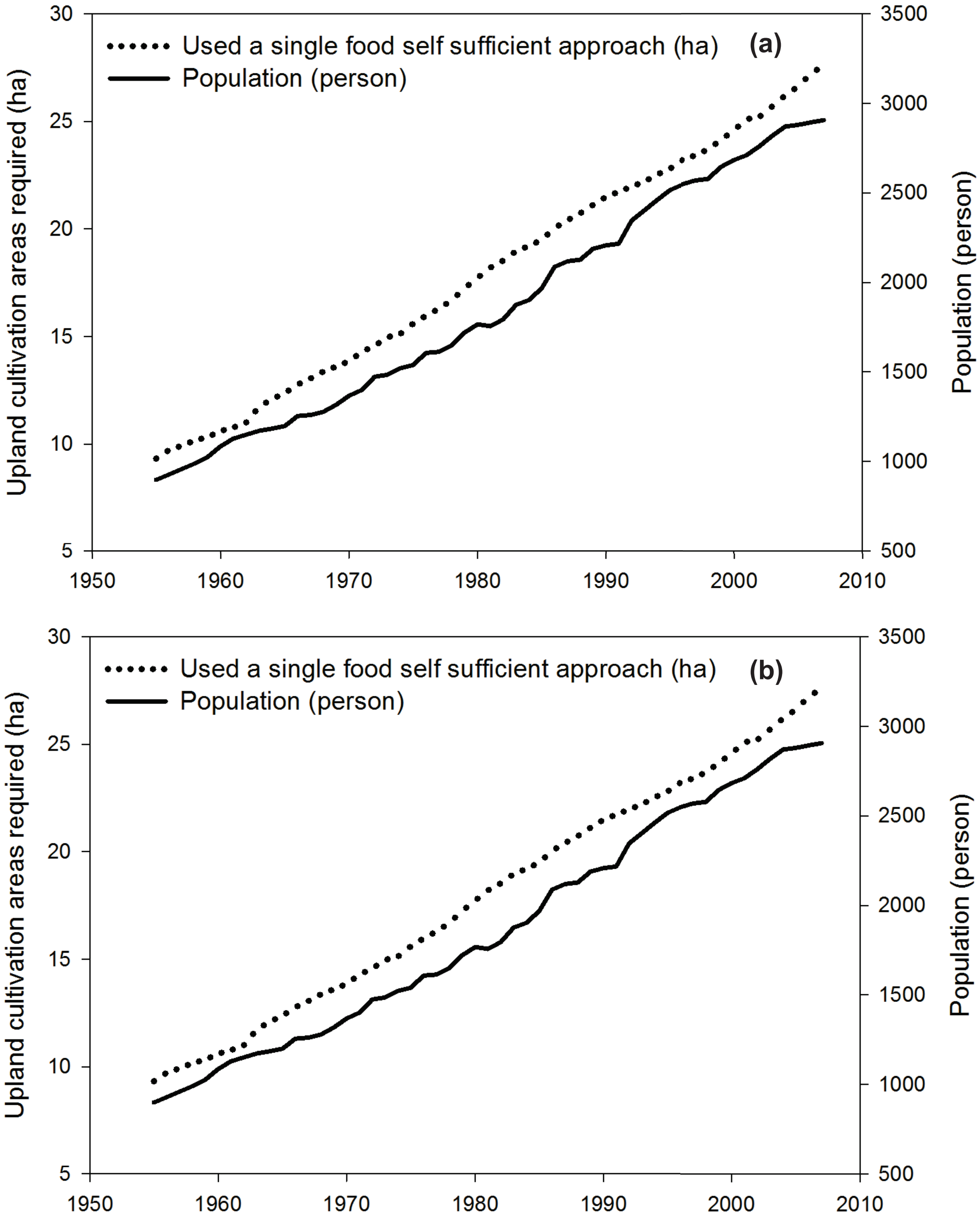


Figure 4.5 Annually added areas required in Chieng Khoi watershed based on the LUC model simulation (a) Used the food self-sufficient approach from 1954 to 2007, (b) added the cash crop factor from 1973 to 2007 (Population data from Statistics Department in Yen Chau district, collected in 2012)

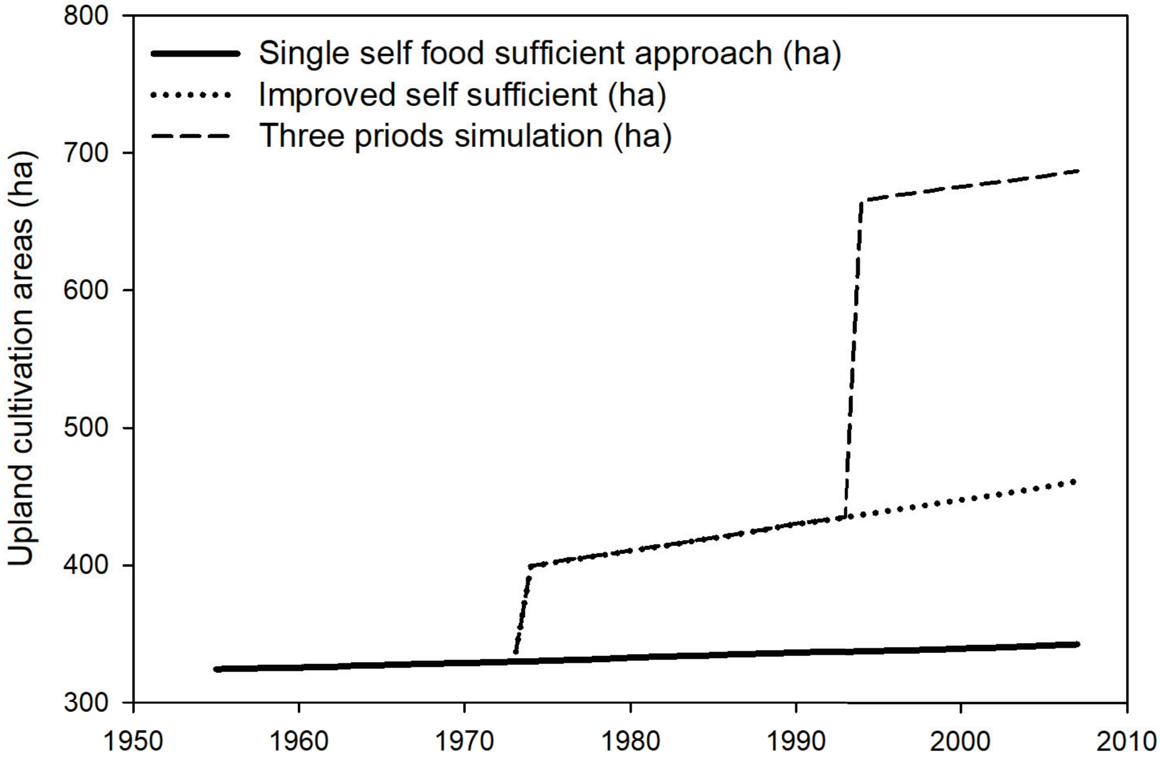


Figure 4.6 Upland cultivation areas in Chieng Khoi watershed based on the LUC model simulation using the model over three distinct periods with map correction processes

4.5.3.2 Simulated maps using LUC model

This section presents the simulated maps using the LUC model in three distinct periods during third simulation exercise. Due to preliminary comparisons between results of the first and second exercises with actual values from remote sensing classification (Section 4.5.4.2, Figure 4.6 and Figure 4.17), the study focused on results and validations from the third model exercise.

Simulation period 1 - 1954 to 1973: Figure 4.7 presents an example of area expansion in the first two years of simulations. First, in 1955, the expanded areas were simulated by the LUC model surrounding residential areas and upland rice was first allocated by the model in these areas. In 1956, the newly expanded areas continued to increase surrounding the residential areas, while expanded areas of 1955 were used for upland rice in the second year (Figure 4.7b, c). From 1957 to 1973, the LUC model continuously computed two actions; (1) expanding cultivation areas; and, (2) rotating crops according crop rotations.

Simulation period 2 - 1973 to 1993: Similar to the first period, upland cultivation areas continued to increase in the surrounding of residential areas. Besides, the expansion of areas also occurred surrounding the newly established artificial lake. Figure 4.8 illustrates the differences of the initial map of 1973 compared to the simulated map of 1993.

Simulation period 3 - 1993 to 2007: Figure 4.9 shows the initial and edited maps of 1993 before the simulation. Herein, the natural forest was separated from the secondary forest class. Expansion of the cultivation area occurred only into secondary forest. Figure 4.10 shows dominant areas of maize compared to other crops and the appearance of a few areas of intercrops between maize and improved cassava.

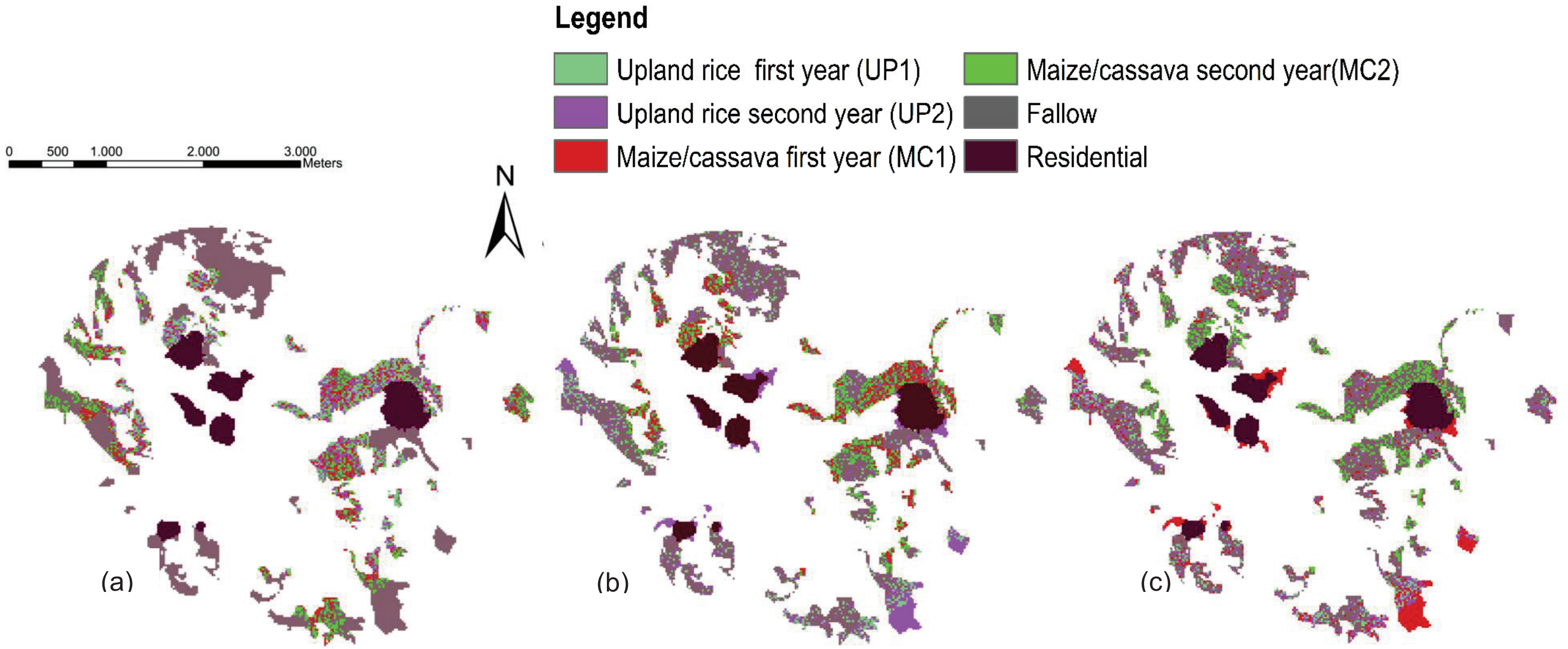


Figure 4.7 Crop distributions in LUC map of 1954 (a) after fuzzy procedure in PCRaster and the example of the simulation maps from 1956; (b) to 1957; and, (c) in Chieng Khoi watershed using LUC model

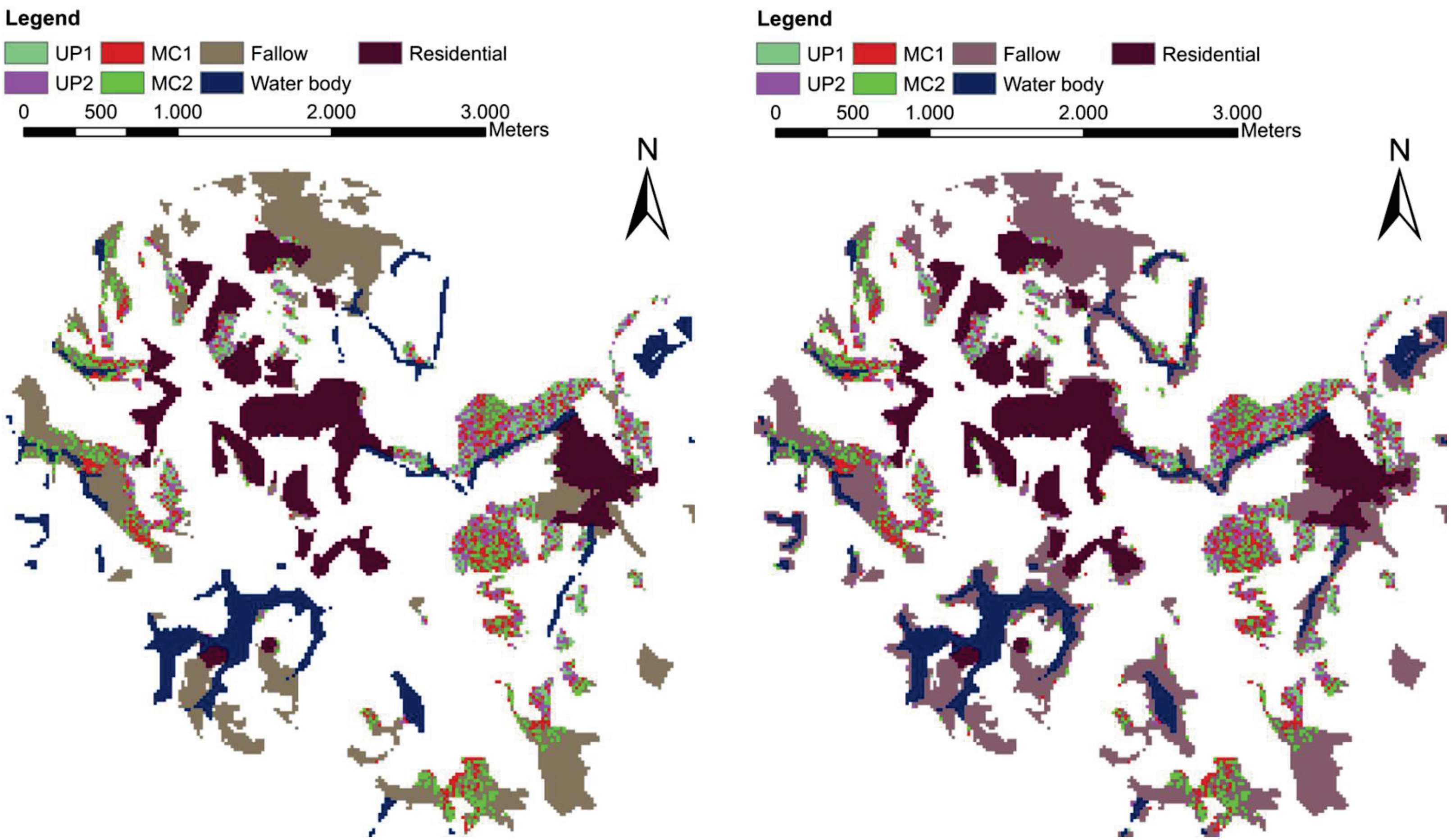


Figure 4.8 Crop distribution in LUC maps from 1973 (left) to 1993 (right) using LUC model. UP1: Upland rice first year, UP2: Upland rice second year, MC1: Maize/cassava first year, MC2: Maize/cassava second year.

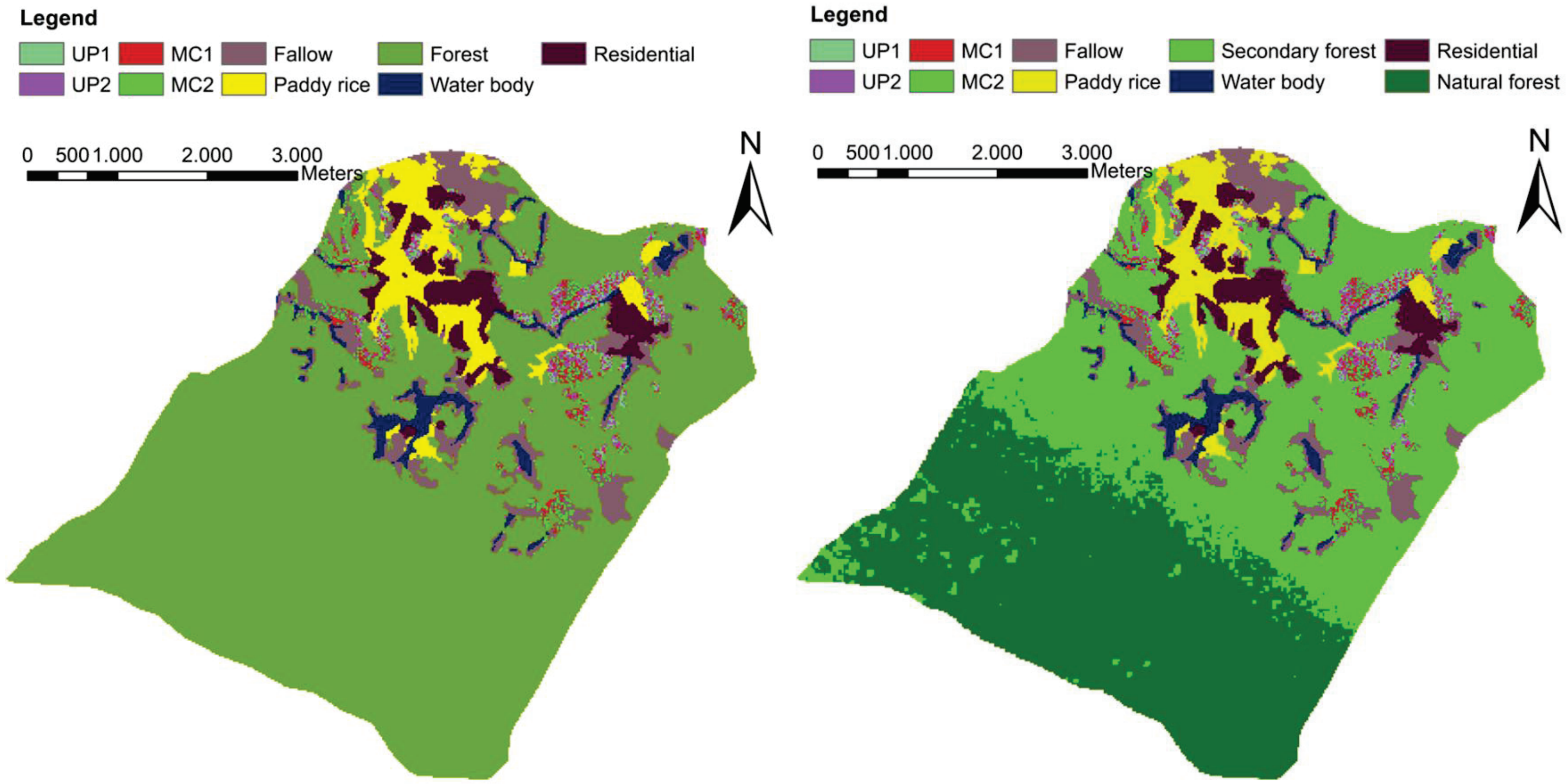


Figure 4.9 Simulation LU map of 1993 using LUC model and the correction map of 1993 using PCRaster, which the natural forest polygon was added. UP1: Upland rice first year, UP2: Upland rice second year, MC1: Maize/cassava first year, MC2: Maize/cassava second year

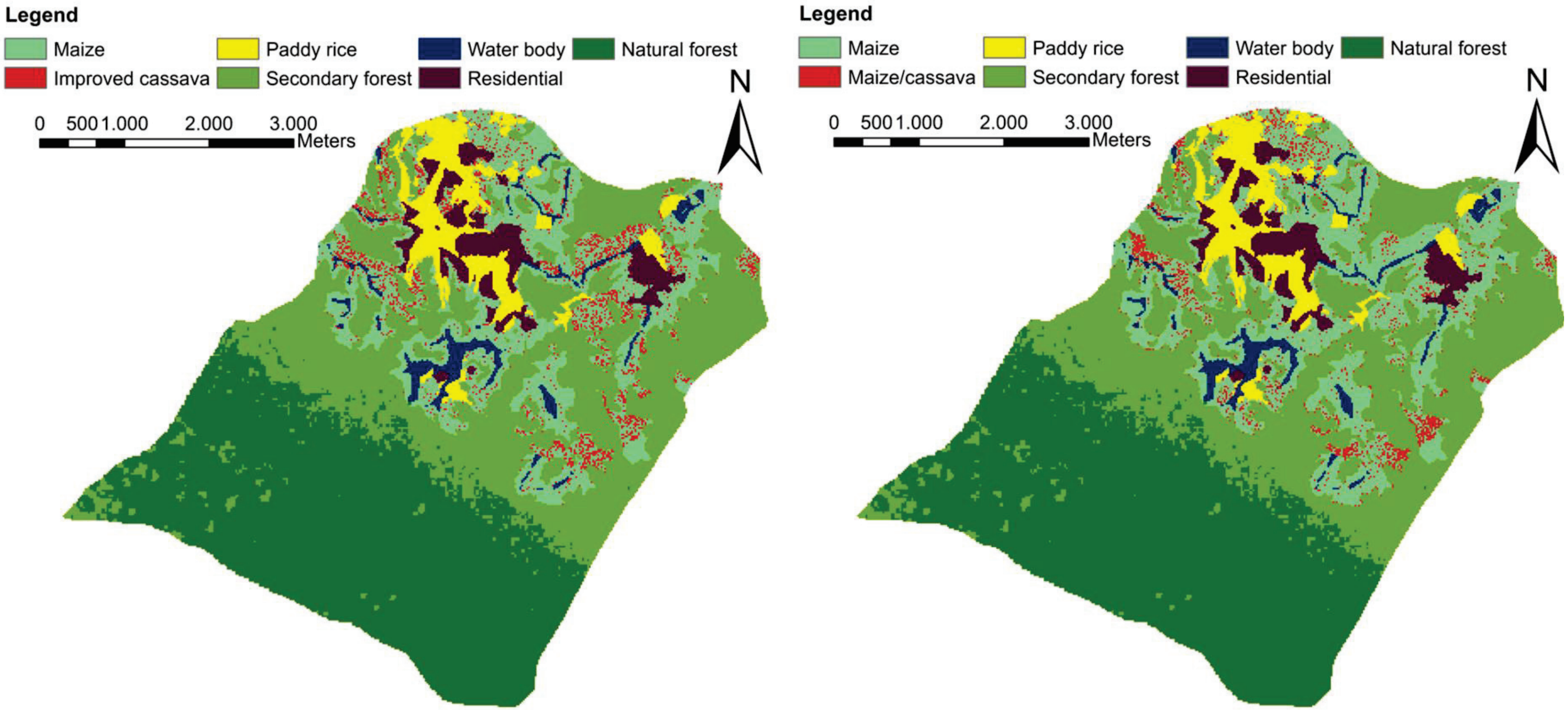


Figure 4.10 LU map of 1999 (a) and 2007 (b) were simulated from the LUC model

4.5.4 LUC model validation

The LUC model was validated at three levels. Overall, the LUC model can simulate the expansion of agricultural land from 1954 to 2007. The single food self-sufficient approach showed a very low value of upland cultivation areas compared to actual values from the Statistics Department and the value from remote sensing classification. Therefore, in this study, the model was validated in the third model exercise where the LUC was simulated using three distinct periods.

4.5.4.1 Validation at point level

The observed points were compared with their corresponding locations on the simulated maps. Results show the average accuracy at point level by 42.9%, 53.8%, 28.6% and 62.1%during the simulated years of 1973, 1993, 1999 and 2007, respectively (Table 4.4). The lowest accuracy occurred in 1999 (28.6%) and the highest accuracy was found in 2007 (62.1%). The median value was 48.4 and mean value was 46.8. Based on the point validation, LUC simulations performed correctly more than 50% in the years 1993 and 2007, and less than 50% in the years 1973 and 1999. The one sample t test results showed t- stat value of -0.43 and t-critical of 2.35. These values indicate that - t-critical < t-stat<t-critical, thus the one sample t-test accepted the null hypothesis, meaning 50% accuracy. Therefore, the assumption that LUC model performed with an accuracy of 50% was accepted at the point validation level.

Table 4.4 The accuracy at qualitative level using the historical GTPs

Subsequent simulated time	**1973**	**1993**	**1999**	**2007**
Amount of total GTPs (P_{total})	7	13	14	29
Amount of fitted GTPs (P_{fit})	3	7	4	18
Accuracy (%)	42.9	53.8	28.6	62.1
Median	48.4			
Mean	46.8			
S.D.	14.5			
t-stat	-0.43			
t-critical	2.35			

4.5.4.2 Validation at area level

To further evaluate LUC model performance, a quasi-validation method was applied using the upland areas extracted from simulated maps using three distinct periods (in the third model exercise) comparing with maps classified from remote sensing in Chapter 3. Table 4.6 shows a chance of 64.6% - no difference between simulated and actual value of upland crop area (the probability equals 0.646). In the case of the forest area, the chance of no difference was 53.6% (the probability equals 0.536). These results correspond to the point validation results. Moreover, Table 4.6 shows a relatively high correlation between the means of simulated and actual areas of upland crop (0.844) and a medium correlation between mean of simulated area and the actual forest area (0.651). Figure 4.11 and 4.12 shows the lower difference between classified versus simulated upland crop areas compared to forest areas. The model simulated the trend of upland crop areas expansion quite well, but could not estimate the absolute areas perfectly, e.g., overestimated the absolute area by 195 ha in 1999.

Table 4.5 P value from tests on the mean differences (t-test) and Pearson coefficients (in brackets) between the simulated and classified values extracted from the simulated maps using three distinct periods

	Upland crop area classified from remote sensing	Forest area classified from remote sensing
Upland crop area simulated from LUC model	0.646 (0.844*)	
Forest area simulated from LUC model		0.536 (0.651)

* Values in brackets indicate the Pearson coefficients; the higher value indicates the higher correlation between two values.

Calculations of forest areas show a large over-estimation in 1993, but also an underestimation in 1999. The differences between the values may either be a function of the model or because of classification data. However, the results of the modelling exercise suggest that the assumption that farmers expanded cultivation areas annually was performed well.

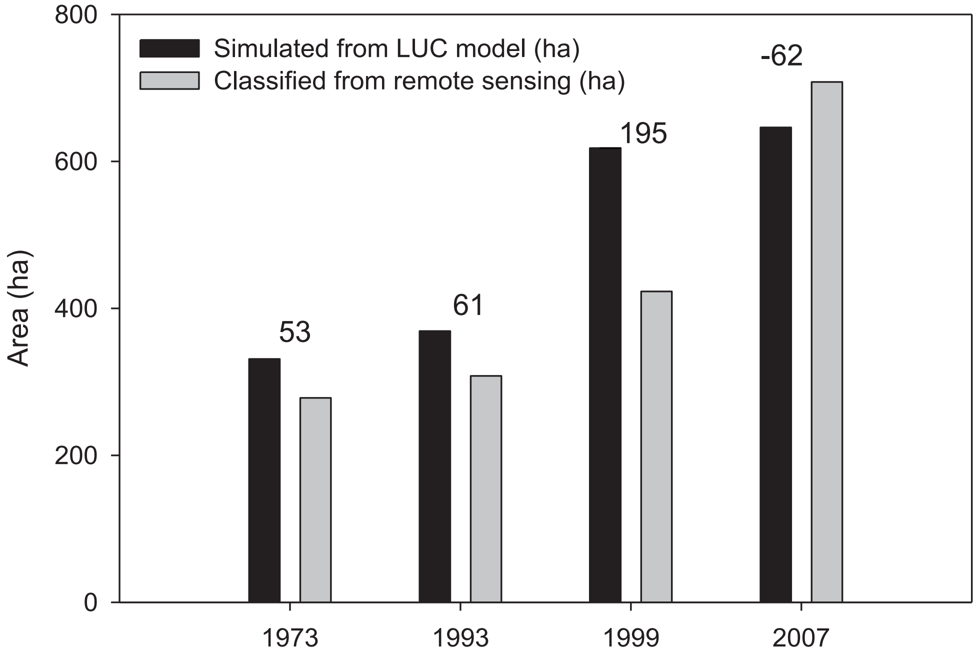


Figure 4.11 Areas of upland crops simulated from LUC model versus area classified from remote sensing; negative value shows the difference between underestimated values; positive values show the difference of overestimated values in between classified and simulated maps (ha).

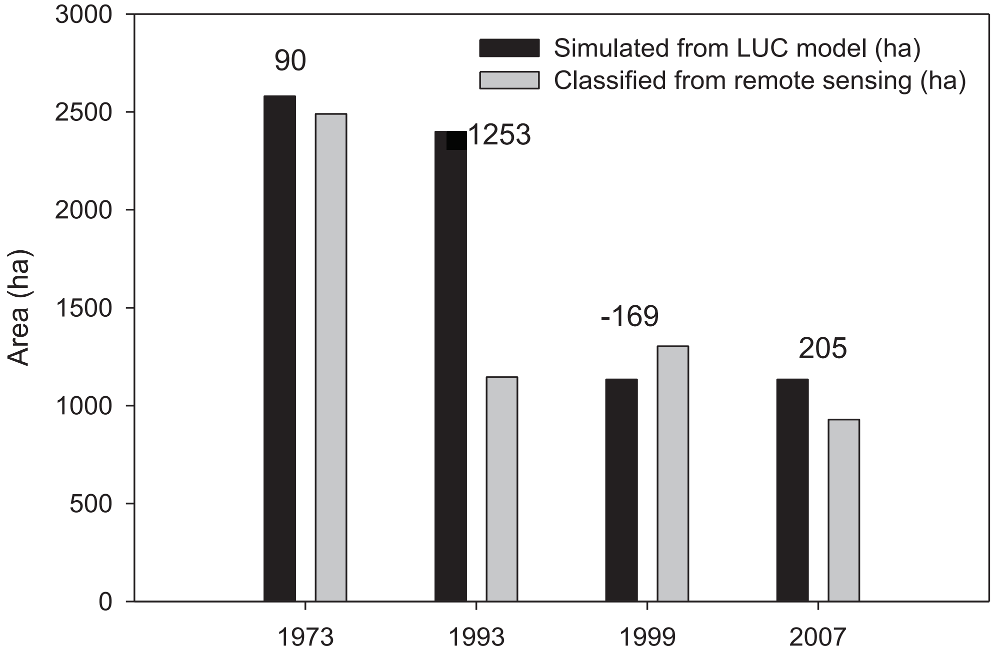


Figure 4.12 Forest areas simulated from LUC model versus area classified from remote sensing; a negative value shows the difference between underestimated values; a positive value shows the difference of overestimated values between classified and simulated maps (ha).

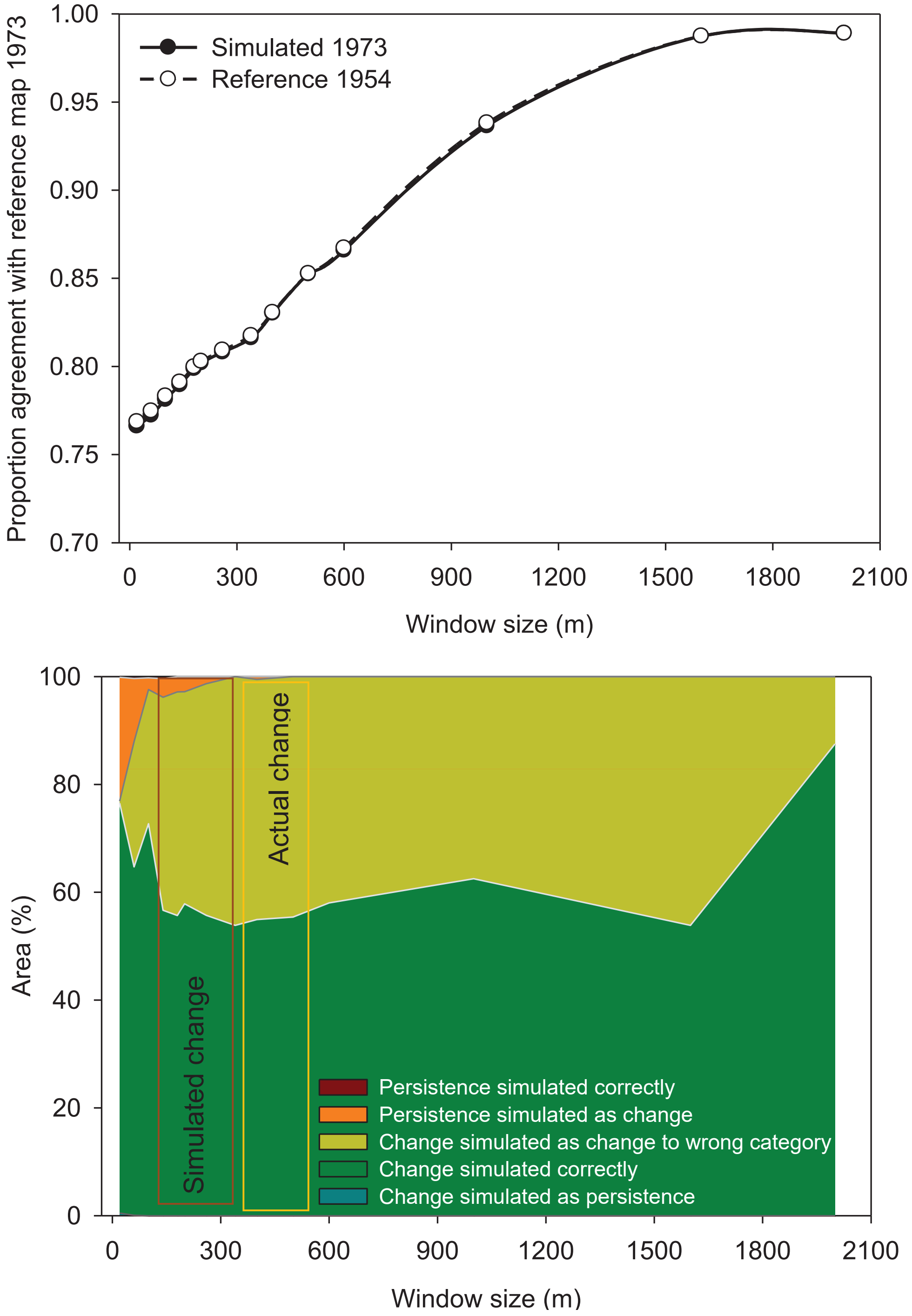
4.5.4.3 Validation at spatially-explicit landscape level

The LUC model was finally evaluated at landscape level. Here, the goodness of fit (GOF) approach was used as it indicates how well patterns of two compared maps fit to each other. The figure of merit (FOM) indicates the ability of the LUC model to predict LUC. Generally, the simulated patterns were relatively like to the classified patterns during the whole simulation period from 1954 to 2007.

In the first period (from 1954 to 1973), a GOF of 0.79 represents a relatively high similarity between simulated and classified maps. FOM values range from 53.8 to 87.5% from original pixel (20 m) to 100 pixels (2,000 m) (Figure 4.13) indicating that the LUC model can simulate more than 50% intersection changes between actual and simulated changes. The highest agreement between the two maps occurred in simulation period 2, where the GOF value of 0.89 presents a high agreement of patterns of simulated and classified maps. FOM values range 71.5 to 100% (at 80 and 100-pixel resolution). At a GOF window size of 500 m, the value slightly reduced. During the increased window size processes, pixels were multiplied with uncompleted kernel at the boundary of the maps. This led to the difference in total areas between simulated and classified maps in this case. Overall, Figure 4.14 shows a greater percentage of correctly simulated change using the LUC model from 1973 to 1993 (greater than 0.86 proportion agreements and greater than 80% correct simulated change).

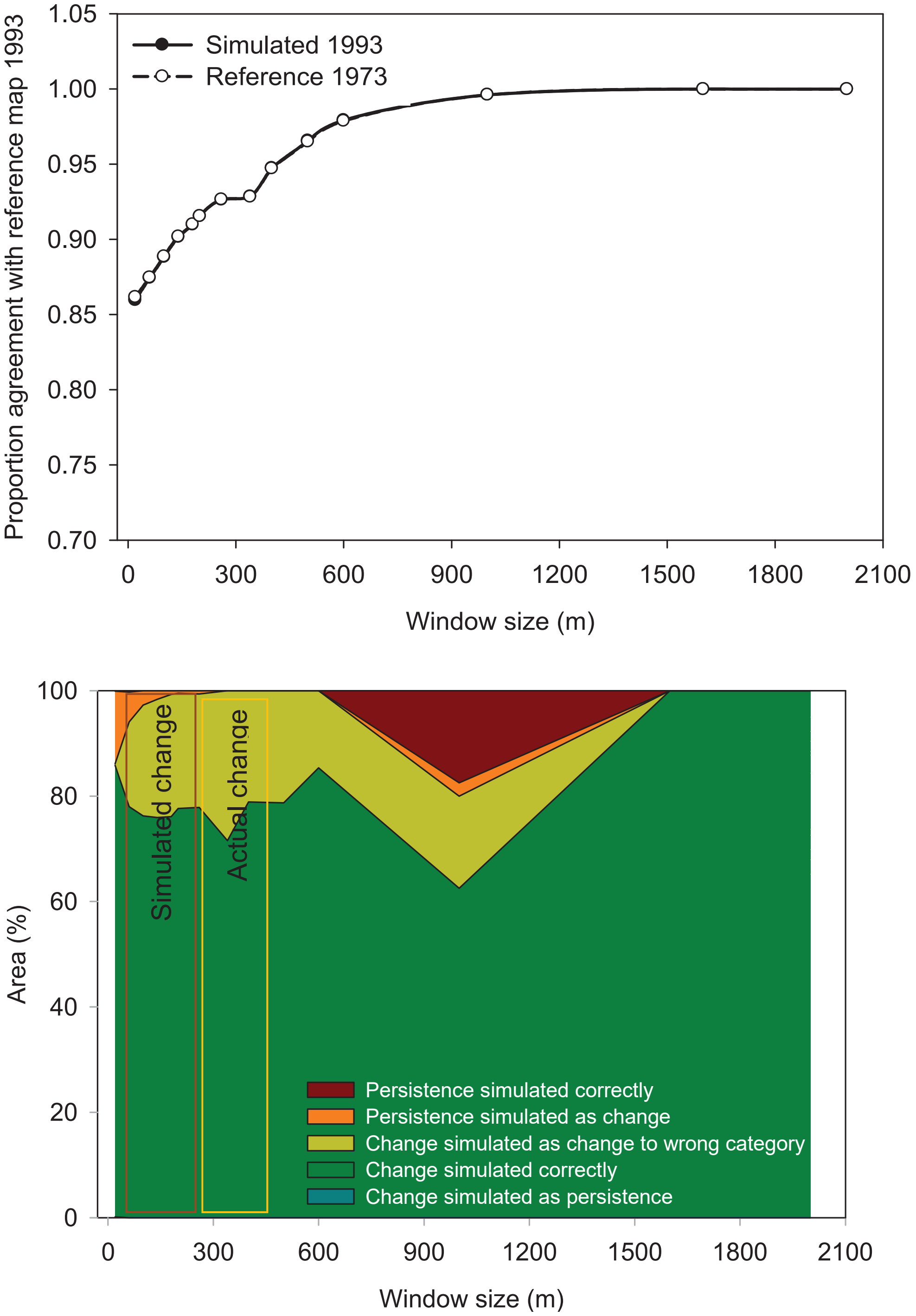
The GOF value of 0.88 of the first sub period 3 (1993-1999) was higher than for the second sub period (1999-2007) with a GOF value of 0.75. The FOM values of the first sub period 3 were also lower than those of the second sub period (Figure 4.15 and 4.16). GOF value declined at window 1,600 m (80 pixels) and 2,000 m (100 pixels). However, results of period 3 show an overall good fit of simulated and classified maps and a possibility higher than 60% that the LUC model can simulate LUC.

In the three periods, GOF values were higher than 0.85 when window size was larger than 600 m (30 pixels) and mostly increased with an increase of window size, except for period 3. The association between increased window size and proportion agreement occurred most effectively during the simulation period (improved from 0.77 at a window 20 m to 0.99 at a window size of 2,000 m), and most LU dynamics occurred in the third period (Figure 4.16). Simulated changes occurred correctly with a large area in all simulation periods. FOM values were reduced in all cases because actual change occurred. Thus, FOM values were higher overall than 50% and independent from the increase of window size.



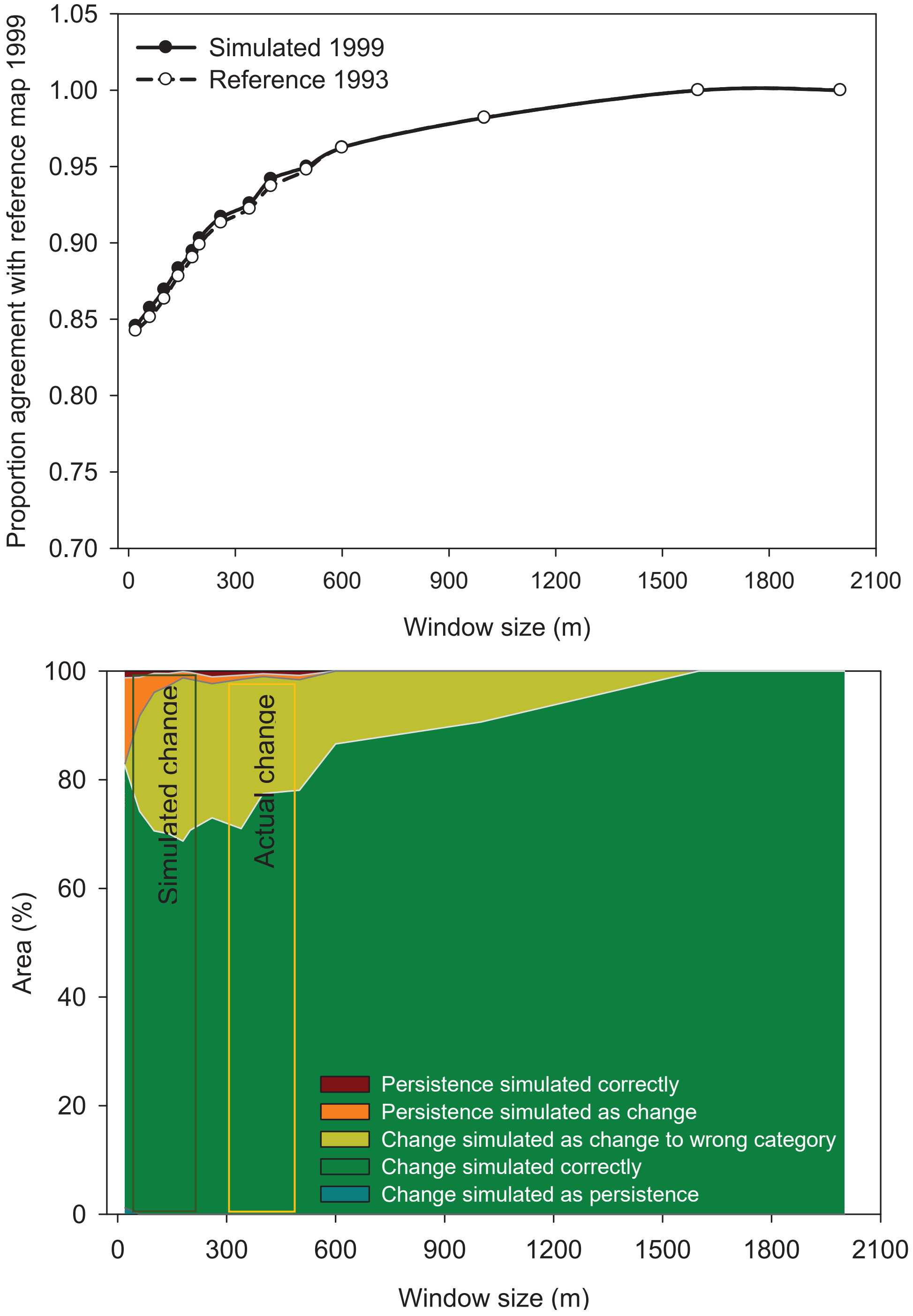
FOM	76.6	65.2	57.1	57.1	55.7	57.9	55.7	53.8	54.9	55.4	58.0	62.5	53.8	87.5
WZ	20	60	100	140	180	200	260	340	400	500	600	1000	1600	2000

Figure 4.13 GOF and FOM validation of LUC model with multiple resolution, window size (WZ) from 20 m to 2,000 m, GOF presents the proportion of agreement between LU map reference 1954 and reference 1973, and the proportion of agreement between reference and simulated maps in 1973. FOM presents the model agreement in simulating LU between actual and simulated changes.



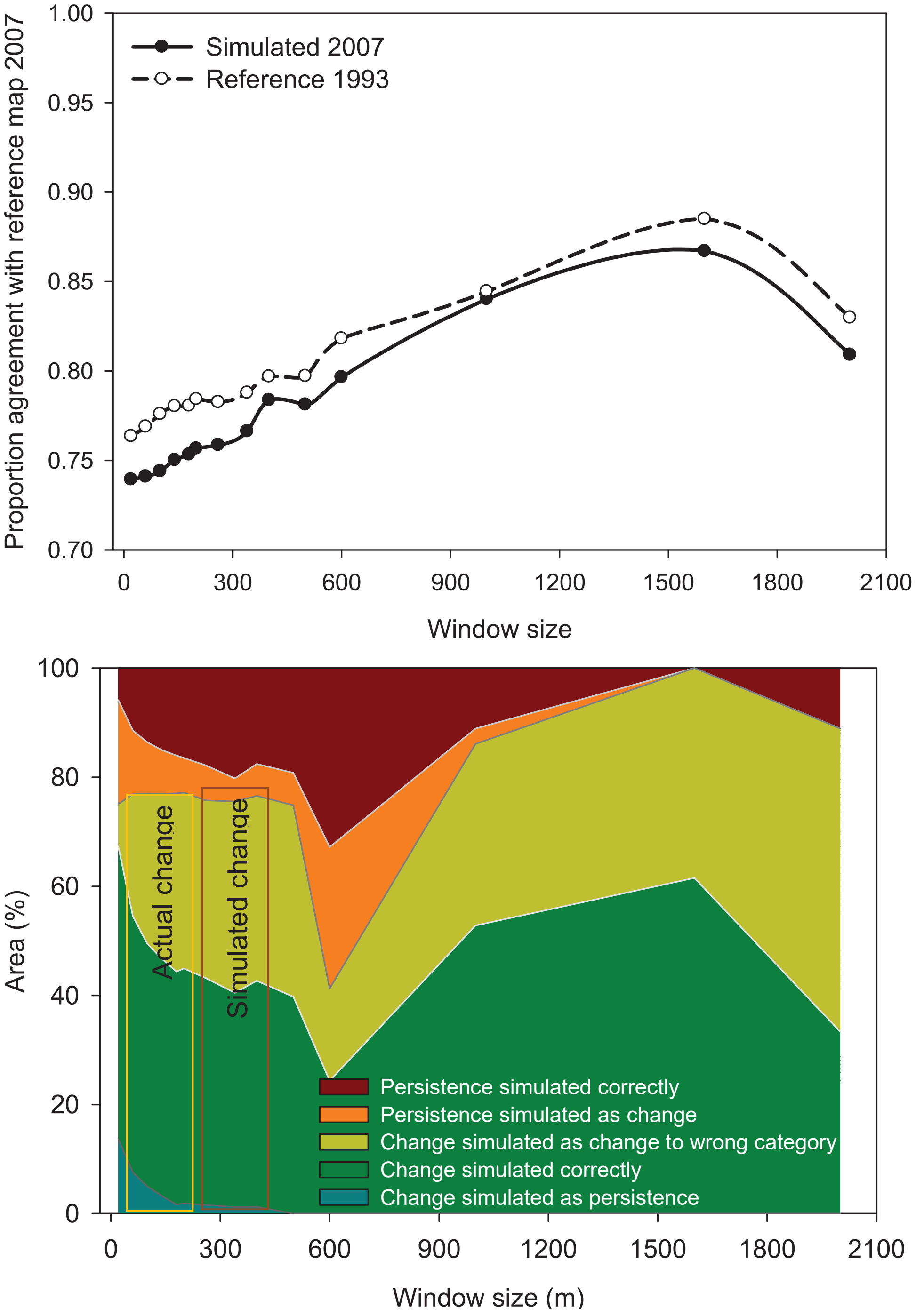
FOM	85.9	78.4	76.3	75.9	76.1	77.7	77.8	71.5	78.9	78.7	85.4	96.2	100	100
WZ	20	60	100	140	180	200	260	340	400	500	600	1000	1600	2000

Figure 4.14 GOF and FOM validation of LUC model with multiple resolution, window size (WZ) from 20 m to 2,000 m, GOF presents the proportion of agreement between LU map reference 1973 and reference 1993, and the proportion of agreement between reference map and simulated map in 1993. FOM presents the model agreement in simulating LU between actual and simulated changes.



FOM	84.4	75.9	71.2	70.7	68.8	71.1	74.6	72.1	78.2	79.3	86.6	90.6	100	100
WZ	20	60	100	140	180	200	260	340	400	500	600	1000	1600	2000

Figure 4.15 GOF and FOM validation of LUC model with multiple resolution, window size (WZ) from 20 m to 2,000 m, GOF presents the proportion of agreement between LU map reference 1993 and reference 1999, and the proportion of agreement between reference map and simulated map in 1999. FOM presents the model agreement in simulating LU between actual and simulated changes



FOM	71.9	67.5	65.6	65.1	64.5	66.1	66.3	67.4	65.1	64.5	70.8	67.9	61.5	42.9
WZ	20	60	100	140	180	200	260	340	400	500	600	1000	1600	2000

Figure 4.16 GOF and FOM validation of LUC model with multiple resolution, window size (WZ) from 20 m to 2,000m, GOF presents the proportion of agreement between LU map reference 1993 and reference 2007, and the proportion of agreement between reference map and simulated map in 2007. FOM presents the model agreement in simulating LU between actual and simulated changes.

4.6 4.6 Discussion

4.6.1 The role of food self-sufficiency in LU process

The LUC model was constructed based on the food self-sufficient conditions during the 1950s. The results show the strong relation between cultivation areas and population through food demand calculation in the past (Figure 4.5). However, self-sufficiency in food became a less important factor when new crop management applied, such as the dominance of mono-cropping practice, use of hybrid varieties, and fertilizer and pesticide. The main cause of these modifications was first, the implementation of the green revolution in the 1960s -1970s and then the speedy adoption of commercialization after economic reforms - known as Doi Moi in 1986 (Minh, 2010). Despite this, the self-sufficiency still played a key role in LUC processes as presented in the newly developed LUC model. Similar findings at global and nation levels, Chand (2008) and Tao *et al*. (2009) indicated that population growth is a significant factor that leads to increased food demand, which is strongly related to cultivation areas. Food security related to the proportion of the cereal areas and its productivities after green revolution.

The self-sufficiency single approach was suitable during the self-food sufficiency period only. This approach became insufficient after 1973 in the study region. Beside the release of green revolution, the establishment of artificial lake also improved the productivity of crops by increasing water supply and improving infrastructure and accessibility to upland fields. For these reasons, the newly developed model was adapted to local and stage conditions and by separating the simulation into three periods. During simulation periods, the model was modified by adding the commercial factor to the self-sufficiency approach. The model used the modification of the basic driving factor the LUC, and used edited the map inputs during each simulation period (Section 4.3.2). These changes were not able to simulate at landscape level, for example, the establishment of the artificial lake or the separation and restriction of natural and secondary forest. Therefore, results show the jump in each period (Figure 4.6). The first jump was caused by two factors: (1) first, the edited map input, the new edited maps increased the possibile areas for expansion, for example, surrounding the established lake after 1973 and the second jump was caused by a shorter fallow period and a wider expansion to the secondary forest after using the new edited map of 1993, (2) a smaller difference was caused by an external factor from the commercial influence, in this case, maize production which slightly increased after 1973 but then strongly increased during the 1990s (Figure 4.4).

Overall, the results from the first model exercise showed a suitable approach to simulate the amount of land needed to satisfy the increased population at a self-sufficiency condition. Using a basic food requirement combined with farmers' decision rules, the study recommends using this model potential for: (1) simulating the LUC at a self-sufficiency and a data limited watersheds/stage; (2) simulating LUC in a pre-survey land use project when the data has not been collected; (3) simulating an amount of land as a preliminary check for a land use planner or before using other LUC models to simulate main trend of LUC; and, (4) simulating the need of land for a self-sufficient system for example planning for a self sufficient market in agricultural products at a national level, which isalso suggested by Tao *et al*. (2009). Because this model could simulate the proportion of land, it should be maintained to produce the basic food requirements of a population.

4.6.2 The role of farmers on LUC processes at watershed level

Vliet *et al*. (2016) reviewed 307 publications considering LUC models, calibration and validation. They argued that land changes fare multi-causal. However, they also indicated that the combination of drivers is directly or indirectly driven by human decisions. In this study, through population and food demand, the LUC model used farmers' decision rules as the main factor driving LUC in last 50 years. Policy and commercialization factors were also considered by using three simulation periods instead of implementing those factors into model codes, because multi factors, such as policy, occurred only once during the simulation period. Overall, the LUC model could perform the trend of upland agricultural expansion, similar to findings from Pontius *et al*. (2008) and Minh *et al*. (2011).

The study site was in a remote rural mountainous region with limited data availability (Chapter 3). However, the validation shows better than 50% agreement between actual and simulated patterns of maps at area and landscape validations. Despite a limitation of historical ground truth points, the fit of total points reached almost 50%. The same situation with all existing models, they could not consider all individual actual driving factors and, consequently, the simulated maps hardly represented the changes occurring (Sohl and Claggett, 2013). In this study, the LUC model performed with a fair validation quality model performance of about 50% accuracy using three validation approaches; this study could suggest that the LUC model was successfully built to simulate agricultural land expansion. Modelling results supported the first hypothesis that a mathematic algorithm can be built from farmers' decision rules using a necessary separation period for a data-limited watershed.

4.6.3 Factors influencing model accuracy

The performance of the LUC model as presented by the overestimated and underestimated values could be either attributed to the model performance itself or the quality of validation data. In this study site, census and data from remote sensing were available. However, census data differed from classification values (Table 4.7). As census data were collected from secondary data from the Statistics Department in Yen Chau district, data collection methods may have varied. Classified values were collected by classifying remote sensing data using ground pattern signatures and farmer decision rules to identify land use types (Chapter 3). Moreover, the quality of both census and classification data were also limited. In case of census data, values were collected from statistic department in Yen Chau and derived using several methods using local units (according to the Head of the Statistics Department). Additionally, the storage and human capacity of the department was poor (Chapter 3). Therefore, the long-term census data were comprised by many factors which may result in relatively low information quality. In addition, census data of land use type areas were inconsistent compared to values classified from remote sensing data. Classified values were derived from classifications of LUC from RS data sources (Chapter 3). Those values were considered as observed values which also needed to be validated and were comprised by a varying level of accuracy because of data source, seasonality or resolution effects (Section 3.3.2).

In this study, from a census database, only the census data of the population were used to construct the LUC model, not the data of areas. These population data were more accurate compared to the land use type areas, as population data were collected at household level; Figure 4.17 shows the high dynamics of upland cultivation areas, because the measurement method for counting the population caused few failure possibilities compared to the measurement of land use areas. According to the Statistics Department Yen Chau, data of areas were measured directly on fields during 1954 to 1990s by government officers, and since 1990, data were collected from village reports based on interviews. However, census data of areas were used to cross check the trend of the LU dynamic. Table 4.7 shows the differences between simulation, census, and classified values of upland cultivation and forest areas. Although the LUC model under- or over-estimated the absolute values during different simulation periods, the trend of increasing cultivation in upland area expansion was simulated correctly as confirmed by the GOF and FOM (Lusiana *et al*., 2012; Pontius *et al*., 2011; Costanza (1989). Figure 4.17 shows the increase in simulation processes using the LUC model, as well as census and classification from remote sensing data. Therefore, the hypothesis could be verified that the LUC model was able to simulate LUC using a limited dataset.

Table 4.6 Statistics of upland crops and forest areas derived from model simulation, classified remote sensing data and census data

Upland crop class	**1973**	**1993**	**1999**	**2007**
Simulated (ha)	331	369	618	646
Classified (ha)	278	308	423	708
Census (ha)	181	245	977	1030
Mean	263	307	673	795
S.D.	76	62	281	206

Forest class	**1973**	**1993**	**1999**	**2007**
Simulated (ha)	2580	2399	1134	1134
Classified (ha)	2490	1146	1303	929
Census** (ha)	2641	2577	1845	1792*
Mean	2570	2041	1427	1285
S.D.	76	780	371	451

* Statistic data from Chieng Khoi commune committee (2010)

** Census data of the forest class were calculated based on the total area of the political boundary (in 2007) and the assumption that the land use dynamic occurred only with forest and upland crop classes

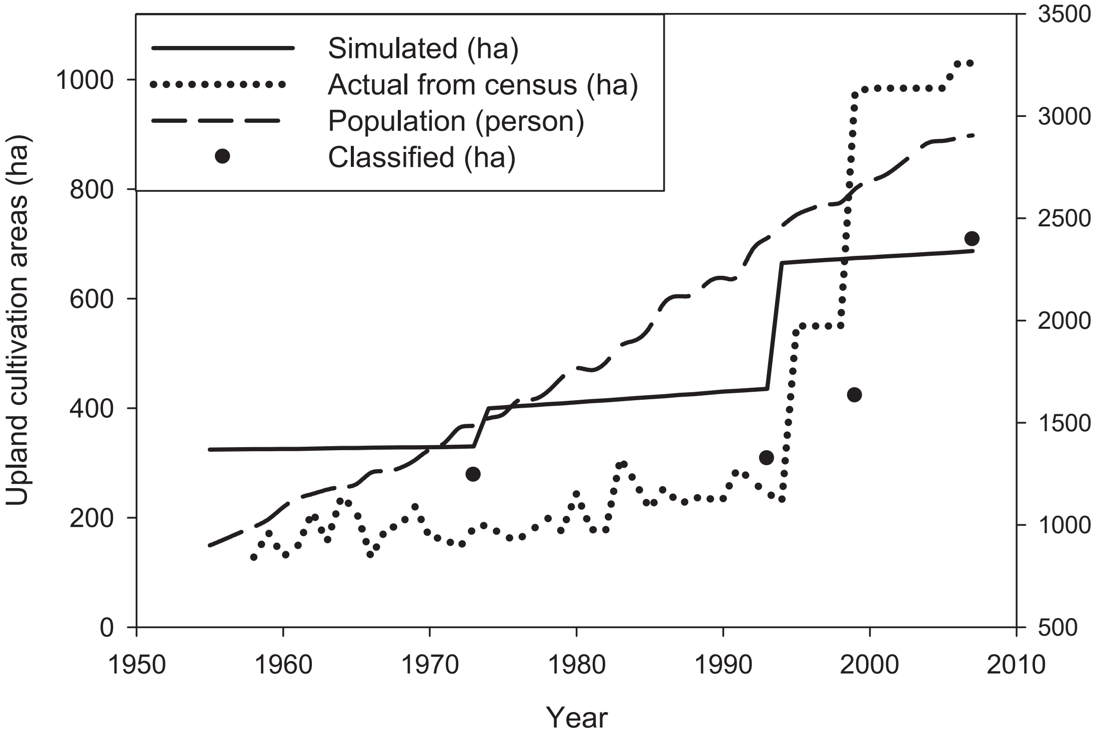


Figure 4.17 Annual addition areas required in Chieng Khoi watershed based on the simulation using the LUC model (Population data from the Statistics Department in Yen Chau district, collected in 2012)

4.6.4 Lesson learnt and suggestions for further implementation

Lessons

This newly developed LUC model presents a suitable approach to simulate the trend of LUCs using a limited dataset compared to a more complex modelling approach. Particularly while the watershed conditions could not provide enough data input for the existing models. The conflict between practical flexibility and precision has been widely discussed in the modelling community. For example, model development often focuses on improving simulation accuracy and to get the modelling routines close to natural processes, but also increases data requirements and model complexity or/and complicacy (Sohl and Claggett, 2013). A user-friendly interface could be an option to bring complexity or/and complicacy models to practice. However, a large dataset and complex components stand behind the interface, which also required a large input dataset (Sohl and Claggett, 2013; Diogo *et al.*, 2014). Therefore, a determination of data availability and model suitability for a specific watershed is a necessary initial process before developing or using a land use model. Moreover, identifying users and target tasks is important to select between practical, simple models (low data requirement and friendly interface) or complex or/and complicated models (more precise and large dataset available).

Validation processes should consider several levels. For instance, Costanza (1989) underlined the difficulty of the quantitative evaluation of the goodness of fit in ecological simulations. With complex patterns, measuring the similarity of the patterns was a suitable and necessary method to evaluate the performance of complex ecological models instead of only pixel by pixel comparison. Besides, the quality of validation data needs to be considered before starting validation processes. Low accuracy of model performance could be caused by a low quality of data, despite accurate model performance.

Implementation

The LUC model developed in this study is suitable for use in watersheds with low data availability, especially when a pre-survey is needed to reduce the cost of time and labor to estimate the trends of LUC. This model is also suitable for land use planners at multi-level to simulate the minimum amount of areas required for agricultural production when: (1) the land use systems need to be modified because of climate change or urbanisation processes; and, (2) to remain being the self-sufficient agricultural production system of a commune or a country as suggested by Tao *et al*. (2009). Furthermore, the newly developed LUC model presented here can be used as an initial step to produce input for more detailed biophysical model applications. Before applying this LUC model, several issues need to be considered:

- The modelling LUC exercise based on decision rules using data such as interviews, expert knowledge and historical local knowledge - this information needs to be verified carefully and cross-checked several times before being used as model inputs. In this case study, farmers' rules were collected from three farmer group discussions in three villages. Moreover, similar questions were repeated during household interviews and transect walks with farmers. The answers were then compared with only matching information used to avoid the uncertain model results (Chapter 3).
- The separation of distinct periods needs to be considered with a long-term run. External and unpredictable factors need to be considered that will influence LUC directions (for example a newly released government law, the establishment of an artificial lake or new infrastructure). In some cases, factors could be implemented as imported variables or maps as model inputs such as diet change, as described by Verstegen *et al*. (2011).
- Input maps and parameters need to be adapted with study site conditions, for example, in the third model exercise, besides the

increase maize production employed as the variable input, the input map of 1973, 1993 were needed to modify, because an artificial lake establishment.

4.7 Conclusion

In this chapter, an LUC model was developed to simulate LUC using a limited dataset. The model exercise was employed for the Chieng Khoi watershed in *NW* Vietnam. The LUC model was constructed using farmers' decision rules as the main driving factors from 1954 to 2007 within three simulation periods. The overall results of validation processes indicated that the LUC model can simulate LUC by showing the expansion of agricultural land in the last 53 years. Besides increasing the complexity of models to a real-world scale, this study also suggests using and constructing a suitable model for poor watersheds that is suitable under local conditions but still provides potential uses for other existing models to simulate the impact of LUC on environmental services.

Chapter 5. Assessment of soil fertility development under land use change

This Chapter investigates the development of soil fertility under land use change. In this thesis, the impact of mono culture maize is considered as a major result of land use changes in the project region of NW Vietnam. To determine the dynamics of soil fertility, conventional soil sampling methods were used. Furthermore, Chapter 5 employs the outputs from the LUC model in Chapter 4 as the input for simulating the development of soil fertility at watershed level using a newly developed model tool.

Herein, the term ‘soil properties’ refers to the physical and chemical characteristics of soil. For instance, the soil colour and bulk density are considered as physical properties, and Nitrogen (N) and Carbon (C) content as well as Cation Exchange Capacity (CEC) and available Phosphorus (available P) are considered as chemical properties. Also, ‘soil fertility development’ refers to the development of total N and total C (including organic and inorganic) in the soil.

5.1 Objectives

In Chieng Khoi commune, soils are described as acidic, poor and shallow soil. Under a tropical climate and especially under the influence of intensive agricultural use, preventing soil degradation is one of the main challenges (Mui, 2006; Clemens *et al*., 2010; Wezel *et al*., 2002a). A previous investigation of soil fertility showed a decline of topsoil thickness and fertility under intensive monocropping systems (Clemens *et al*., 2010; Cong, 2011). Moreover, soil fertility decreased due to the depletion of OM, N, and Available P in the soils, because the richest fine aggregates were eroded. The deeper topsoil related to higher CEC, OM, P, and N and higher crop yield (Wezel *et al*., 2002b). Soil fertility decline threatens sustainable agricultural development, which provides livelihood for future generations; to investigate the dynamic of soil fertility and its speed, the objectives of this Chapter are: (1) assessing soil properties and determining the development of total N and C under maize mono-cropping system in Chieng Khoi commune; (2) selecting an approach for constructing a model tool to assess the development of total N and C distributions at watershed level; (3) validating the model; and, (4) identifying the potential soil degradation hotpots under data-limited conditions of such a watershed.

This Chapter hypothesizes that: (1) soil fertility decreases under long-term monocropping; and, (2) a simple model tool can estimate the trend of decreasing soil fertility under land use changes.

5.2 Materials and methodology

Soils deliver ecosystem services through diverse functions, such as a provision of food, fiber, fuel, construction materials, habitat for human and other organisms, source of pharmaceuticals and genetic resources, pool for carbon sequestration together with water purification. Soils also regulate climate and flooding as well as contributing to nutrient cycling (FAO, 2015). A change in soil properties could influence its functions with both positive and negative consequences, especially on cultivation activities and productivities. Therefore, estimating, measuring, and characterizing changes in soil properties are important, not only for field management at steady state conditions, but also for conservation, planning, and policy development (Tugel *et al*., 2008; Pickett, 1989).

The comparison study method refers to comparing two or more studies in which the time is calculated by a substitution technique to derive differences in time (chronosequence). The difference in time allows inferences about associated changes in soil properties. Tugel *et al*. (2008) indicated that the comparison studies method is a common approach to determine soil property change. However, substituting space for time could be a fail to derive sensible dynamics, because information about time is derived from the assumption that locations are initially equal. Therefore, in this case, soil change was determined under the same management condition on the same soil type within the known **history along the transect walks**. Moreover, to enhance the precision of soil property detection processes, a comparison of study methods combined with field monitoring was applied. This presents an option to reduce the limitation concerning time the calculation of comparison studies, as recommended by Pickett (1989). For instance, soils used in a previous study were re-sampled. The **re-sampling method** allows determining changes of soil properties on the same soil within an exact time, similar to the soil property change monitoring method but more efficient and simpler.

As mentioned above, soils can be sampled and the timings of cultivation can be recorded in the field to derive soil property changes. The comparison study and re-sampling method were considered as a conventional approach. Recently, Pansak *et al*. (2010) proved that the WaNuLCAS (Water Nutrients Light Capture in Agro Forestry System) model can predict soil loss and runoff. By this method, a prediction of nutrient content inputs and outputs in the system can be achieved. Moreover, DDSAT (Decision Support System for Agrotechnology Transfer) is a crop model which is also able to simulate nutrient flow in the system from the interaction between plants and soils (Hoogenboom *et al*., 2015; Jones *et al*., 2003). Lippe *et al*. (2014) highlighted the potential in using the EROsion and sediment DEPosition (ERODEP) model and its integration within the LUCIA (Land Use Change Impact Assessment - a biophysical assessment) tool at landscape level (Marohn *et al*., 2013; Lippe *et al*., 2014; Ayanu *et al*., 2011). These modelling tools are currently commonly used for assessing dynamic soil processes under cultivation conditions. However, they all require a high demand of data input considering both physical and socio-economic information. Moreover, these models need parameterization, calibration, and validation processes before applying for a particular watershed. Under data-limited conditions, the existing models cannot be employed. Therefore, this study presents **conventional soil sampling methods**, and then focuses on developing a **modelling** tool to assess the distribution of soil fertility changes at watershed level.

5.2.1 Soil sampling methods

5.2.1.1 Transect sampling

Transect sampling is a well established conventional soil sampling method where soils are sampled along a known transect (Staalhl *et al*., 1997). The method allows tracking soil conditions within a crop history. In this study, transect walks were designed using the land use map 2007 (Chapter 3) to assess the total soil C and N level, soil texture, and colour at different ages of cultivation. After recording the history of several transects, three transects were selected for soil sampling, because interviews derived a consistence of history of those transects. These three transects consisted of a similar slope and crop history. According to interviews with owners and observations in the field, farmers extended their plots near the protected forest at an average of 5 m every one to two years. A similar observation was reported by Haering *et al*. (2013). Therefore, the transect design used the boundary with the protected forest as a fixed point, and soil samples were collected in two directions from the fixed point:

- towards cultivation areas: soils were sampled every 5 m along the slope to determine development of soil properties under the crop history.
- into the forest: soils were sampled every 5 m to determine the influence of slope to soil properties (Figure 5.2).

At each sampling point, three soil samples were collected using an auger tool (Figure 5.2). Soil horizons were determined based on observations of soil colour and texture, thereafter, the horizon thickness was recorded. The composited samples were produced from three individual samples around the same sampling point to analyze chemical properties (Section 5.2.1.4).

Figure 5.1 An example of soil samples from auger in 2010

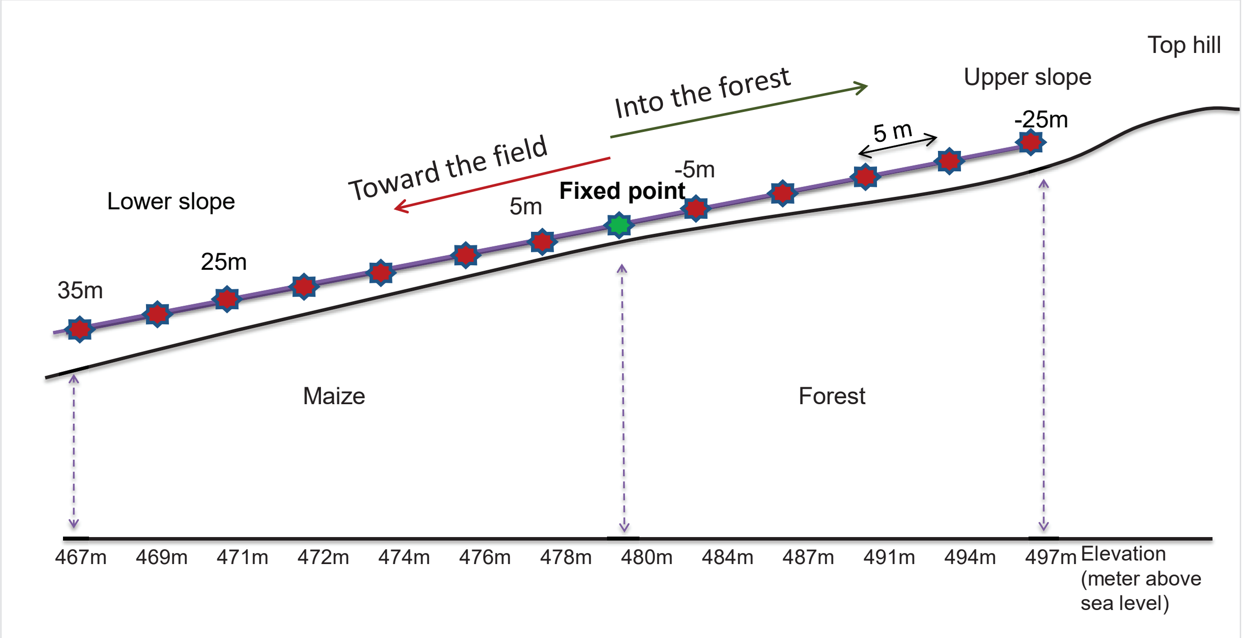


Figure 5.2 An example of a transect design scheme for soil sampling in Chieng Khoi commune. Soils were sampled toward two directions from the fixed point, which presents the boundary between crop fields and forest.

5.2.1.2 Re-sampling

Besides sampling soils along the slope of transects, the re-sampling method was used to determine the development of soil fertility within an exact time of cultivation. The re-sampling method means sampling the soil at an identical location where the soil was sampled before.

Research conducted by Wezel *et al*. (2002b) in 1998 showed the influence of slope and cropping frequency on soil fertility and soil properties of maize fields. Using the given GPS points, soil samples were taken and total C and N were analyzed. The land use history of each plot was derived from plot owner interviews from 1998 to 2011. Physical and chemical properties were measured. In this case, the study shows results on the investigation of soil total C and total N. During the sample collection process, 12 points were found at the exact locations within the well-known history from plot owners. Furthermore, information on fertilizer application and crop yields were collected together with land use history during farmer interviews. This information derived management practice changes, which could be used to explain the current status of soil properties and crop productivities.

5.2.1.3 Random sampling and secondary data

During the study pre-survey in 2009, a random dataset was collected and samples were collected randomly in the watershed. This dataset consisted of 30 sampling points in the watershed. The auger tool was used to collect the samples (Figure 5.1). Similar to transect and re-sampling design, three samples were collected at each sampling point and these were mixed to produce composite samples. Soil horizon thickness, soil colour, and texture were determined the method as transect and re-sampling design and analysis that will follow in Section 5.2.1.4 below.

Besides, an auxiliary dataset was reviewed from the studies in the same study region. The information and use of this will be further described in Section 5.2.2.2 (Table 5.1).

5.2.1.4 Soil properties analyses

After soils were sampled using the auger tool in the fields by transect and re-sampling methods, topsoil samples were analyzed for physical properties (bulk density, soil colour and estimated field test texture) directly in the fields. Moreover, a full texture analysis of selected samples was conducted in the laboratory. Chemical properties (such as total N and total C) were also analyzed. In the case of transect samples, Available P and CEC were additionally determined to obtain an overview of the soil fertility conditions of the study site. Detailed analyse procedures follow:

Bulk density: Around each sample point, three soil cores (using a steel ring with a volume of 100 cm^3) were collected to measure bulk density in topsoils. Samples were weighed as fresh mass, and then dried at 105° C over 24 hours to measure the bulk density (FAO, 2006). In total, 132 samples were collected along three transect walks. Furthermore, 36 samples were collected in the re-sampling design.

Soil horizon and CEC: As mentioned earlier, soil horizons were determined based on observations of soil colour and texture. The topsoil thickness was considered the first horizon of the soil profile. Two soil profiles roughly 1 m depth were selected to measure the CEC. Elements (Al, Ca, K, Mg and Na) were measured using an inductively coupled plasma optical emission spectrometry (ICP-OES) method. In this study, soils were first extracted using the Bray method, and then the extracted solutions were used to detect Al, Ca, K, Mg and Na. The method required two machines: (1) a simultaneous spectrometer with cyclonic spray chambers; and, (2) a Meinhardt atomizer - 'VISTA Pro radial' (Varian, Australia) machine. Results released an overview of CEC distribution along different soil depths.

Soil colour and texture: Herein, soil colour and texture from 35 points of transect design and 12 points of re-sampling were considered. At each sampling point, all the horizons of the soil profile from the auger were evaluated. In total, 167 samples were used to determine soil colour and texture. The results focused on the colour and texture of topsoil, because the topsoil is more sensitive to crop productivities (Lynch, 2007). The soil colour was assessed using the colour chart from Munsell (1994). Besides, changes of soil colour were also determined by farmers during informal interviews together with plot history (Chapter 3). Soil texture was estimated using the field test method of the FAO (2006), and the texture of selected soil samples was analyzed in the laboratory using the Bouyoucos method (Anderson and Ingram, 1993) to calibrate the estimations in the field.

Total N and C: After sampling, soil samples were air dried. In total, 77 points were considered including 35 points from the transect design in 2011, 12 points from the re-sampling design in 2012, and 30 points from the random sampling in the field in 2009. Each sample consisted of three individual samples from the auger tool as composite samples. Each sample was analyzed twice by total N and C by a combustion method using an auto-analyzer (Elementar Analysensysteme GmbH, Germany). In total, 264 samples were analyzed including top and subsoil layers. Herein, this study focuses on the dynamic of total N and C concentration in the topsoil.

According to Clemens *et al*. (2010), soils in the study region do not contain carbonate in the topsoil. Therefore, the total soil C organic (C_{org}) equals total C of the soil, and the soil OM content was calculated by multiplying C_{org} by 1.7

P: The Available P was measured using P Bray 1 method. A selected sample set (70 samples) was analyzed for available P in top and subsoil. P available in acid soil in tropical soil contains a high amount of P, but relatively immobile elements (Sims and Sharpley, 2005), therefore P available in subsoil was considered in this study.

5.2.2 Modelling the development of soil fertility at watershed level

5.2.2.1 Principle

Besides the conventional methods, soil fertility development furthermore could be identified using modelling tools (Campell and Paustian, 2015; Batlle-Bayer *et al.*, 2010). On order to use modelling tools, this study additionally applied the main findings from previous studies which were conducted in this study region. Previous studies prove that soil fertility is strongly affected by slope, crops, crop history, relief position, and parent materials (Clemens *et al.*, 2010; Wezel *et al.*, 2002b). Therefore, the **Dynamic of total C and N distribution** (DyCNDis) model was developed in two phases:

Phase 1 - Mapping the initial soil fertility map: This phase aimed to build the initial map which determines the initial total carbon and nitrogen distribution at watershed level. The map was constructed using the relationship between C and N with determinant factors. Land use, soil type and slope were selected as variables due to conclusions from previous studies (Clemens *et al*., 2010) and availability of data.

Phase 2 - Simulation of the development of soil fertility: This phase indicated the dynamic processes of soil fertility from the initial status (from phase 1) of soil fertility. The processes were ruled by the relationship between time of cultivation and total N and C using transects and literature information. However, the information for ruling the development was limited. Therefore, suitable approaches were investigated and analyzed based on the available data at first. The appropriate approach was indicated by a high regression fit between time of cultivation and total N and C. Thereafter, the soil fertility development was simulated using the most appropriate approaches.

Figure 5.3 illustrates the concept for the assessment of the dynamics of total C and N development. This approach simulated the component processes at annual level based on crop history (derived from the transect data), and the crop rotation and the fallow (Chapter 3 and Chapter 4). Detailed analyses and procedures are described in four steps in the next sections. The first phase comprised two steps: (1) determination of the relationships (correlations) between total C and N with selected determinant factors; and, (2) mapping. The second phase comprised two more steps: (3) simulation of C and N development; and (4) model validation.

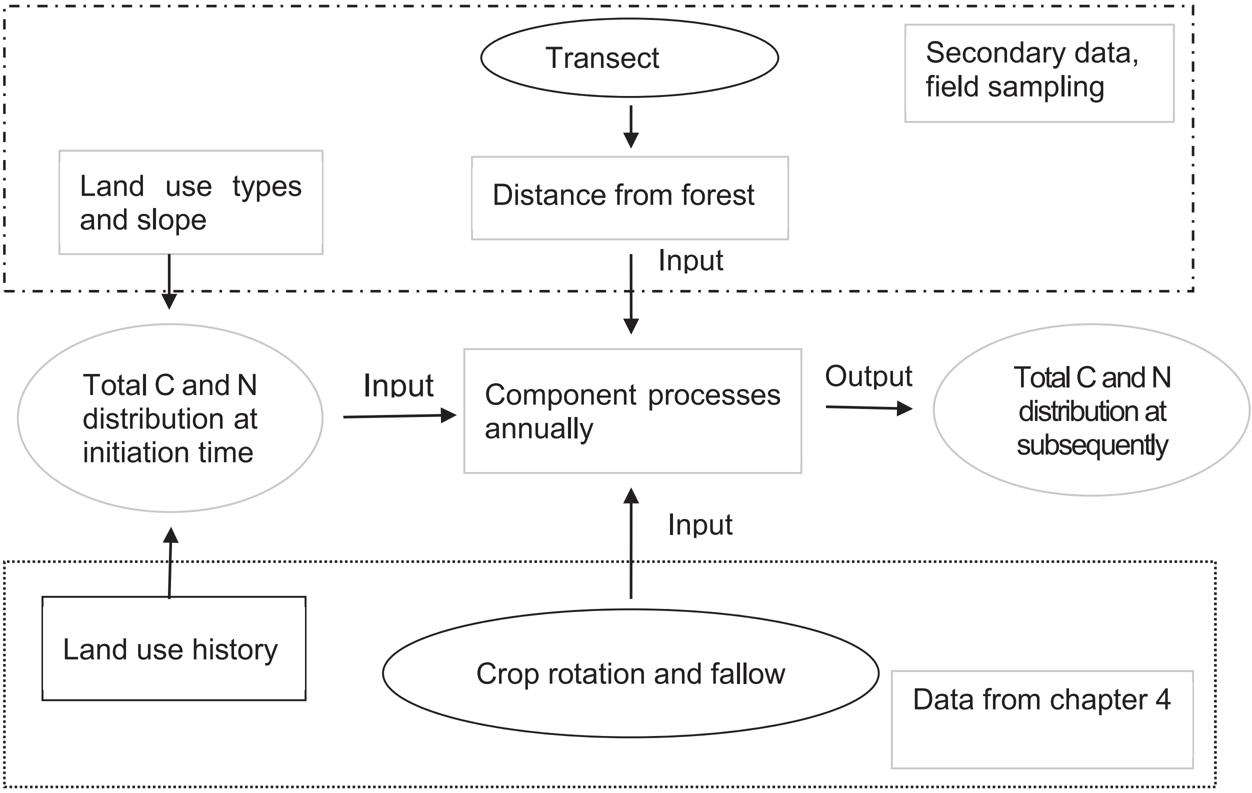


Figure 5.3 Scheme of the Dynamic of total C and N distribution (DyCNDis) concept

5.2.2.2 Processes

To assess the development of soil fertility, the soil dataset consists of three parts in this chapter: Dataset 1 included the field random sampling (2009) and secondary data was used to determine the correlation between nutrients and determinants to build the initial nutrient maps. Dataset 2 included field transects sampling (2012) and Dataset 3 included data from Haering *et al*. (2013), which were used to investigate the suitable approaches for simulating and validating the development of soil fertility. Furthermore, the LUC was assessed from Chapter 4, which provided the expansion of cultivation areas over 20 years. Figure 5.4 shows the connection of the four steps and the use of the three datasets. Details of used data are described in following four steps:

Step 1: Determine correlations

As mentioned earlier, the DyCNDi model was constructed in two phases. During the first phase, the initial total C and N distribution needs/needed to be determined from determinants of the distribution of soil fertility. For this purpose, a secondary dataset was collected from studies in the same study region. Table 5.1 shows the list of studies that contributed information for respected land use types. The secondary data consisted of published scientific articles, and master and bachelor theses. Those secondary data provided detailed information on 90 sample points including the relationship between total C and N with slope, soil type, and land use information. In addition, soils had been sampled randomly at 30 points in 2009 collecting equivalent information (Section 5.2.1.3), which were used as secondary data in this study. These soil samples were taken by the same method as described in 5.2.1. Overall, 120 sample points (Dataset 1) were used to determine the correlation between land use, slope, and soil type versus total C and N.

Regarding to the correlation of land use types and total C and N, land use classes were used including forest, trees, paddy rice, upland crop, and lake, which are described in detail in Chapter 3. However, the correlation examination focused only on three classes: upland crop, paddy rice, and others, because this model exercise focused on the development of soil fertility under the historical expansion of agriculture.

The correlation of total C and N with slope used the slope map, which was created from terrain information in Chapter 3 (Figure 3.4).

Additionally, to define to correlation with soil types, a soil map was utilized, which was a simple classification soil type. Following farmers' classifications, good and not good soil types were mentioned as two general soil types based on colour (Figure 3.3).

Correlated variables were weighted and the interaction between them was also analyzed to determine possible regressions, which could influence the distribution of total C and N. Those analyses were computerized using SAS software. The r value is the correlation coefficient measuring the correlation of two variables. This correlation coefficient ranges from -1 to +1. At 0, there is no correlation. At -1 there is a maximum negative correlation, and at +1 there is a maximum positive correlation. Higher r values indicate a close correlation of the total C/N to the used variables. In this study, r values greater/smaller than ±0.5 were considered to have a positive/negative correlation. The weight of factors was measured by the r value as well. The higher the r value indicated, the greater the influence of the respective factor on the independent variable using the statistical software package SAS (Institute, 2014). Moreover, the R^2 and the RMSE values were used to measure the regression model performance between variables and the total C and N. The higher R^2 values indicate a correlation between total C/N with variables, the higher R^2 indicate the closer correlation between the factors (slope, land use, soil type) with dependent variables the total C/N in a linear regression. Smaller RMSE values indicate a close correlation of predicted values to measured values, and RMSE that equals zero indicates is a perfect regression of the simulation processes.

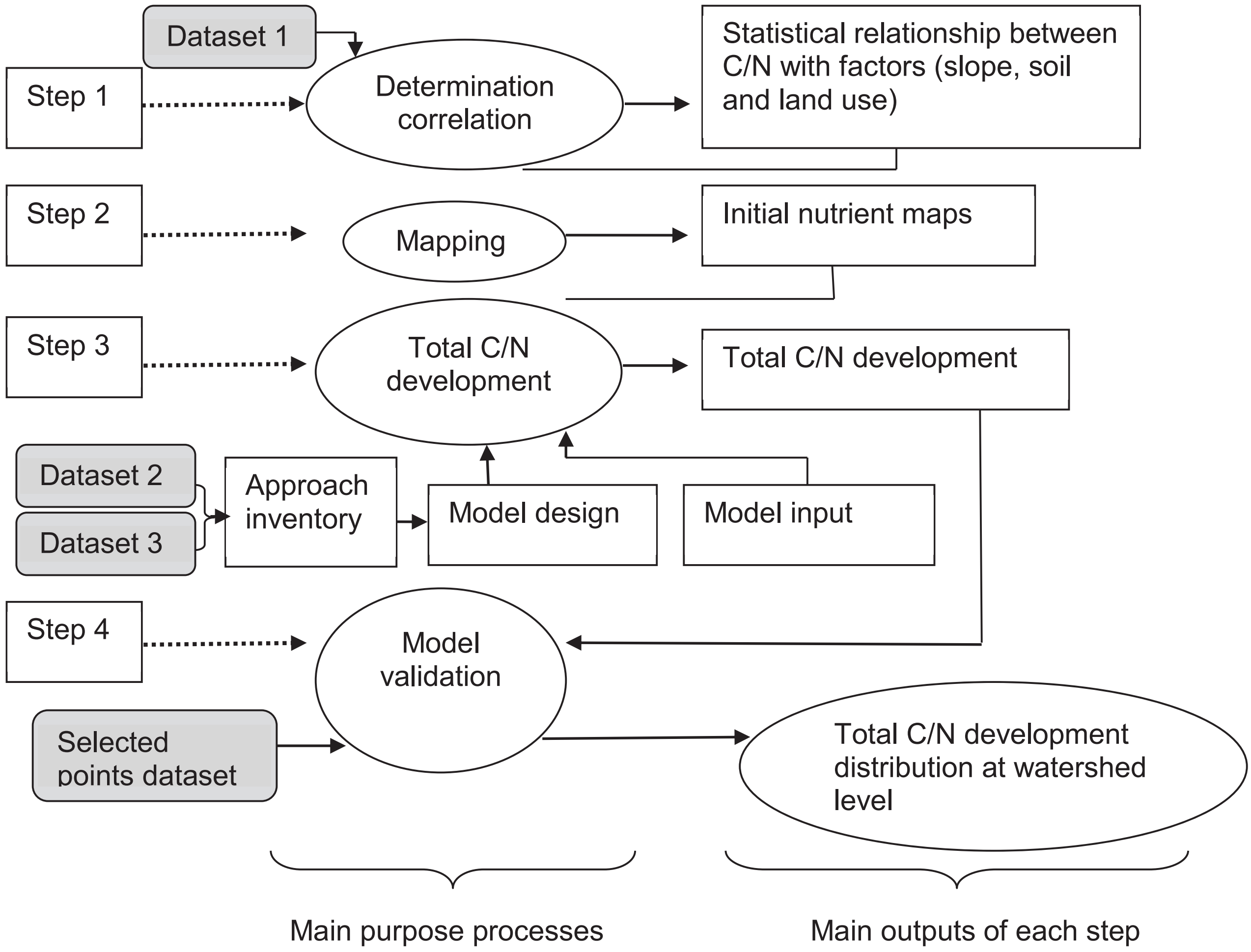


Figure 5.4 Connections and data used in four steps to assess total C and N development

Table 5.1 Secondary data sources and their respective foci on land use types

Land use*	Sources
Paddy rice	Schaufelberger (2012), Schmitter *et al*. (2011), Reinhardt (2012)
Upland crop	Boll (2008), Reinhardt (2009), field random sampling in 2009
Forest	Haering *et al*. (2014)
Tree	Field sampling in 2012

* Used the same land use classes as described in Chapter 3 and 4, forest class was considered as a fixed value, water body (or lake) was excluded in this study, tree class including secondary forest, residential and fruit tree plantation.

Step 2: Mapping initial nutrient maps

After defining the correlation of total C and N with variables, an initial nutrient map was constructed. The nutrient map of 1993 was selected as an initial stage of the model exercise, because LUC occurred more consistently towards the agricultural expansion and the intensive cultivation at the upper slopes. Detailed/precise historical crop data to construct the initial nutrient map were only available from the year 1993 to present. Therefore, statistical models and regressions that resulted from step 1 were employed to construct an initial map of the nutrient distribution of 1993.

The development of total C and N were individually, simulated; therefore, two initial maps were constructed, one initial total C map and one initial total N map. Both maps were constructed using the PCRaster program. The procedure depended strongly on the results from the first step. Therefore, the mapping process will be described in more detail in the result section after presenting the findings of the first step.

Step 3: Simulation of C and N development

Previous sections described processes to construct the distribution of the initial nutrient status at watershed level. Step 3 further explains the dynamic of nutrients in the following 20 years. For this purpose, a simple model tool (DyCNDis model) was developed using PCRaster to determine the distribution of C and N in the watershed in the above-mentioned period (Figure 5.3).

Firstly, data of nutrient development included transect field sampling and published data from Haering *et al*. (2013) and separated into two datasets. The data investigation aimed to select an approach based on the available dataset within an acceptance level of validation to construct the model, and the separation aimed to use independent data for calibration and validation procedures. Secondly, three regressions were constructed from two single datasets alone and a combination of both datasets. The best model was selected based on a highest fit to simulate the dynamic of nutrients using a preliminary validation by a short check with validation points. The DyCNDis model was based on the regression between independencies (total C and N) and variables (time of cultivation and crop rotations).

The DyCNDis model was developed based on the below listed assumptions, which consider the lack of data within the datasets:

- All processes that cause soil nutrient dynamics were accounted for using a function as a component process. Single processes were not considered in this study (e.g. erosion, plant uptake, nutrient depletions, fertilizer application).
- The rate of building nutrients during fallow periods was assumed to be the same speed as its diminishing speed during cultivation periods. However, fallow periods in this model exercise occurred only twice in the period from 1993 to 1999. Findings from Chapter 3 showed that after 1999, the farmers did not leave the soil for fallow, but planted maize continuously instead.
- The nutrient level of natural forest was assumed to remain stable, where natural forest is defined as the forest without human disturbance activities. Even though, the nutrient level of a natural forest still strongly depends on slope, soil type, plant density and plant type (Haering *et al.*, 2010; Wright, 1992). However, this model exercise excluded this factor because the model focused on the nutrient development in cultivated areas.

After selecting an approach, the constructed model required the following inputs:

- Initial total C or/and N maps, which were constructed from Step 2.
- Suitable equations constructed after inventory and separation processes, which were derived from Step 3.
- The distance from forest was revealed as a time series, which was represented for the length of cultivation.
- A test point map that was mapped to indicate the point to assess the output of the model simulation.

After simulating for a period of 20 years, total C and N levels at subsequent times were extracted and validated as described below.

Step 4: Model validation

The model performance was validated using modelling efficiency (EF – equation 5.1) and root mean square error (RMSE – equation 5.2). EF represents the correspondence between actual and simulated values. Similarly the RMSE value was used in Step 2 for correlation determinations, herein, RMSE is known as a standard statistical measure to evaluate the dynamic model performance from much research (Chai and Draxler, 2014; Lippe *et al*., 2014, Pansak *et al*., 2010, Mousia *et al*., 2007; Hussein *et al*., 2007; Bhuyan *et al*., 2002). Chai and Draxler (2014) demonstrated that RMSE is not as ambiguous as Willmott *et al*. (2009) claimed. Therefore, this study employed both EF and RMSE as a combination of measures to validate the model performance.

According to Lippe *et al*. (2014) and Pansak *et al*. (2010), a range of 0.36 < EF < 0.75 is acceptable, EF>0.75 is considered as a good fit between observed and simulated results. Considering the RMSE, smaller values indicate a close correlation of simulated values to observed values, an RMSE of zero indicates the perfect model simulation processes as simulated values are the same as observed values.

Modelling efficiency (EF):

$$EF = \frac{\sum_{i=1}^{n}(Oi-Om)^2-\sum_{i=1}^{n}(Si-Oi)^2}{\sum_{i=1}^{n}(Oi-Om)^2} \qquad (5.1)$$

Root mean square error (RMSE):

$$RMSE = \left(\frac{\sum_{i=1}^{n}(Si-Om)^2}{n}\right)^{0.5} \qquad (5.2)$$

Where n: Number of samples
Oi: Observed values
Om: Mean of observed values
Si: Simulated values

5.2.3 Identification of soil degradation hotspots

Soil degradation is an important issue globally. Soil degradation is defined by many terminologies. Currently, FAO (2017b) defines it as a change in the soil health status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries. Closely to the current definition, Lal *et al*., (1989) defined soil degradation as the diminution of soil quality for both its current and potential multi–purpose productivities. Moreover, they divided soil degradation into three phases. Phase 1 represents a slightly reduced soil productivity. Phase 2 represented the rapid rate of soil degradation with drastically declining crop yields. In Phase 3 the soil is so degraded that it passes the so-called the point-of-no-return. Soils in this phase can neither further deteriorate nor are restored for crop production.

In the previous sections, two methods were applied to identify the development of soil fertility in sloping areas at watershed level. Haering *et al*., (2013) showed that the fertility of soils declined fast in the first 10 years of continuous cultivation. After 10 years, the speed of nutrient reduction slowed down but still occurred. The reduction of soil nutrient content with continuous cultivation is threatening agriculture on sloping land (Clemens *et al*., 2010; Lippe *et al*., 2015; Haering *et al*., 2013; Wezel *et al*., 2002b, Marohn *et al*., 2013; Dalat and Mayer, 1986). Especially in mountainous regions in NW Vietnam, farmers have practiced mono cropping maize since 2000 (Keil *et al*., 2009). More recently, the negative effects on soil fertility, such as the erosion of nutrient and sedimentation, were investigated and reported in detail by Schmitter *et al*. (2012), Tuan *et al*. (2014), Slaets *et al*. (2016a,b), and Brandt *et al*. (2016). Therefore, the identification of the most threatened areas is a critical issue to avoid degradation which may lead to the point-of-no-return of soil degradation. Using this information, farmers could apply a suitable soil conservation method before irreversibly degraded soil occurs. Thus, the early identification of possible hotspots of soil degradation provides a low-cost and easily applicable tool to contribute to sustainable agricultural production.

For that purpose, results from the DyCNDis model exercise were used to determine hotspot areas where soil fertility was low after a simulated 20 years of cultivation. Within the low values of nutrient levels, these areas could at high-risk of soil fertility depletion. The areas were recognized by a visualization method. Furthermore, a spatial analyst tool in ArcGIS was used to select areas that contain deficiency levels of nutrients.

To identify the level of nutrient deficiency, soils were sampled in nine cropping plots where farmers claimed that there was no crop productivity during the last three years, even after the application of mineral fertilizer (e.g. if cassava produces no tuber or maize produces no cob). In those cases, farmers considered abandoning cultivation in the next season and leaving the plots to fallow. Soils were sampled with the same soil sampling method as described in Section 5.2.1, and these samples were selected from dataset 1.

This study considered total C as the major indicator of soil degradation, because on all cropping plots mineral fertilizer was applied even though type and amount of fertilizer differed (Field survey, 2011). However, plots could still retain a level of unused N from fertilizers and hence total N of soil could become an ambiguous indicator of soil degradation. Importantly, threatened areas of soil degradation employed in this study were equivalent to the stage between phases 2 to 3 of soil degradation levels used by Lal *et al*. (1989).

5.3 Results

5.3.1 Overview of the development of soil properties in the study site

The study site was under the investigation of several studies considering soil properties (Clemens *et al*., 2010; Wezel *et al*., 2002a; Lippe *et al*., 2014; Haering *et al*., 2014; Tuan *et al*., 2012; Schmitter *et al*., 2011). This study found that soil properties at the Chieng Khoi watershed were very diverse even within soils of the same type. The overview information here summarizes the main soil characteristics based on all the samples that were collected in transect samplings.

Bulk density: Along three transects, the bulk density ranged from 1.2 to 1.57 g/cm^3, the bulk density values are in the expected range of mineral soil which ranges from 1.0 to 1.6 g/cm^3.

Soil horizon and CEC: On average, the topsoil was 15 cm in three transects. Figure 5.5 illustrates the distribution of soil CEC elements in two selected soil profiles. Soil cations remained relatively constant throughout the profile Al, which increases the soil depth.

Soil colour and texture: Soil colours were mostly in yellow and red colour. All soils were characterized by high clay content. In a few locations, texture was estimated as silt loan clay rich. Farmers indicated that the soil colour changed due to cultivation activities. Table 5.2 shows the description of soil colour development of two typical soil types - red and yellow soil under cultivation practices in Chieng Khoi commune until the 1990s. Red soil was described as the soil became reddish after one to two years of planting crops, then the black colour could recover in the third year when farmer plant a three year cassava, because the three-year cassava cannot be harvested in less than three years, thus the soil was cover continuously without disturbance for the whole period. The soil colour continued to become 'more red' within planting maize in next two years and only became more to back after the 4th year of fallow. Similar processes occurring in the second soil type; the yellow soil that was described as the soil became yellowish after a few years under cultivation, and became 'more black' after the third year of cassava crop and after four years of fallow (Table 5.2). Presented colours were simulated based on descriptions from farmers. After seven years of cultivation, soils were left for fallow for six more years. Therefore, soils lost the black colour but could recover partly under a certain length of fallow period. According to farmers' opinions, the fallow period should have a minimum duration of six years.

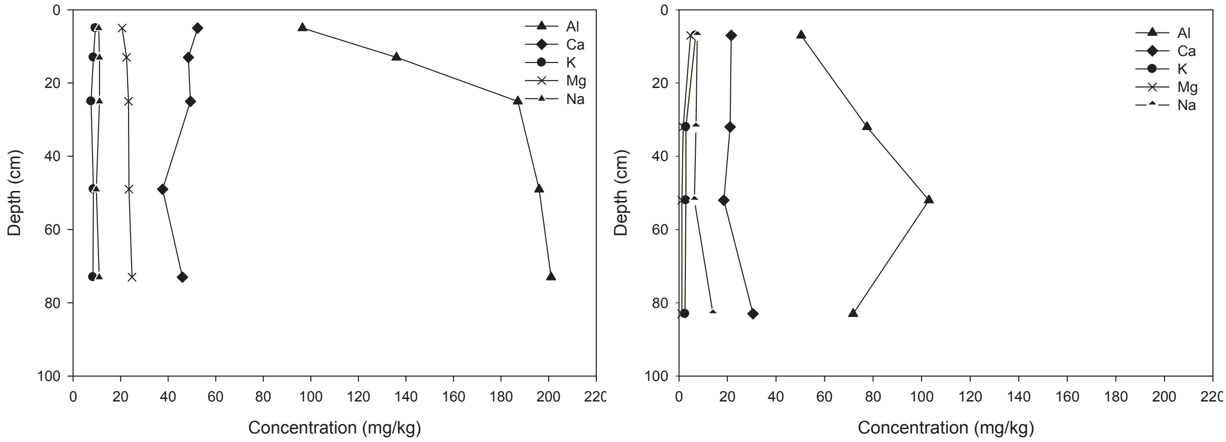


Figure 5.5 Variable of CEC along the soil profiles

Total N and C: The ranges of total N and C both varied widely in three transects; total N ranged from 0.05 to 0.11%, whereas total C ranged from 0.76 to 2.28%. Results show the common range found in agricultural lands.

Available P: Values ranged from 0 to 4.31 mg P/kg considered to be the low range. Under tropical humid weather conditions and acid soils (pH ≤ 7 - Clemens *et al.*, 2010) soils are generally deficient in P – in tropical humid range from 0.9 – 3.6 ppm P while the required from crop is often 20 -25 ppm P (Dabin, 1980; Sims and Sharpley, 2005).

Table 5.2 General development of colour in two typical soil types based on farmer descriptions in Chieng Khoi commune; type 1 represents for red soil, type 2 represents for yellow soil

Time after clearing the forest	Land use type	Soil colour type 1	Colour described by farmers	Soil colour type 2	Colour described by farmers
Year 0	Forest	⬛	Black	⬛	Black
Year 1	Upland Rice	⬛	Black	⬛	Black
Year 2	Upland Rice	▒	Less black	▒	Less black
Year 3	Cassava	▒	Less black	▒	Less black
Year 4	Cassava	🟥	Reddish	🟫	Yellowish
Year 5*	Cassava	▒	Less black	▒	Less black
Year 6	Maize	🟥	Reddish	🟫	Yellowish
Year 7	Maize	🟥	Red	🟫	Yellowish
Year 8	Fallow	🟥	Red	🟧	Yellow
Year 9	Fallow	🟥	Reddish	🟫	Yellowish
Year 10	Fallow	🟥	Reddish	🟫	Yellowish
Year 11	Fallow	▒	Less black	▒	Less black
Year 12	Fallow	▒	Less black	▒	Less black
Year 13	Fallow	▒	Less black	▒	Less black
Year 14	Fallow	⬛	Close to black	⬛	Close to black

*The colour became less black because the cassava was not harvested annually, only in the third year; therefore the colour was partly recovered to less black

5.3.2 Soil properties development using the transects sampling method

The LU history of each transect was recorded, and the time of the cultivation along three transects was calculated. From the history and the annual expansion record, the cultivation time was determined. Figure 5.6 shows an example of a transect within the time of cultivation from 4 to 19 years.

Table 5.3 shows the physical properties of three transects. Topsoil (O-horizon) was found only on points further into the forest. Soils were classified as red or yellow soils in all three transects. From texture estimations, soils were clay, and for a few points in the forest or close to the forest, loamy textures were found in all three transects (at 10 m from fixed point to the forest in transect 1 - N2, at 5 m from fixed point to forest in transect 2-2N1, at 10 m from fixed point to agricultural area in transect 2-2NN2, at 5 m from fixed point to cultivation area in transect 2-2NN1 and at 25 m from fixed point to forest in transect 3-3N5). First horizon depths varied in both forest and cultivation areas along three transects without any trend. However, soils in cultivated areas were slightly deeper than those in natural forest areas. Shallow soils appeared more in the upper slopes.

BD did not differ along the transect length. In Transects 2 and 3, BD slightly increased, however the trend was opposite in transect 1 (Figure 5.7). The r^2 regression values were low at all three transects (within r^2 of 0.30 and 0.02 and within r^2 of 0.01, respectively). This information indicated that BD was very diverse, and there was no correlation between BD and the time of cultivation.

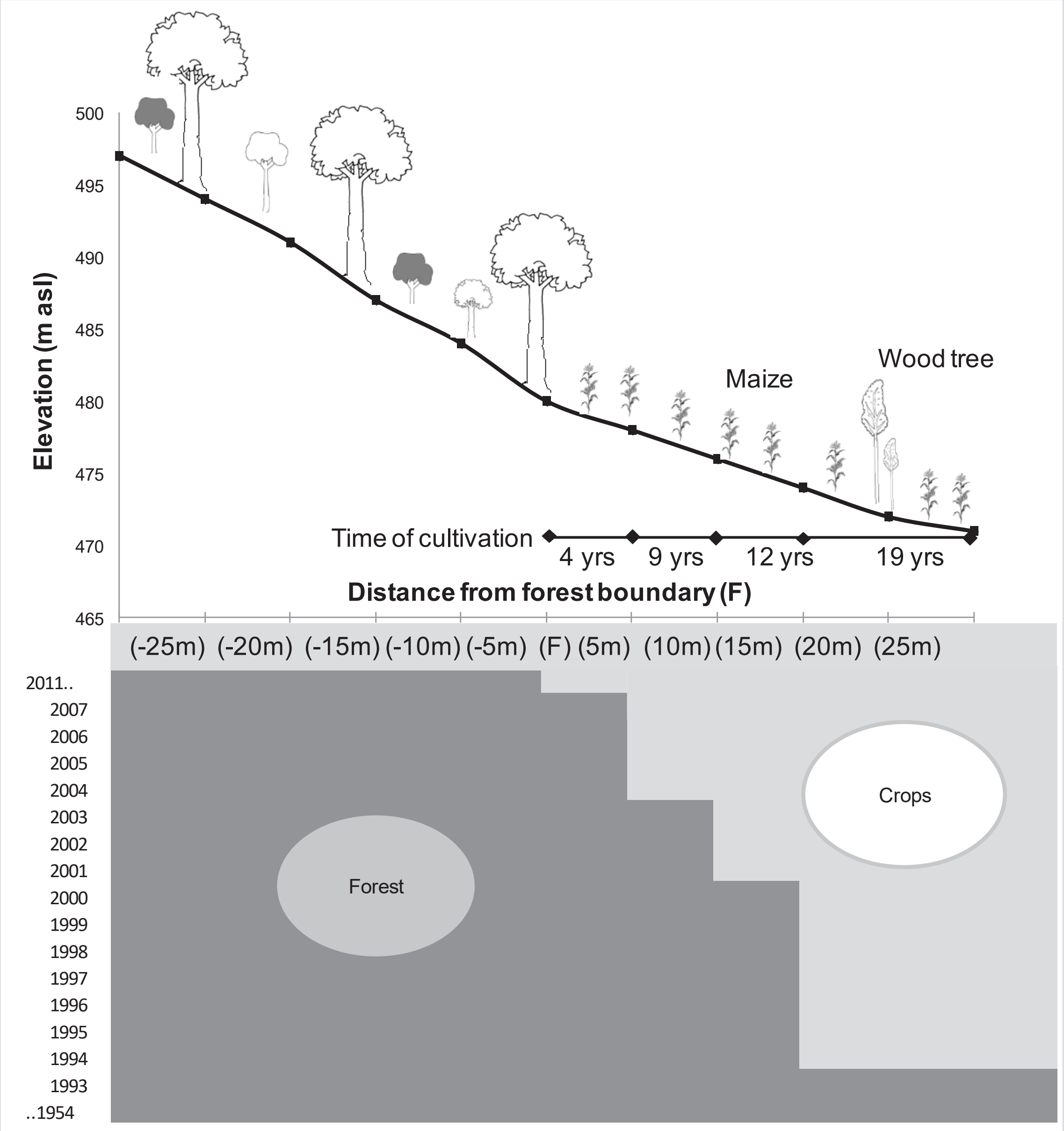


Figure 5.6 Example of transect 2, its history and time of cultivation along the transect was based on farmer interviews (the history and elevation of transect 1 and 3 are presented in Appendix 5.2)

Table 5.3 Physical topsoil properties in three transect walks in Chieng Khoi commune, NW Vietnam

	Field code	Distance from fixed point	Layer names	Colour	Texture	Thickness
					(Figure estimation)	(cm)
Transect 1	NN5	25 m	A	4/4 5YR	Silt clay rich	18
	NN4	20 m	A	4/4 7.5YR	Silt clay rich	15
	NN3	15 m	A	4/3 5TR	Silt clay rich	15
	NN2	10 m	A	4/6 2.5YR	Silt clay rich	15
	NN1	5 m	A	4/4 5YR	Silt clay rich	20
	N0NN00	Fixed point	A	3.5/3.5 2.5YR	Silt clay rich	9
	N1	(-5m)	A	3.5/3.5 2.5YR	Silt clay rich	8
	N2	(-10 m)	A	4/4 2.5YR	Silt clay loam	10
	N3	(-15 m)	A	4/4 7.5 YR	Silt clay rich	6
	N4	(-20 m)	A	4/4 7.5YR	Silt clay rich	7
	N5	(-25 m)	A	4/3 5YR	Silt clay rich	9
	N6	(-30 m)	O	4/4 7.5YR	Silt clay rich	3
	N7	(-35 m)	O	4/3 5YR	Silt clay rich	3
Transect 2	2NN5	25 m	A	4/3 5YR	Silt clay rich	21
	2NN4	20 m	A	3/4 2.5 YR	Silt clay rich	20
	2NN3	15 m	AB1	3/3 2.5YR	Silt clay rich	13
	2NN2	10 m	A	4/2 2.5YR	Silt clay rich	14
	2NN1	5 m	A	3/3 YR	Silt clay rich	9
	2N0NN0	Fixed point	A	4/4 2.5 Y	Silt clay rich	12
	2N1	(-5m)	A	4/3 2.5YR	Clay loam	19
	2N2	(-10 m)	A	4/2 2.5YR	Silt clay rich	21
	2N3	(-15 m)	A	3/3 2.5YR	Silt clay rich	10
	2N4	(-20 m)	A	3/2 2.5YR	Silt clay rich	10
	2N5	(-25 m)	A	3/2 2.5YR	Silt clay rich	18
Transect 3	3NN5	25 m	A	4/6 5YR	Silt clay rich	17
	3NN4	20 m	AP	4/4 5YR	Silt clay rich	19
	3NN3	15 m	A	4/4 5YR	Silt clay rich	19
	3NN2	10 m	A	4/4 5YR	Silt loam clay rich	32
	3NN1	5 m	AP	3/3 5YR	Silt loam clay rich	25
	3N0NN0	Fixed point	A	3/3 5YR	Silt clay rich	17
	3N1	(-5m)	A	4/3 2.5 Y	Silt clay rich	20
	3N2	(-10 m)	A	3/3 5YR	Silt clay rich	6
	3N3	(-15 m)	AP	3/4 5YR	Silt clay rich	21
	3N4	(-20 m)	A	3/3 2.5YR	Silt clay rich	9
	3N5	(-25 m)	A	3/4 5YR	Silt loam clay rich	20

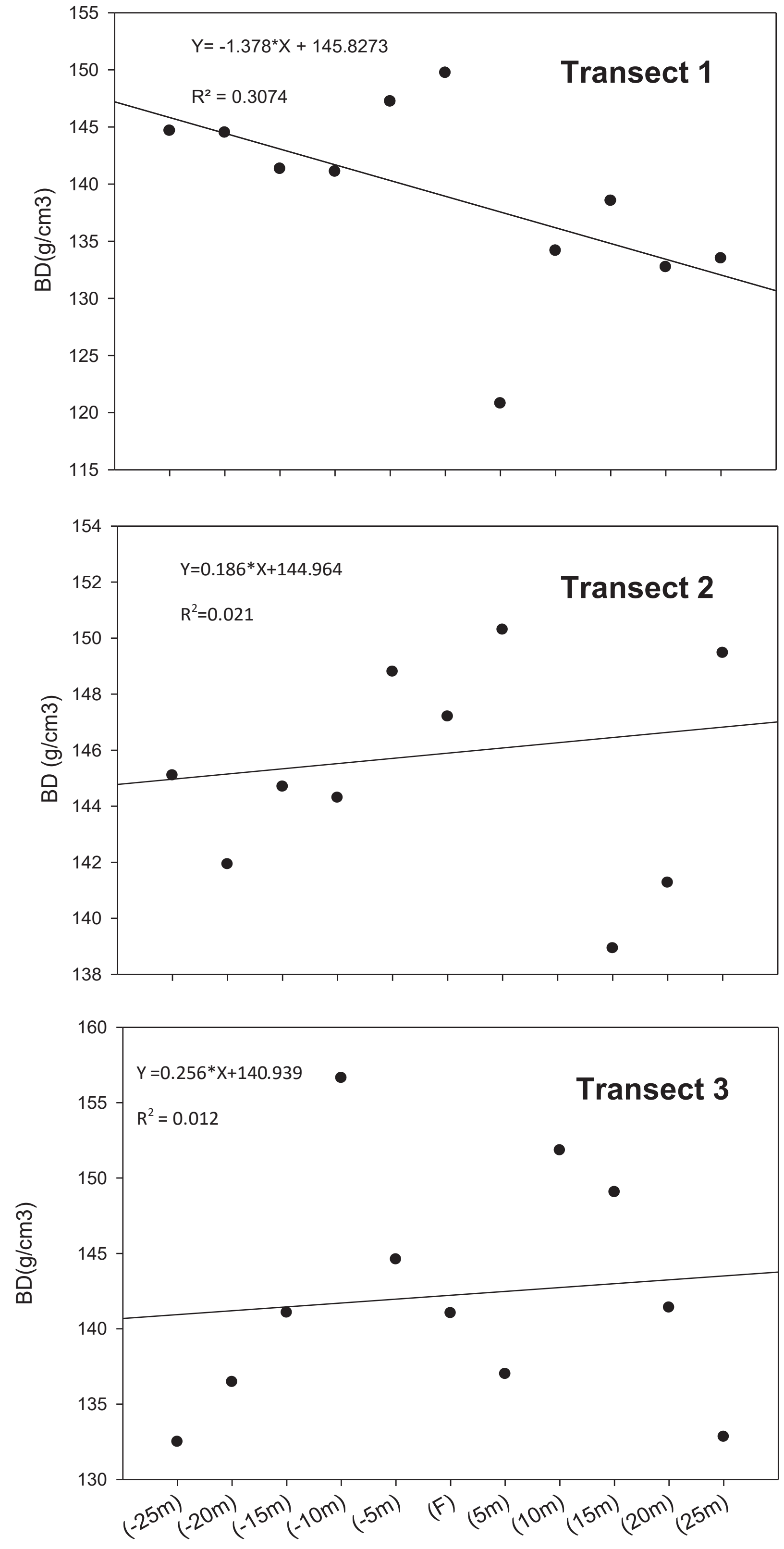


Figure 5.7 Topsoil bulk density (BD) along the three transects sampled after maize harvesting in Chieng Khoi commune

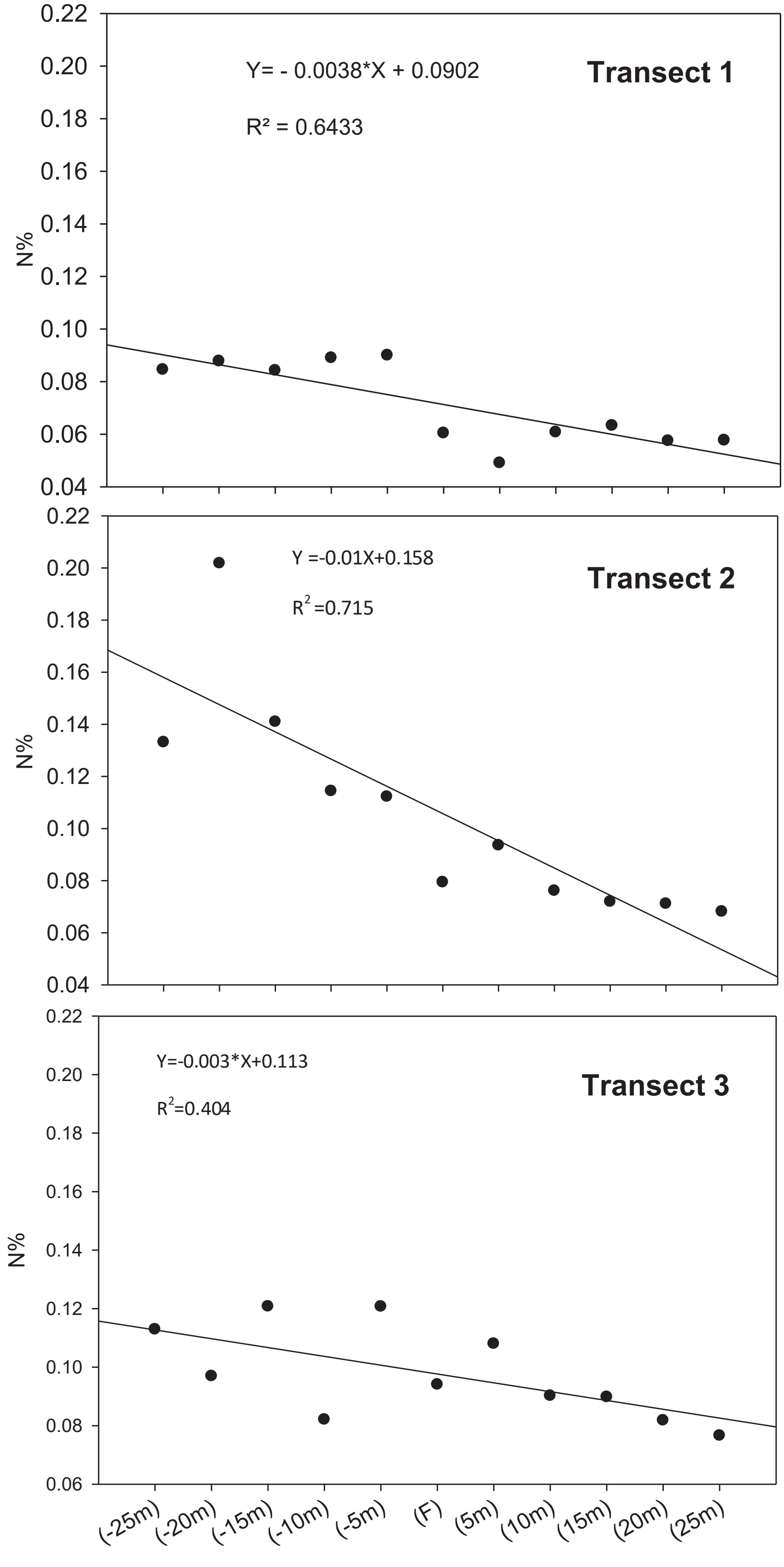


Figure 5.8 Total N along three transects sampled after maize harvesting in Chieng Khoi commune

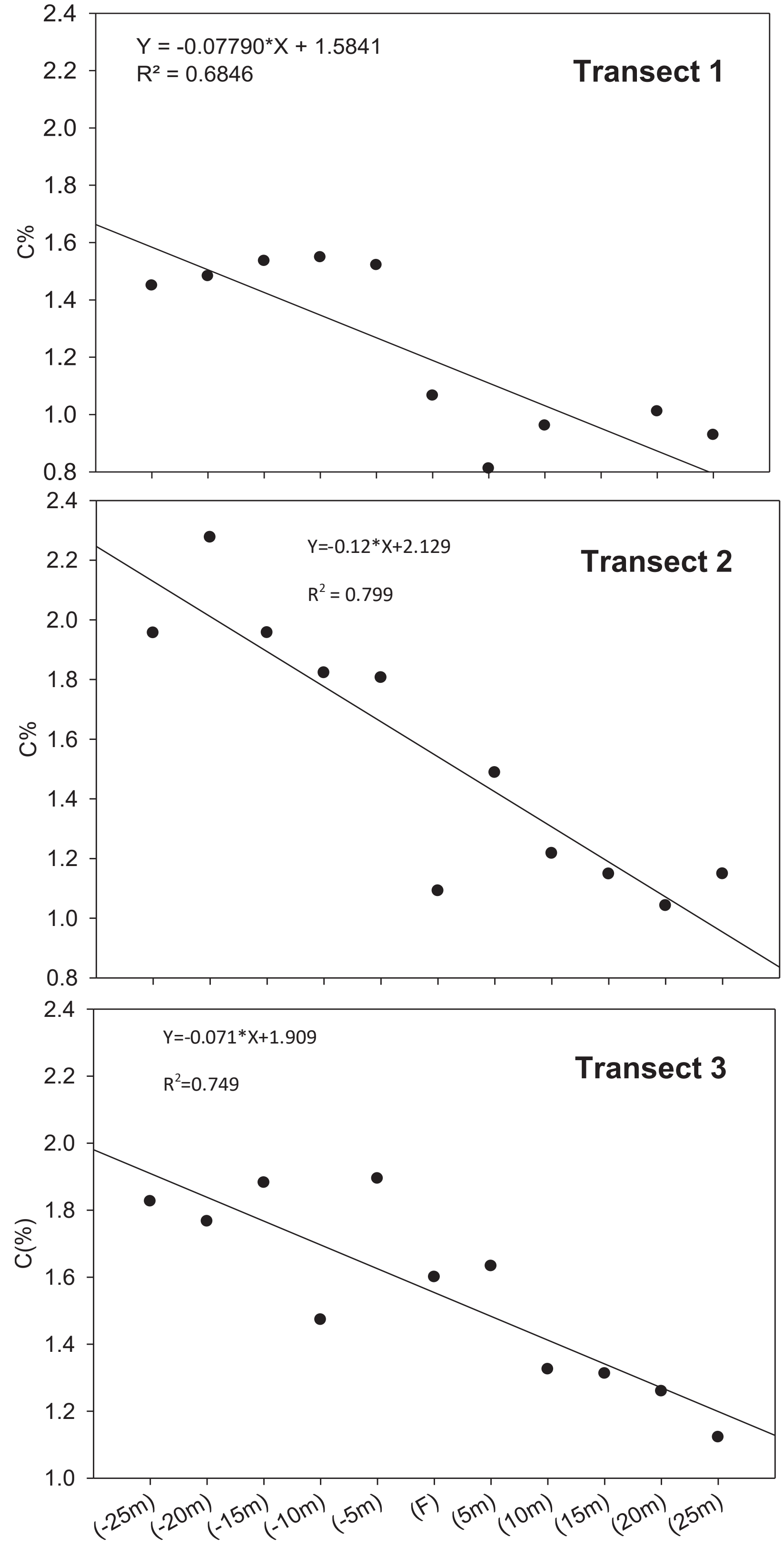


Figure 5.9 Total C along three transects sampled after maize harvesting in Chieng Khoi commune

In case of total soil N, N in transect 1 slightly decreased after a longer time of cultivation in maize fields. However, total N was visibly higher in the forest compared to agricultural areas (r^2 = 0.64). In transects 2 and 3, decreasing N contents were found in points with a longer time of cultivation. Again, values of total N were higher inside the forest. All transects showed a high correlation between decreasing N after a longer time of cultivation, except transect 3 was quite low (r^2 of transect 2 = 0.71, and r^2 of transect 3 = 0.4) (Figure 5.8).

The trend of decreasing total C was identified from top to lower positions in all transects. These results also show that the longer the cultivation, the lower the total C in the soils. Results could also be interpreted that the deeper the sample point was in the forest, the higher the C was found (Figure 5.9). High r^2 values showed a high correlation of total C with time of cultivation in the three transects. From transect 1 to transect 3, r^2 achieved values of 0.68, 0.79, and 0.74 respectively.

Figure 5.10 illustrates the distribution of P available in top and subsoil along three transects. The topsoil showed higher Available P compared to subsoil. However, the P available in both top and subsoil differed along the transect walk. Thus, there was no significant difference of P between three transects. Considering all three transect points, the value slightly increased along transects from lower to upper slopes, from long-term cultivation areas to recently cultivated areas and the forest. This result also indicates that the available P was diminished according the cultivation period. Soils of areas with a longer cultivation history had less P available compared to areas where cultivation had started more recently, even if chemical fertilizer had been applied annually.

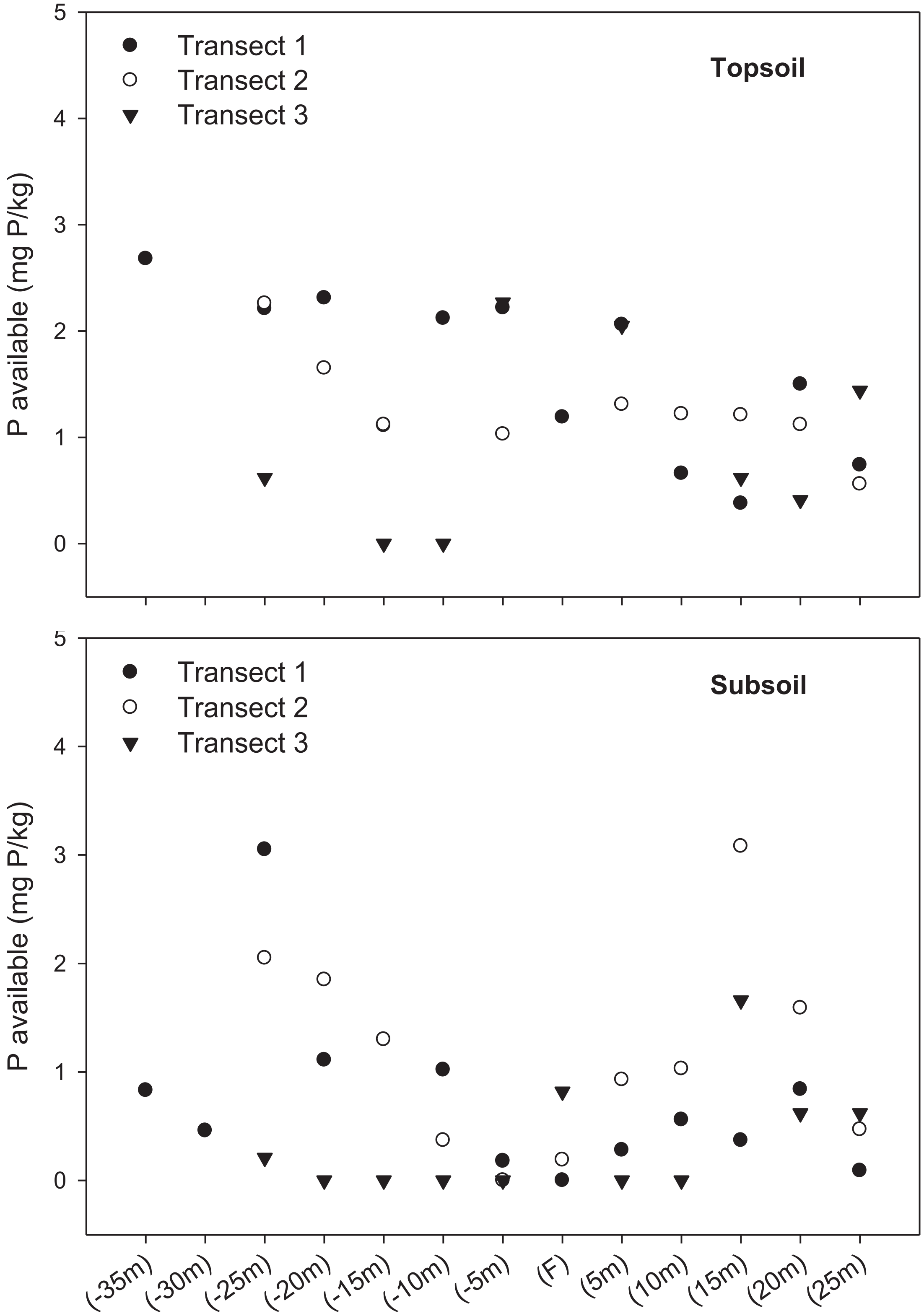


Figure 5.10 Available P (P-Bray 1) in top and subsoil along three transects

5.3.3 Soil fertility after 14 years of cultivation using re-sampling soil data at plot level

To enhance the information from the transect sampling results presented previously, herein, the re-sampling method shows the dynamics of total N along the slope after 14 years of cultivation by comparing the status of N and C over two time series. This comparison showed the effect of cultivated length, combining the compensation by external nutrient supply. Table 5.4 shows that during 14 years of maize cultivation, total N decreased in most of the fields. These results are in accordance with the results from the transect sampling. Only in 1 of 12 points (Nam Un 5 - Table 5.4), the total N increased slightly from 0.11% to 0.13%. In case of total C, 6 of 12 points show a decrease of C% after 14 years of cultivation. However, the other six points show a contrary trend in both upper and lower positions (Table 5.4). From field observations, these other points were close to the natural forest, which could be the reasons for the contrary trend in total C content.

Table 5.4 Comparison of total N and C in same plots the soil in 1998 and 2012, under maize fields with application of chemical fertilizer in Yen Chau district, NW Vietnam

Location*	Crops	Fertilizer applied	Field position	N total % in 1998	N total % in 2012	C % in 1998	C % in 2012
Nam Un 1	Maize	Yes	Upper	0.23	0.09	2.67	1.98
Nam Un 1	Maize	Yes	Lower	0.16	0.07	2.09	0.70
Nam Un 3	Maize	Yes	Upper	0.16	0.08	1.66	0.88
Nam Un 3	Maize	Yes	Lower	0.14	0.10	1.79	1.23
Nam Un 4	Maize	Yes	Upper	0.13	0.10	1.61	1.20
Nam Un 4	Maize	Yes	Lower	0.15	0.11	1.94	1.51
Nam Un 5	Maize	Yes	Upper	0.11	0.13	1.08	1.98
Nam Un 5	Maize	Yes	Lower	0.11	0.10	1.06	1.24
Ban Cang 12	Maize	Yes	Lower	0.11	0.09	0.96	1.32
Ban Cang 12	Maize	Yes	Upper	0.12	0.10	1.01	1.45
Ban Cang 13	Maize	Yes	Lower	0.10	0.08	0.96	1.19
Ban Cang 13	Maize	Yes	Upper	0.12	0.12	1.04	1.54

*Location names were used according to Wezel *et al*. (2002a), total N was significantly different between 1998 and 2012 at p-value of 0.01, while total C was not significantly different

5.3.4 Soil fertility distribution at watershed level

The previous sections presented the soil fertility conditions using conventional and well-established methods. This section firstly presents findings of correlations of total C and N with relative factors (land use type, slope, and soil type) (Step 1). From those results, two initial nutrient maps were created (Step 2). Before assessing the development of total C and N, the most suitable approach was determined. Combining initial nutrient maps, a spatial model tool was built and then applied for Chieng Khoi watershed (Step 3). At the end, this section presents the validation processes to assess the advantages and disadvantages of each approach (Step 4).

Step 1: Correlations of total C and N and other factors

Figure 5.11, Figure 5.12, and Figure 5.13 present the distribution of land use type, soil type, and the range of slope in relation to total C and total N, respectively. From those data, statistical results of the correlation are listed in Table 5.5. Concerning the correlation of total N and the considered determinants, there was a slight correlation with slope (r =0.03, R^2 = 0.56) and a stronger correlation with total C (r=-0.26, R^2 = 0.97). In the case of total C, findings showed a correlation of total C with land use type (r=0.771, R^2 = 0.641), slope (r=-0.434, R^2 = 0.645) and total N (r=-0.26, R^2 = 0.92). A strong relationship between total C and total N is shown in Figure 5.14. However, a significant relationship was found where total C was greater than 0.18% (R^2=0.91, p<0.01), whereas at low total C content, there was a lower correlation (R^2 = 0.74, ns) between total C and total N (Figure 5.14).

Table 5.5 Correlation coefficient and the coefficient of determination of C and N with land use, slope, soil type, C and N

Dependent variables	Land use	Slope	Soil type	N	C
N	No r -0.125 (R^2 0.016 RMSE 0.85)	Yes r 0.03 (R^2 0.56 RSME 0.65)	No r 0.061 (R^2 0.03 RMSE 0.85)	n.a.	Yes r -0.26 (R^2 0.97 RMSE 0.16)
C	Yes r 0.771 (R^2 0.641 RMSE 0.69)	Yes r -0.434 (R^2 0.645 RMSE 0.79)	No r 0.143 (R^2 0.02 RMSE 1.1)	Yes r -0.26 (R^2 0.92 RMSE 0.41)	n.a.

**na: not applicable*

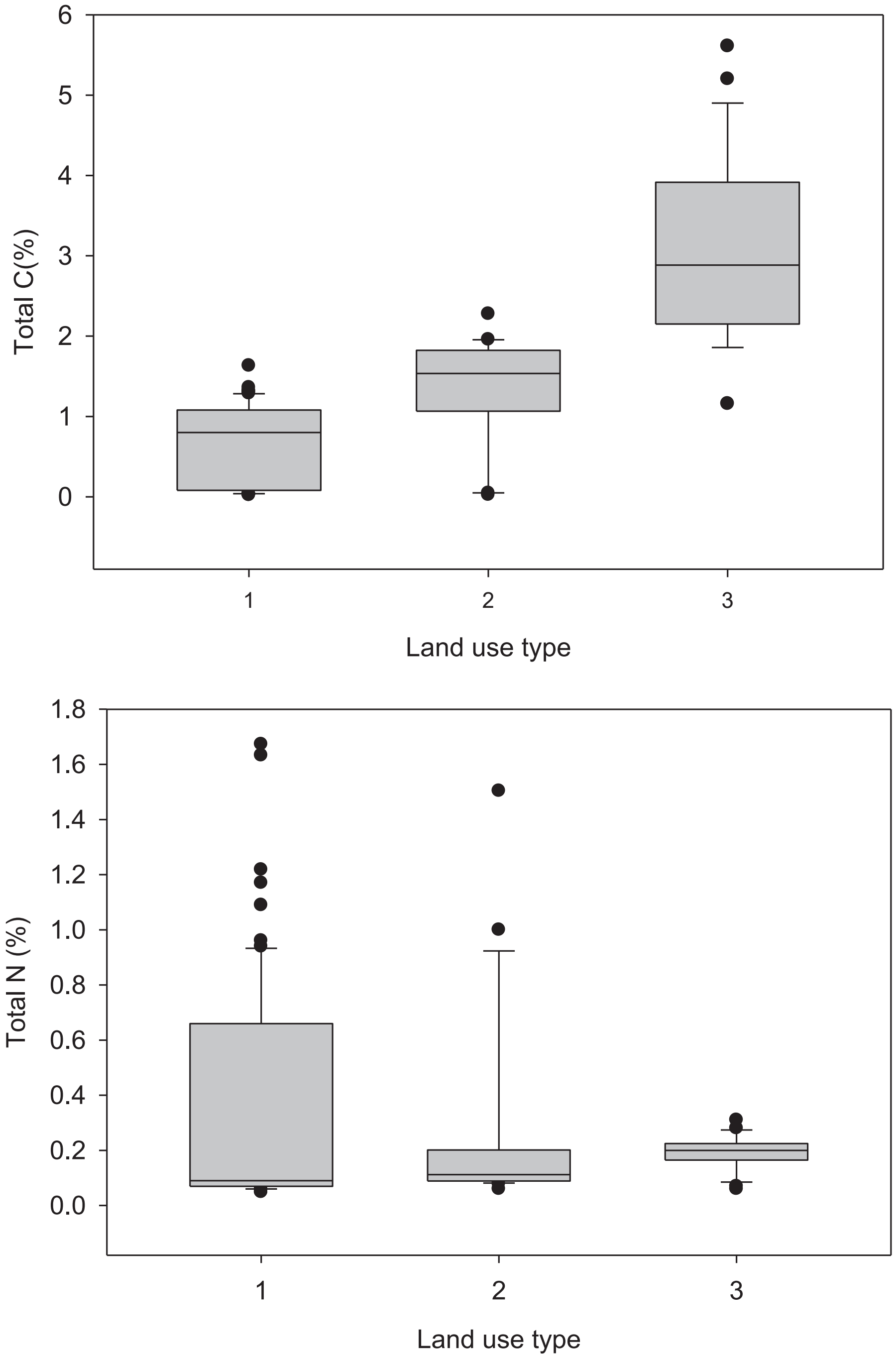


Figure 5.11 Distribution of total C (%) and N (%) in three land use types (1 represents the upland crop class, 2 represents the tree and secondary forest class, and 3 represents the paddy rice class), significant level of total C vs land use was $p<0.001$ no significance was found in case of total N.

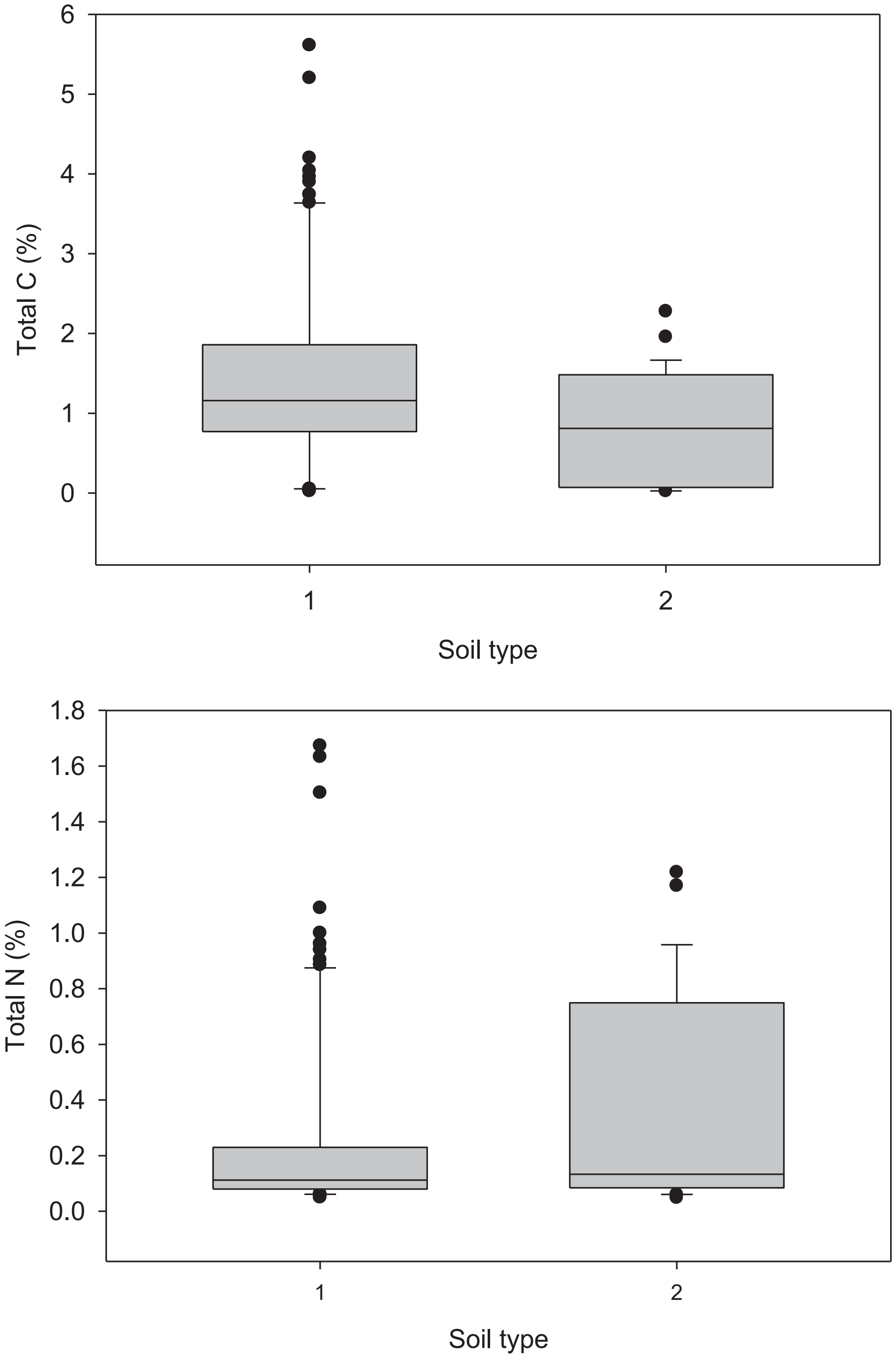


Figure 5.12 Distribution of total C (%) and N (%) in two soil types (1 represents ‘bad’ soil and 2 represents ‘good’ soil type as classified by farmers based on non-black colour (yellow or red) for bad soils and black colour for good soils (Chapter 4).

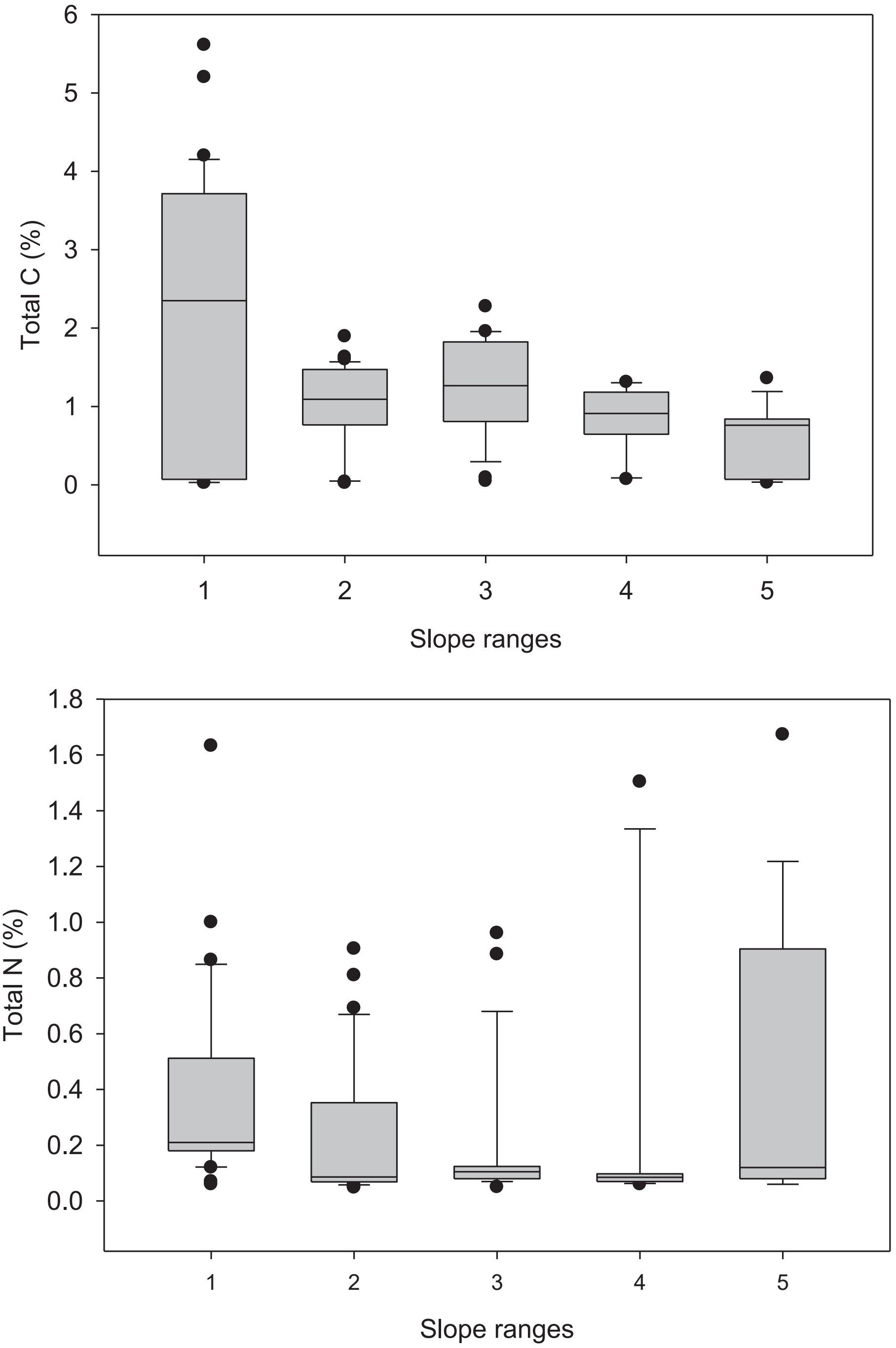


Figure 5.13 Distribution of total C and N (%) in 5 slope ranges (from 1 to 5 represent the ranges 0-10, 10.1-30, 30.1-38, 38.1-46, greater than 46 degrees, respectively). Significance level $p<0.001$ for both total C and N.

Besides the correlation of variables, the interaction between correlated factors was determined by constructing a statistic model of factors. In case of total C distribution, land use and slope variables, and their interactions and level of influence were further analyzed. In all cases, p-values were greater than 0.05, which indicated no interaction between slope and land use variables on total C distribution. Additionally, the weights of influence were similar (R^2 land use = 0.641, R^2 slope = 0.645). Therefore, a single regression model was possible to determine the total C distribution. The co-regression model was not possible.

Regarding on total N distribution, there was no interaction between the slope and total C. However, total C influenced the total N distribution stronger than the slope (R^2 slope = 0.56, R^2 total C = 0.97). Furthermore, Figure 5.14 shows a relationship between the distributions of total N with total C.

From the results mentioned above, several conclusions are drawn applied for the next steps:

- ⇨ The C distribution in the watershed was first simulated using land use, slope information based on findings of correlations.
- ⇨ Second, total N distribution was simulated using the relationship between C and N (Figure 5.14).

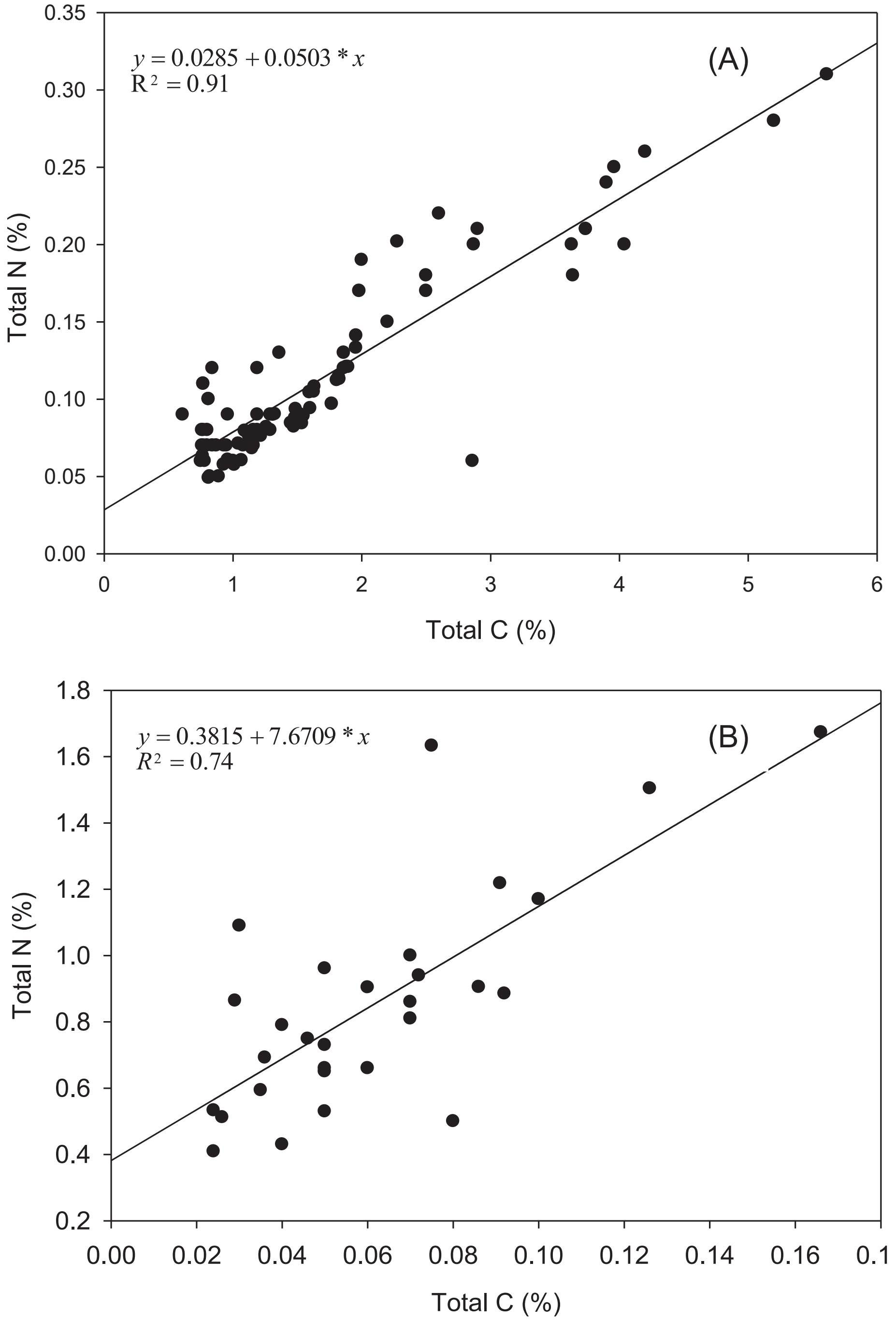


Figure 5.14 Relationship of total soil N and C within range of total C greater than 0.18 % (Significance level = 0.01) (A) and relationship of total N and C within range total C lower than 0.18 (%) (ns) (B).

Step 2: Mapping total carbon and nitrogen map of 1993

Applying the results from the previous section (Step 1), a sub watershed was selected to calibrate the DyCNDis model (Figure 5.15). This watershed was delineated from Chieng Khoi watershed from DEM using Soil and Water Assessment (SWAT) - ArcGIS Tool.

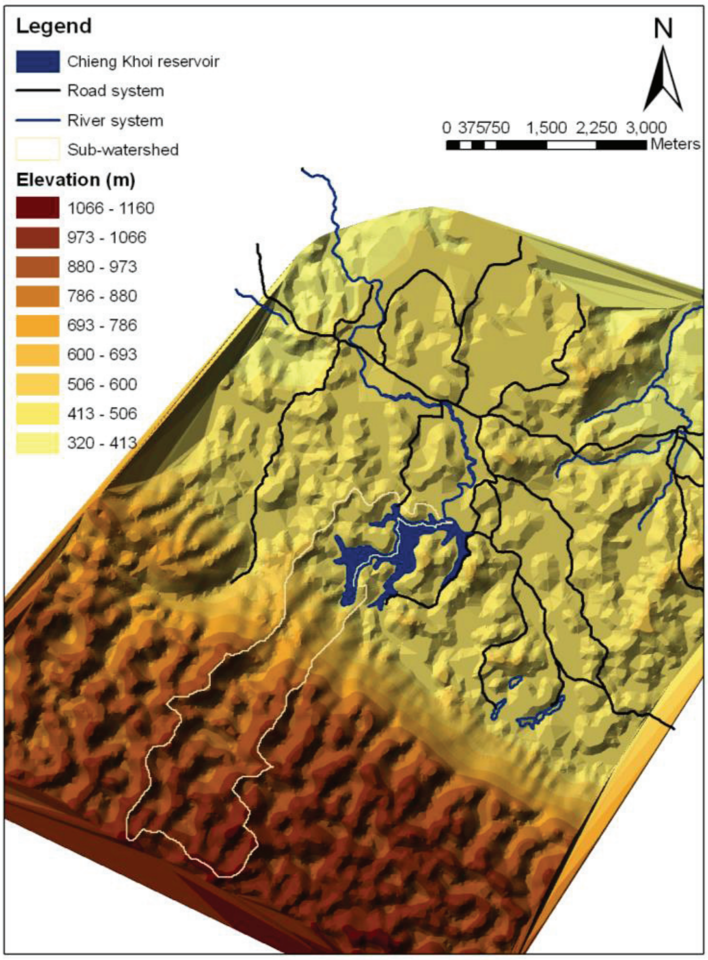


Figure 5.15 A selected sub-watershed, delineated from Chieng Khoi watershed using SWAT - ArcGIS software

Table 5.6 presents statistic models that show total C distribution simulated from land use type and slope. A total C distribution map of selected sub watersheds was constructed based on findings from the regression models; regression is based on the correlation between total C and land use and slope factors (Table 5.5). The total C distribution of 1993 was built (Figure 5.16). Total N distribution was computerized using the findings of the relationship between total C and total N. The regressions were applied from Figure 5.14. Thereafter, the total N distribution of 1993 was derived, which is shown in Figure 5.16.

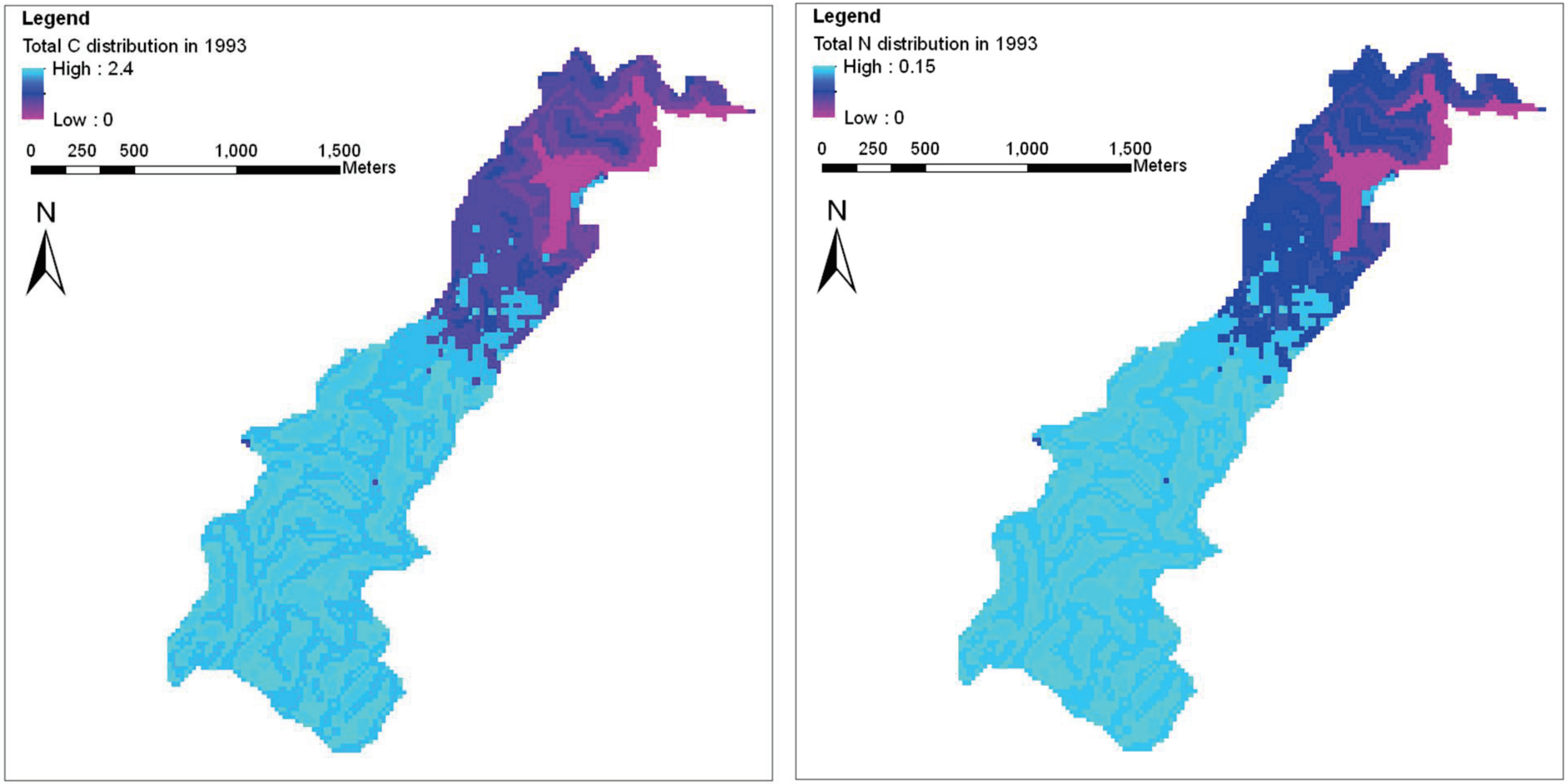


Figure 5.16 Total soil C (%) (left) and total N (%) (right) distribution of 1993 using PCRaster

Table 5.6 Statistic models simulating the correlation between total C and land use and range of slope

Variables	Parameter	Estimate	Standard error	p value
Land use	Intercept	3.134	0.148	<.0001
	Land use 1 (Upland crop)	-2.449	0.169	
	Land use 2 (Residential-secondary forest)	-1.835	0.199	
	Land use 3 (Paddy rice)	0.000	.	
Slope (degree)				
	Intercept	0.077	0.322	<.0001
	Range 0-20	0.946	0.565	
	Range 10-30	0.460	0.661	
	Range 30-38	0.978	0.603	
	Range 39-46	0.769	0.645	
	Range 47-90	0.681	0.631	

Step 3: Development of C and N distributions at watershed level

Step 1 had shown that total C development must be estimated first. After that, total N distribution was estimated using the relationship between total C and N. Step 2 previously provided the initial C map and total N in 1993. Before constructing a model tool to assess the development of total C and N, the most suitable approach was identified by comparison of the available data.

Herein, dataset 2 (transect sampling) and dataset 3 (from Haering *et al*., 2013) and partly of dataset 1 (field random sampling points with land use history) were selected to investigate the suitable approach (See data cloud in Appendix 5.3). Figure 5.17 shows the distribution of total C within the time of cultivation. Evaluating the data, dataset 2 and 3 showed similar trends of relationship between C distribution and time of cultivation. Both datasets demonstrated the reduction of total C in the soil after a period time of cultivation (Figure 5.17). Thus, two approaches were considered in this study:

(1) Use single transect data to assess the C development (Figure 5.18).
(2) Use transect data combined with secondary data from Haering *et al*. (2013). It was assumed that the secondary forest was already disturbed before 25 years (in the 1970s) and data were collected during the three transects where farmers re-opened the following

secondary forest (Figure 5.19). This assumption is based on information from previous Chapters. Chapter 3 found that land use changes in the forest began in 1973 when the artificial lake was established. Chapter 4 shows closer interactions with the forest after this period. The secondary forest was separated for the first time in 1993. On the other hand, the first interaction could have occured during the construction of the artificial lake in the 1970s, about 25 years before 1993.

Besides, selected points from dataset 1, which contained history of the points, were used for the validation process. Furthermore, as mentioned earlier, after assessing the development of total C, the dynamic of total N analyzed.

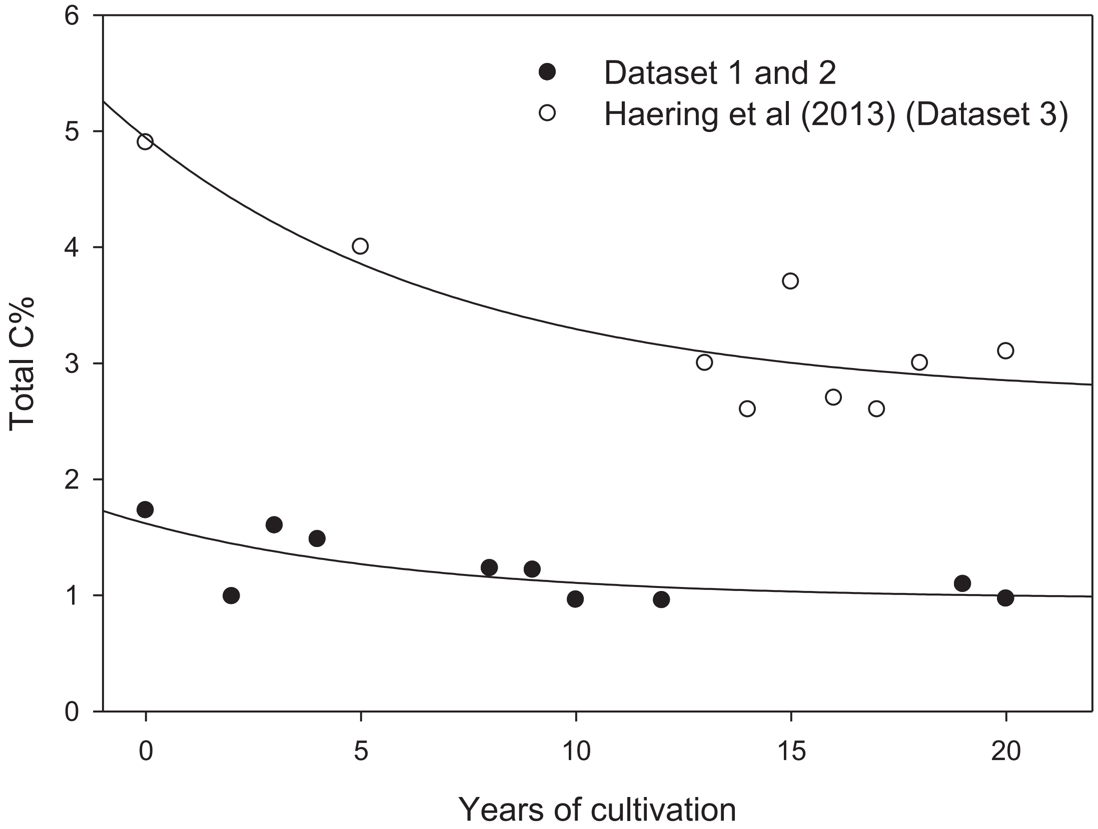


Figure 5.17 Comparison transect data and data from Haering *et al*. (2013) in Alisols and Luvisol

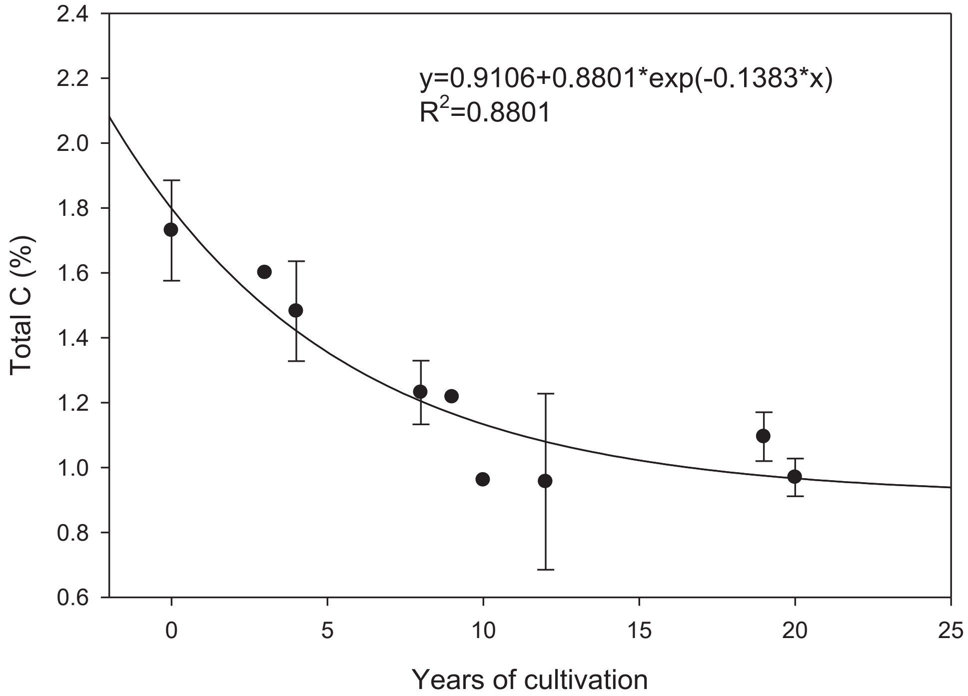


Figure 5.18 Relationship between years of cultivation and total C (%) in three transect sampling period

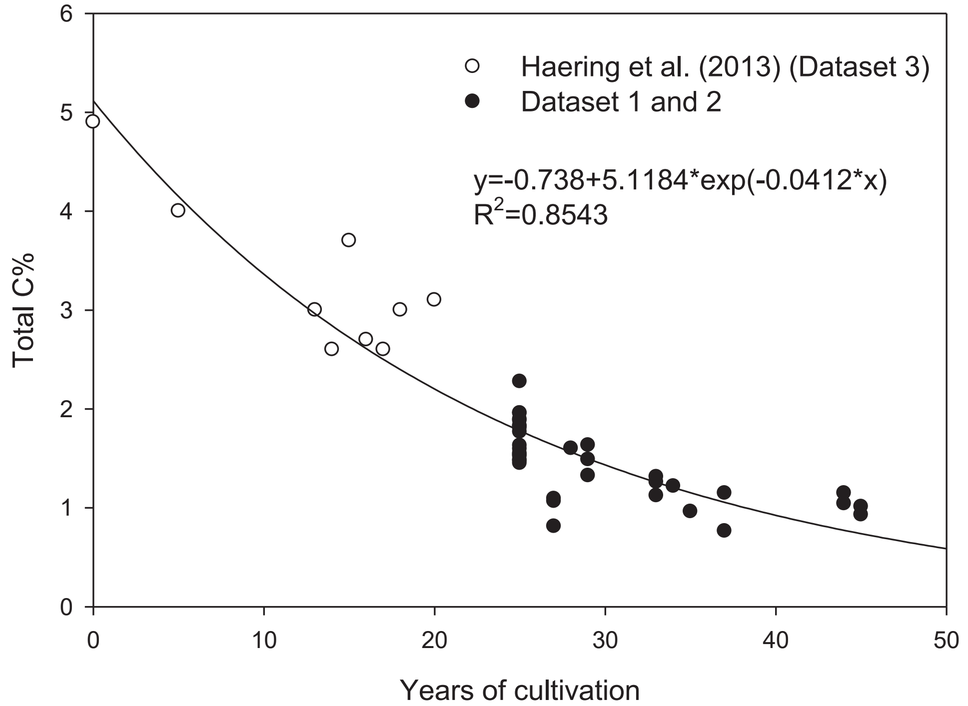


Figure 5.19 A combination of data of Haering *et al*. (2013) with the assumption that, initially secondary forest had been disturbed in the 1970s (25 years earlier) and the total three transect data were sampled where farmers opened the secondary forest

Total C and total N distribution development

In this section, two approaches are presented and compared and preliminarily validated. Approach 1 is the assessment of the development of C and N distribution using transect data, and approach 2 developed C and N distribution using transect data combined with secondary data with a comprehensible assumption.

Figure 5.20 shows the comparison between statistical results of total C development at test points after model exercises using the two approaches. Approach 1 shows closer outputs to the validation points compared with approach 2. Further validation results are presented in the next step. From statistical results, this study focuses on the output maps from approach 1.

Therefore, the DyCNDis model tool applied Equation 5.1 below to simulate total C (%):

$$Total\ C\ (\%) = 0.9106 + 0.8801 \times exp(-0.1383 \times Years\ of\ cultivation) \quad (5.1)$$

The total N (%) was simulated based on the relationship between Total C (%) and total N (%) as presented in Figure 5.14. A high concentration of total C (greater than 0.18%) was simulated as:

$$Total\ N\ (\%) = 0.00285 + 0.00503 \times Total\ C\ (\%) \quad (5.2)$$

A low concentration of total C (lower than 0.18%):

$$Total\ N\ (\%) = 0.3815 + 7.6708 \times Total\ C\ (\%) \quad (5.3)$$

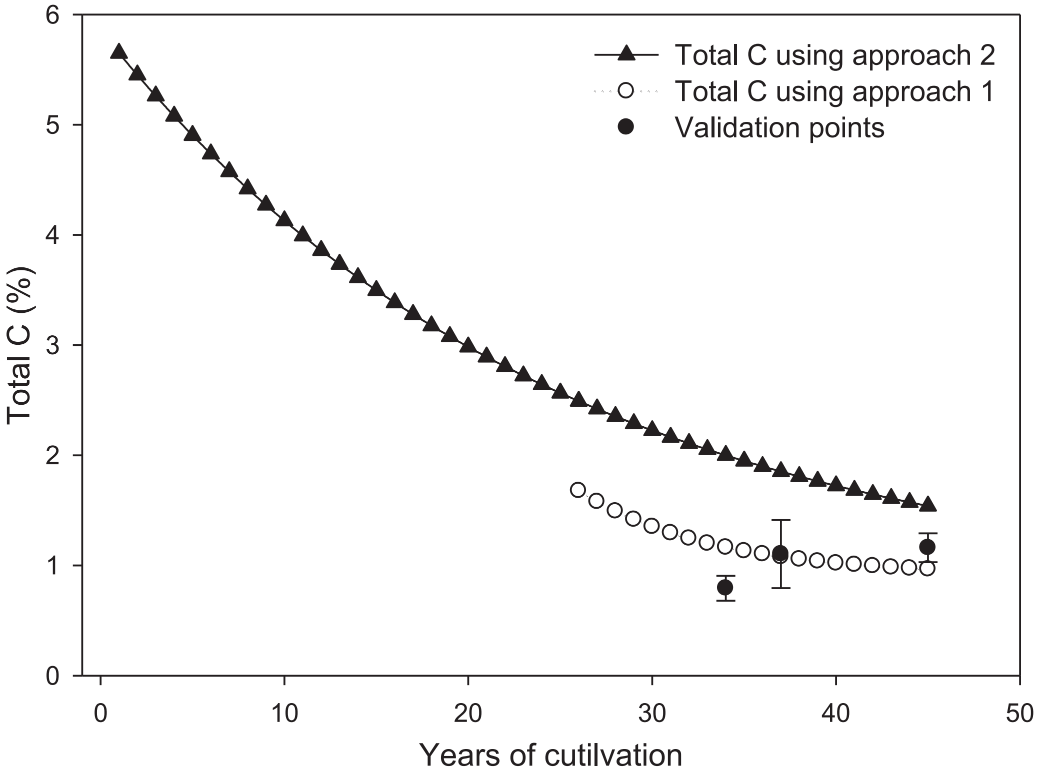


Figure 5.20 The prediction of total C development using two approaches based on (1) transect data alone, and (2) combined transect and Haering *et al*. (2013) data

Figure 5.21 shows the spatial distribution of total C (%) in the soil in the sub-watershed after 10 and 20 years of simulation using approach 1. Lower total C (%) concentrations developed closer to water body (artificial irrigation lake) and lower total C became more dominant in the watershed after 20 years of cultivation. A similar trend occurred in the case of total N distribution. Surrounding the lake, total N (%) in the soil declined after 20 years (Figure 5.22). Overall, after continuing cultivation in upland areas for 20 years, the areas with low values of both total C and N were enlarged in the same direction as the expansion of cropping areas. This, again, indicates further un-sustainable crop cultivation currently and the near future.

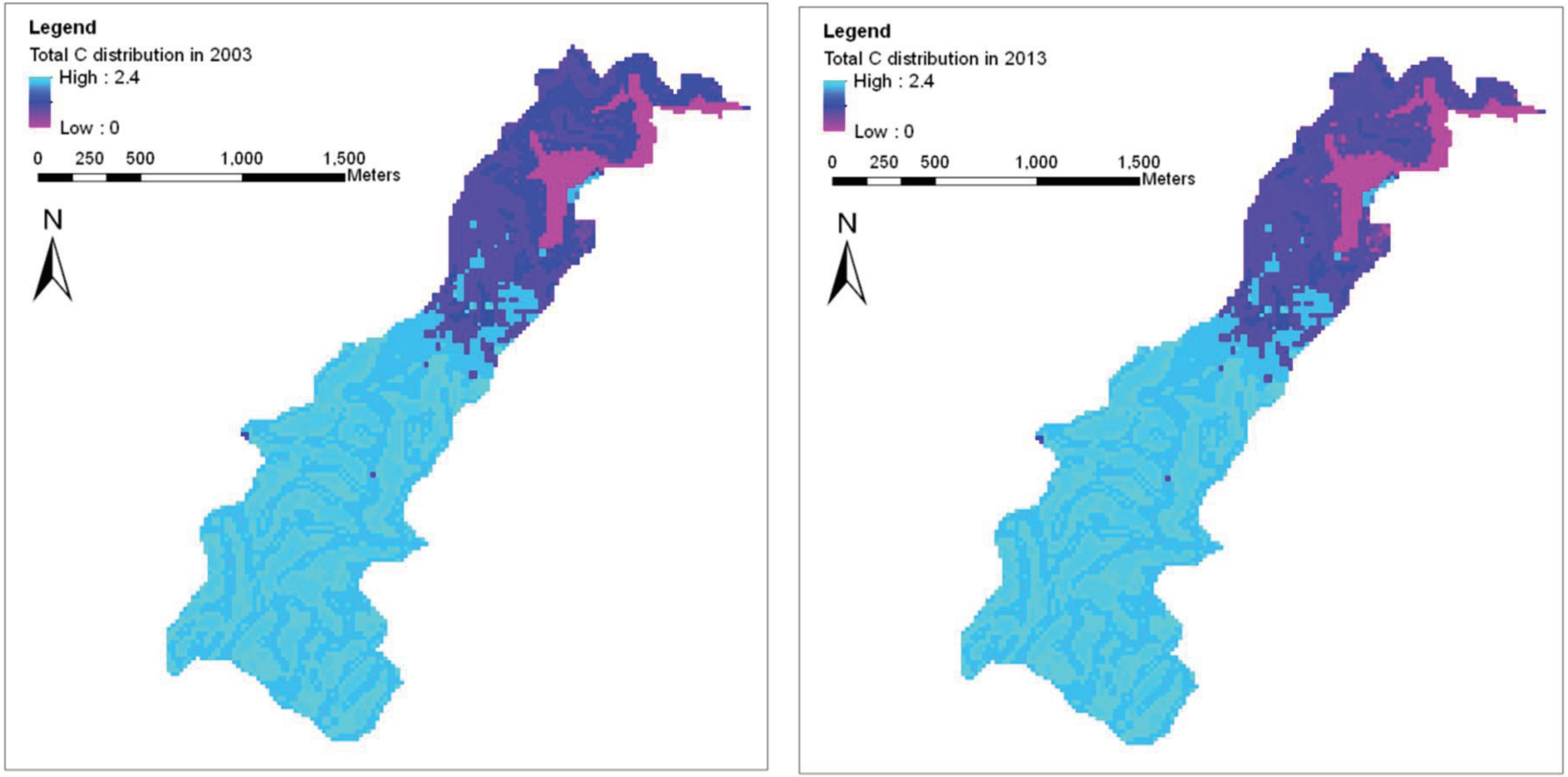


Figure 5.21 Simulated total C (%) distributions in Chieng Khoi watershed in 2003 and 2013 simulating using the DyCNDis model tool using approach 1, which was the approach using the transect data (Equation 5.1) for simulating the total C development in the soil

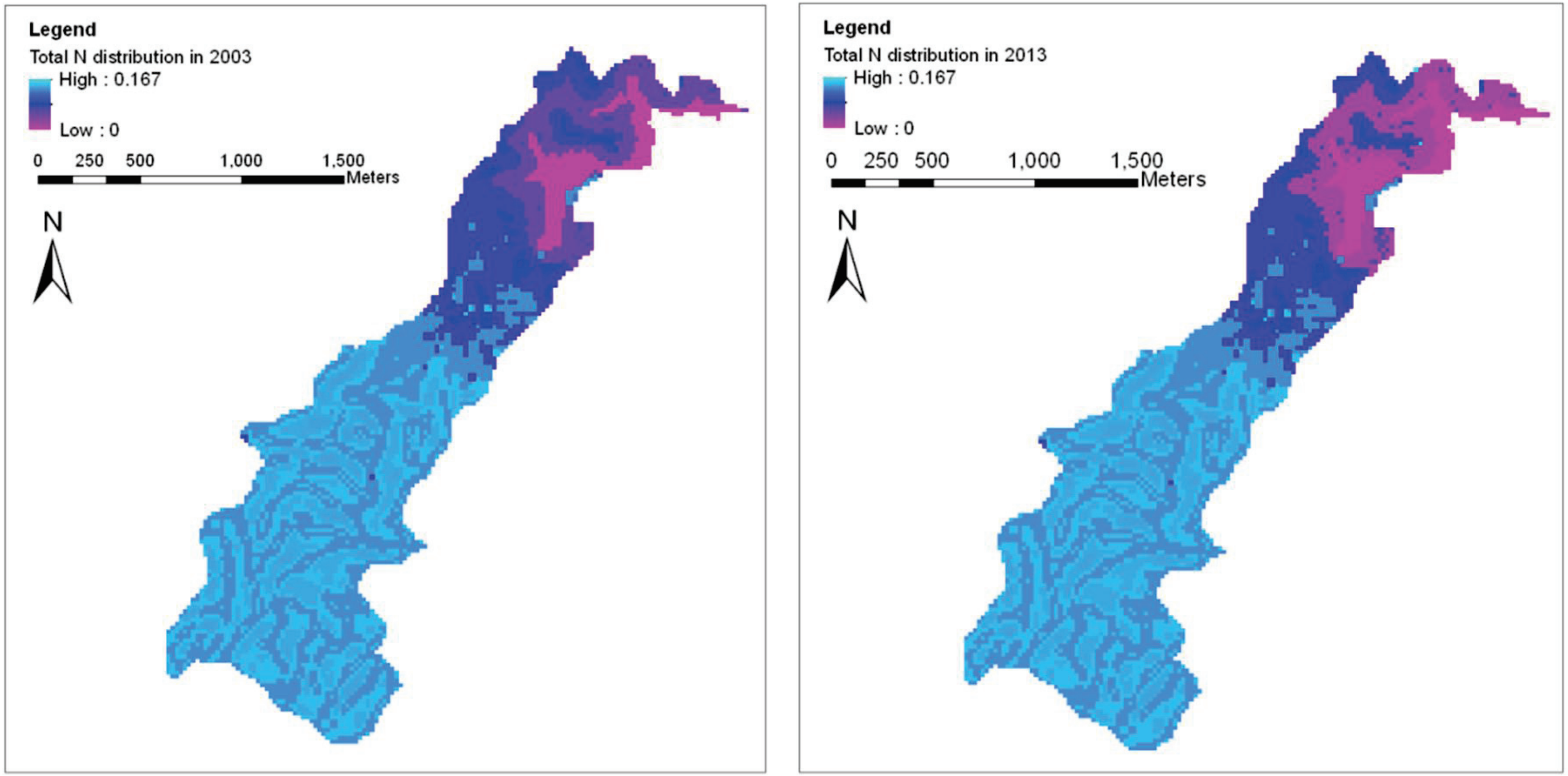


Figure 5.22 Simulated total N (%) distributions in Chieng Khoi watershed in 2003 and 2013 simulated using the DyCNDis model Tool using approach 1 which was the approach using the transect data (Equation 5.2 and 5.3) for simulating the total N development in the soil

Step 4: Validation

Approach 1 was validated as the most suitable for simulating total C distribution, resulting in an EF of 0.71 and an RMSE value of 0.42. In case of approach 2, the EF value was below zero (-0.35) with a higher RMSE (0.7). These results reveal the better fit of approach 1 compared measured data.

From validation results, this study proved that a simple model can be utilized estimate the development trend at an acceptance level. However, due to limited available data, this study does not recommend this model for simulating absolute values using either approach.

5.3.5 Identification of soil degradation hotspots

In the previous sections, soil fertility level was determined by the field measurement method and simulation using the model tool. Both methods show a reduction of nutrients in soils after continuous cultivation.

Table 5.7 Total C in top and subsoil in the plots that farmers considered abandoning cultivation in the following cropping season, were considered as having a high-level of soil degradation

Plot number	Total C in topsoil (%)	Total C in subsoil (%)	Crops
1	0.05	0.02	Maize, cassava
2	0.02	0.03	Cassava
3	0.04	0.05	Cassava
4	0.04	0.03	Maize, cassava
5	0.03	0.03	Cassava
6	0.04	0.03	Cassava
7	0.04	0.02	Maize
8	0.05	0.02	Maize
9	0.05	0.05	Cassava
Mean	**0.04**	**0.03**	
Median	**0.04**	**0.03**	

Table 5.7 shows the total C in top and subsoil in nine plots that farmers indicated that the soil was unresponsive (very poor) at the sampling period. All the points illustrated a low level of total C, was found under maize, cassava, and intercropping maize and cassava. The total average C level was 0.04% in the topsoil and 0.03% in the subsoil. Based on these findings, the average level of these total C concentrations represents a threshold of soil degradation for Chieng Khoi commune area. The threshold level was subsequentl used to identify soil degradation hotspots at watershed level.

For identification hotspot areas of the watershed, the validation process in the previous section showed that approach 1 was more suitable for predicting the total C at sub-watershed level within the limited dataset. Therefore, approach 1 was applied for the whole Chieng Khoi watershed. Figure 5.23 shows the total C distribution in Chieng Khoi watershed using approach 1 in two subsequent periods: 10 years after cultivation (in 2003); and 20 years after cultivation (in 2013). From a visualization, the lighter colours represent lower total C content in the soil. After continuous cultivation, the lighter colour became enlarged in the watershed; except forest and paddy rice areas, which were excluded from this study. Figure 5.23 presents a reduction of total C after 20 years of continuous cultivation on the agricultural areas all over the watershed. Figure 5.24 presents simulated areas where total C content in the topsoil was lower than 0.04%, when using the DyCNDis model tool for a period of 20 years. The water body areas were excluded, because the model exercise coded water body with a value of zero, although water body in this case could be the sink/pool of nutrients from erosion and sedimentation processes (see the Discussion section). Hotspot areas occupied 134 ha, accounting for 4.3% of total area of the Chieng Khoi commune (3,125 ha) and 18.9% of total upland cultivation area of the commune (708 ha). The area of commune and upland cultivation were used from the latest data in Chapter 3.

These hotspot degraded areas were scattered more in northern and northeastern parts of the watershed. More clusters of hotspots exist from the middle to the northeastern and west northern direction. Based on the study site descriptions in Chapter 2, the elevation was lower in the northeast and higher in the southern parts of the watershed. Herein, more cluster hotspots appeared in the lower elevation while scattering areas appeared in upper areas and surrounding the artificial lake, which was established in the 1970s in the middle of the watershed. This also indicated that the longer the cultivation, the more the total C content in the soil decreased. First more scatter appeared after a short time of cultivation, and then these areas aggregated after a longer time of cultivation. This study showed that after about 20 years of cultivation, hotspot areas largely consolidated, these areas were scattered widely in the watershed. This finding can support degradation mitigation processes, as, at later stages of degradation, measures to conserve soil fertility becomes more difficult than treating scattering spots.

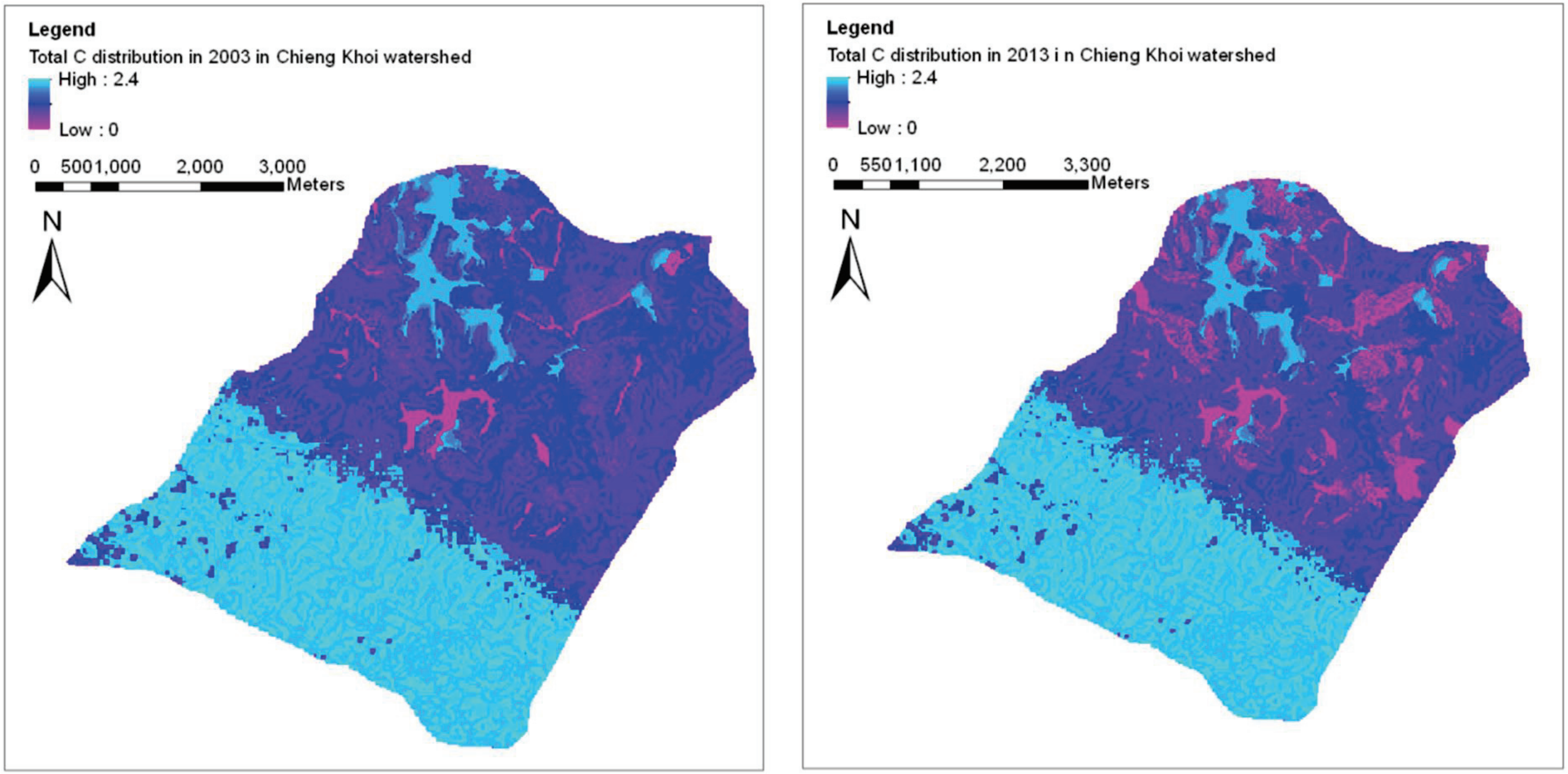


Figure 5.23 Total C and total N distribution after 10 years (2003) and after 20 years (2013) of cultivation in Chieng Khoi watershed using the DyCNDis model tool

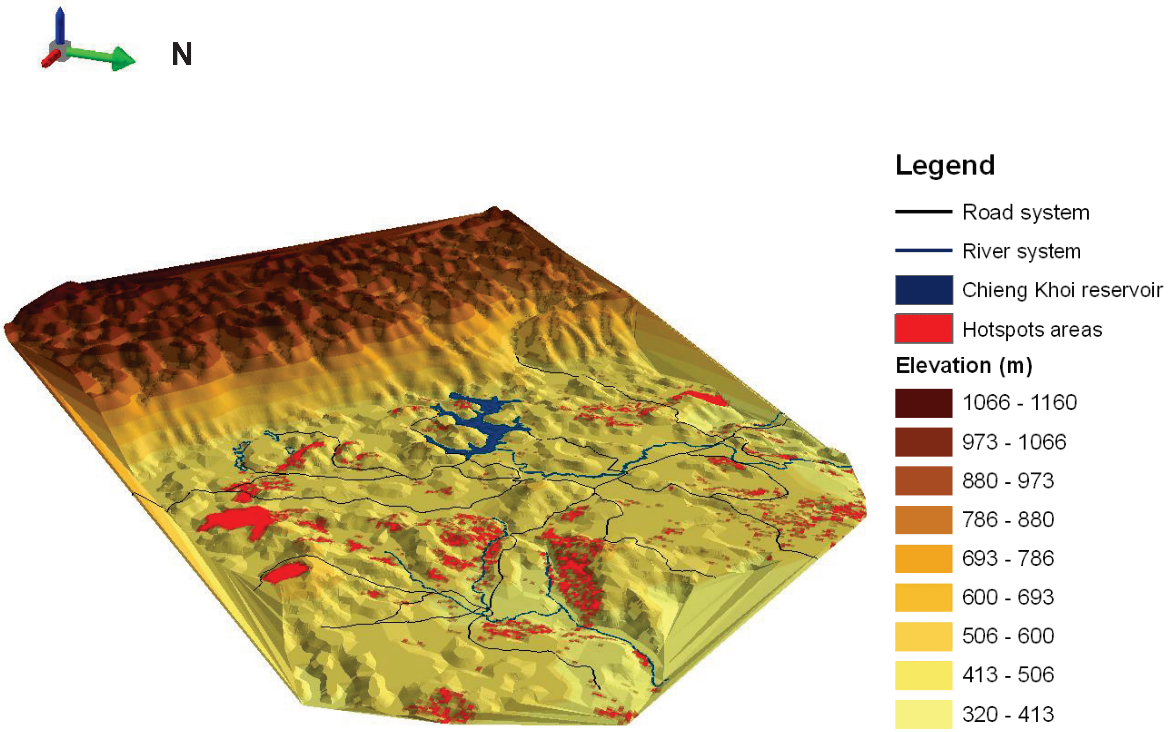


Figure 5.24 Hotspot areas after 20 years of cultivation in Chieng Khoi watershed using the DyCNDis model tool. Hotspots are those with a total C content below the threshold level of 0.04% defined by the plots that farmers indicated whereby no benefit can be obtained from crops in the next year of sampling. The green arrow direction is to the North

5.4 Discussion

5.4.1 Soil fertility development under mono cropping practice

The results from both transect and re-sampling represented, as the established conventional method, mostly showed the same trend of soil nutrient development. Soil fertility was lower after an extended time of cultivation. Haering *et al*. (2014) and Wezel *et al*. (2002a) showed similar findings in the reduction of total C and N concentrations under a long-term cultivation of mono cropped maize in NW Vietnam. The continuous tillage practice in slope areas could increase the amount of topsoil loss in the early rain season during the soil preparation period. Furthermore, the slash and burn practice could cause a reduction of biomass input from the aboveground maize stover after harvesting, which in turn could reduce the decomposition rate (Haering *et al*. (2014). Consequentially, a high loss of SOC and a lower decomposition could be the main causes of reduction in total C and N in Chieng Khoi watershed.

However, the re-sampling method showed several contrary results of total C content occurring at a few plots (Table 5.4). The total C content was higher after 14 years of cultivation. In all sampled plots, maize was cultivated continuously over 14 years without a fallow period. Additionally, residues from maize after harvesting were slashed and burnt, in most cases to reduce weeds before the new cropping season started. Moreover, maize production was practiced under rain-fed system conditions, with planting after the first heavy rain of the season in Yen Chau district. Nevertheless, these plots were close to the existing natural forest. Grazing cattle and buffalo were often found providing random dung distribution all across the region, and maize residues materials were still found in the field (Figure 5.25). This may explain the reason why at these plots, total C content was higher in 2011 compared with total C of 1998. This may be associates with the description from Lal *et al*. (1989) that soil fertility diminished slowly in the first phase of soil degradation in the first 10-15 years. After 20 years, the speed of soil degradation is assumed to be faster, because the soil structure has deteriorated from the previous stage (Lal *et al*., 1989). The soil in these plots could be the same trend but not following the same stage as the soil in transects and random sampling designs that were simulated using the DyCNDis model. The soil degradation of these plots could be at an earlier stage (Phase 1) of soil degradation while the DyCNDis model showes the dynamic of soils that were in a later stage of soil degradation (between phase 2 and 3).

Figure 5.25 Soil re-sampled in the plot within maize residues and near to forest in 2012

Combining the analysis process of soil samples using the re-sampling design, the detailed plot history and farm information of the five fields were collected from farmer interviews to compare them with findings from pedological analyses. Although mineral fertilizer was applied annually, its application seems unable to compensate for the erosion-induced N losses. Consequently, N levels were lower than in 1998 in all cases. The investigation on fertilizer applications over the last 14 years in the maize plots shows that all farmers applied from 100% to 367% (from 0.025 NPK kg/m^2 in 1998 to 0.092 kg/m^2 in 2012) more chemical fertilizer than in 1998 (Figure 5.26a). In 2012, in two of fields, the mineral fertilizer applications were reduced due to a lack of capital. Consequently, maize yields remained almost constant until 2005. After that, yields slightly increased (Figure 5.26b). The farmers indicated that they planted more hybrid varieties since the 2000s instead of improved varieties (improved varieties relate to open-pollinated varieties that can be used again in next seasons). Using hybrid varieties could be the reason that maize yields doubled from around 5 t/ha in 1998 to 11 t/ha compared to yields in 2012 according to information from farmers (Figure 5.26b).

This information shows that increasing cultivation on steep slopes could lead to an increase in the processes of the depletion of soil fertility further in the upper slope. Soil fertility was solely alone affected after a prolonged time of cultivation. Schweizer *et al*. (2017) further showed that soil aggregate stability was also strongly influenced under the long-term continuous maize cultivation.

Additionally, hotspots susceptible to soil degradation were found all over the watershed (Figure 5.23, Figure 5.24). After 20 years of cultivation, the model exercise showed a large area with a low value of total C equivalent to 18.9 % upland cultivation areas. The model results show that using the mono-cropped maize, that could lead to increase to large areas which may not sufficient for planting crops in the near future in Chieng Khoi commune. Furthermore, soils could be further deteriorated physical and chemical properties to the stage the point-of-no-return without a soil conservation method (Lal, 1989). For instance, Clemens *et al*. (2010) indicated that sandy soils were degraded from cultivation practice did not recover even after 50 years of fallow.

Additionally, the question remains where do soil nutrients go? In this study, we focused more on agricultural areas, not at the water body, which was excluded from the model exercise. However, water bodies play an important role for sedimentation and nutrient transportation. Chapter 2 described the topography characteristics of Chieng Khoi watershed. It shows that the artificial reservoir is located at a higher elevation, which supplies the water for the river and irrigation channels for downstream paddies. Therefore, the river flows from higher to lower elevations. Increasing cultivation on the slopes could lead to increased sedimentation and siltation in the lake, due to erosion from the higher elevation to lower areas, which also affects the river system in case of Chieng Khoi watershed. Schmitter *et al*. (2011) showed a high concentration of organic C from upland fields loaded into paddy rice fields with irrigation water. Moreover, Slaets *et al*. (2014) developed a method used to quantify (Saets *et al*., 2016a) organic C and N from erosion and irrigation to rice fields and then to the river system. For instance, in the case of sediment associated with organic carbon, the amount of 1.35 Mg per year was captured by paddy rice fields while 0.40 Mg per year was exported (account of 22.9% of total 1.75 Mg per year eroded from surrounding upland fields), and, in case of sediment associated nitrogen, 0.20 Mg per year was captured by paddy rice fields while 0.07 Mg per year was exported (account of 26% of total 0.27 Mg per year). These studies show that a high share of nutrient budgets from upland fields are captured by paddy rice fields, but still a high amount is exported before arriving to paddy rice fields and is being further exported to the river.

Similar processes could occur if cultivation is expanded to the surroundings of the artificial lake. Consequently, the cultivation in the upper slopes could be the cause of losing a high amount of nutrients through erosion and sedimentation, exporting them to lower areas. Brant *et al*. (2016) estimated the erosion under different land uses in this system and findings from Weiss (2008), showing major sedimentation processes from cropping fields surrounding the artificial lake in Chieng Khoi watershed. Therefore, the lake was a pool of sediment from surrounding fields and then further contributed them towards lower areas, such as paddy rice fields and finally to the river before leaving the watershed (Slaets *et al*., 2016a). The linkage between the upland and lowland should be considered in future research, especially considering erosion and sedimentation processes surrounding the artificial reservoir.

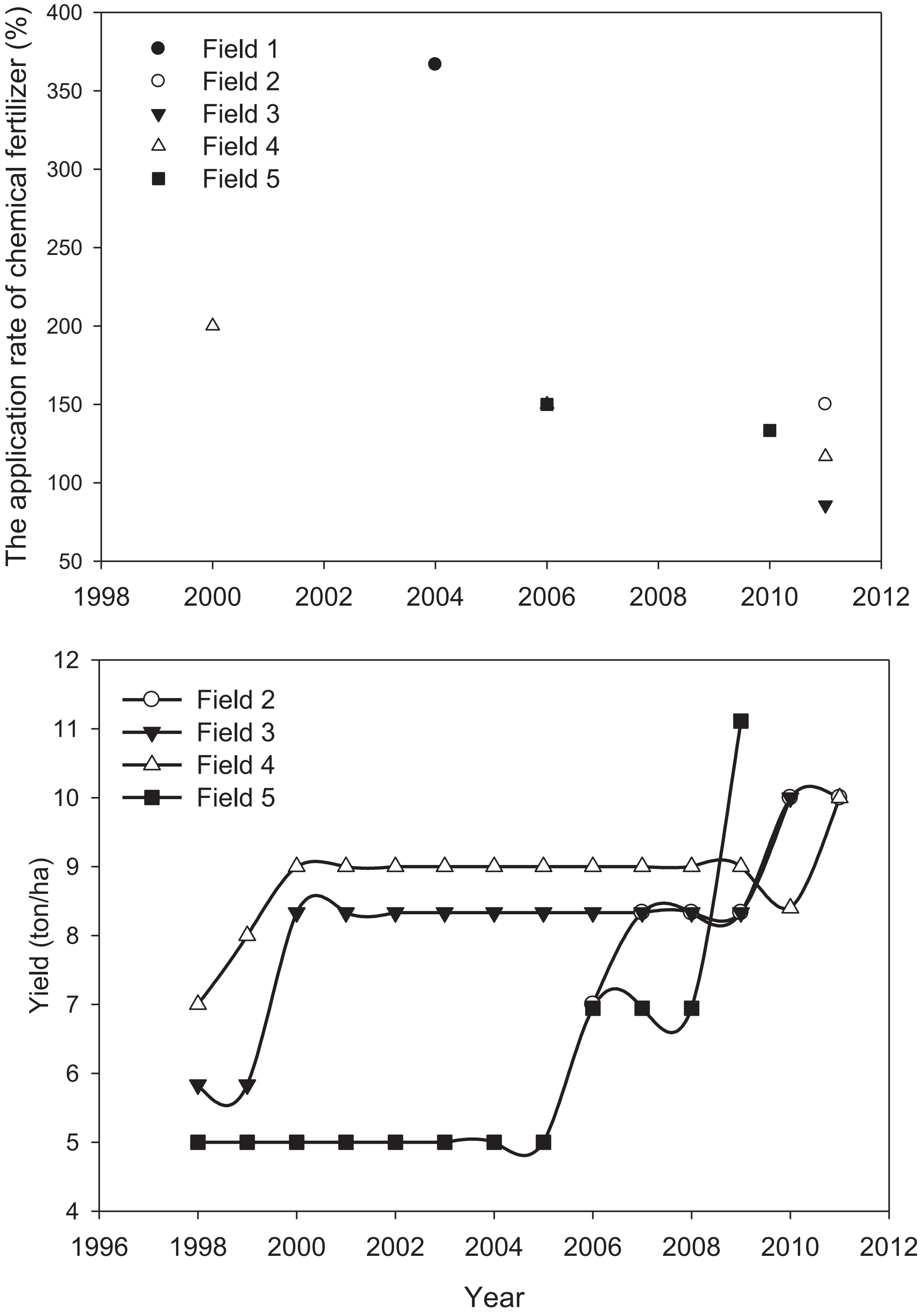


Figure 5. 26 (a) Application rate of chemical fertilizer (Urea) comparing with the amount in 1998, and, (b) yield in maize fields in Yen Chau district, NW Vietnam. Data were collected at the same locations as data of 1998 (Wezel *et a*l., 2002a)

5.4.2 Potential and limitations of using a model approach

The model exercise showed the potential use of two approaches to simulate the development of total C and N at watershed level. Figure 5.20 shows the validation data compared to simulated values. However, if the validation dataset was larger, approach 2 used to predict the long-term development of total C and N, because there was a lack of data at the early stage of cultivation that caused the failure of validation for using approach 2 (Figure 5.20).

Besides, using transect data results as a component process for a simple model tool was a suitable solution for such conditions, i.e. limited available data. There has been a trade-off between a complex and a simple model (Sohl and Claggett, 2013 – discussed in Section 4.6). In validation, a simple model could bring significant difference between observed and estimated values (Bellocchi *et al*., 2010). However, the trend of the development was the main target that could be assessed using the simple model. In the more complex model, detailed and single processes required a larger dataset. A component process plays a role in the black-box approach, which was criticized by many researchers but also recommended as an approximate method to assess soil degradation (Lal *et al*., 2000), especially under difficult conditions within multiple processes (Nikolic *et al*., 2010). This approach included many minor processes that could contribute a share to a large sum of impacts. For example, Slaets *et al*. (2016a) showed that before contributing to paddy rice, a small amount of the N was made up of overland flows from surrounding upland fields and a small amount was over flow from the reservoir. However, in total there was a large amount of N exported out of the system before arriving to the paddy rice fields. The major focus of this study was the trend of nutrient depletion, which could be clearly assessed.

Moreover, a modelling approach was generated from results using a conventional method. The actual component processes were observed and investigated; meaning, what actually occurred in the field. Thus, even without the absolute values of total C and N content development in the soil, the trend of its development was successfully identified. This approach allowed for an illustration of the development at the spatial level instead of the point level. The spatial variability of soil properties could be simulated by geostatistics integrated with mid-infrared spectroscopy, but again, a large soil dataset would be necessary for the calibration process (Cobo *et al*., 2010). Therefore, this modelling approach is recommended for a pre-survey or for predicting future trends for small watersheds with limited data availability. Lastly, the approach developed in this study could reduce the costs of an intensive soil sampling data collection.

5.4.3 Actual and future situation of soil degradation on sloping land

In the study region, the soil degradation issue was raised, not just from academics. Farmers themselves are also aware of this issue from losing crop productivity and their observation of the changes in soil colour. This study showed a trend leading to soil degradation at both plot and watershed level. In the case of plot level, farmers observed a changed soil colour after few years planting crops on their fields (Table 5.2). The sloping areas in particular; total C and N declined significantly/drastically after a longer cultivation period (Figure 5.8 and Figure 5.9). Wezel *et al*. (2002a) and Haering *et al*. (2013) showed similar trends in case of OM and soil nutrients by the distance from the forest along a gradient. At watershed level, hotspot areas with a low level of soil nutrients were expanding all over the watershed (Figure 5.24). According to Lal (1989), soil degradation by decreasing nutrients and from crop productivity that continues to occur in the mountainous regions in NW Vietnam is a serious issue.

5.5 Conclusion

In this Chapter, based on the results from a conventional soil sampling method, a simple model was developed to assess the dynamics of changes in total N and total C concentrations at watershed level. Findings showed a decrease of total C and N after a prolonged period of intensive cultivation on sloping land. The model exercise results illustrated the locations that could be threatened the most by soil degradation. The results could support land use planners and farmers to identify locations that are extremely susceptible to soil degradation. Those areas are most likely need to urgently benefit from soil conservation measures to retain soil fertility. Overall, this study provided potential tools that could derive information to improve the development of agriculture towards more sustainable agricultural production system in mountainous regions.

Chapter 6. General discussion

The overall aim of this study was to understand the causes and dynamics of LUC, to assess impacts of LUC on soil fertility and to derive implications for natural resource management at landscape-level. A deeper understanding of LUC and its causes and drivers provide information to support decisions for a more sustainable agricultural development in the sloping lands of NMR of NW Vietnam.

This chapter discusses opportunities of using a mixed method approach relying on qualitative and quantitative components to overcome data-limited situations. It continues in discussing the role of local stakeholders in mitigating soil degradation and further highlights goal conflicts of food security and rural agricultural development for the case of NMR. A focus on how the newly developed landscape modelling tools can be used to link historical land use perspectives to future LUC trajectories is discussed. The chapter closes by resuming the PhD thesis hypotheses and eliciting recommendations for further studies in this field of research.

6.1 How to compensate data limitations in rural environments to provide information for decision support

Building on the examined local LUC trends (Chapter 3) and other regional studies, it can be expected that LUC will continue in the near future in NW Vietnam, indeed, also in many other mountainous regions of Southeast Asia, e.g. North Thailand, South China and Laos (FAO, 2017; Truong *et al.*, 2017; Yang *et al.*, 2016, Lippe *et al.*, 2014; Friederichsen *et al.*, 2010). Common for all these areas is an increasing population and a transformation of traditional cultivation systems to become intensified and market-oriented. Especially in such rural and data-limited environments, information of LUC dynamics and its impacts are important for decision support and natural resource management.

The presented dissertation demonstrated the potential of an integrated mixed methods approach, combining qualitative and quantitative methods to assess LUC and its impact on soil fertility. For example: quantitative methods such as RS analyses and household interviews were adopted in Chapter 3 and 4; qualitative methods such as Participatory Rural Appraisal (PRA) were used in farmer group discussions as presented in Chapter 3, 4 and 5; and, outcomes of field soil sampling and laboratory analyses were combined with PRA as shown in Chapter 3 and 5. Two newly developed modelling tools were used to simulate LUC trajectories and to examine soil degradation hotspot areas (Chapter 4 and 5). Building on local stakeholders' information in formulating 'farmer decision rules' that can be used to simulate LUC was very meaningful, because local decisions will be one of the more important factors that will drive LUC (Lippe *et al.*, 2011; Wezel *et al.*, 2002. This is relevant because farmers are key local stakeholders that will continue driving future LUC patterns. The combination of analysed RS data and historical information as derived from local people could be used to construct a LUC modelling tool. Furthermore, decision rules on farming practice were further beneficial in developing more detailed historical LU maps compared to remote sensing analysis alone. The study illustrates that PRA can enhance and support historical data in LUC research at local level such as watersheds (Lippe *et al.*, 2014; Castella *et al.*, 2007; Castella *et al.*, 2005; Lusiana *et al.*, 2011; Magcake- Macandong *et al.*, 2011; Endo *et al.*, 2017).

In remote and fragile areas with limited data availability, modelling tools are promising in decision support for local stakeholders. But even though LUC model tools often require large amounts of data, the two newly presented model tools (Chapter 4 and 5) were able to simulate the main trends of LUC as well as the dynamics of soil fertility over a long period of intensive cultivation, building on a mixture of qualitative and quantitative information. The study shows that for the purpose of trend simulations, a simple model tool can be suitable for the identification of key LUC trends, as well as to assess how current or past management practices may risk landscape sustainability in the long term. The newly developed modelling tools show their potential for a data-limited watershed in particular, as they were able to:

- simulate the trends of LUC, based on food demand increments by increasing population,
- assess developments of soil properties in the past and explain causes of current situations, such as the reduction of total C and N under an intensive cash crop system,
- test alternative management scenarios or soil conservation methods, e.g. replacing mono-cropped maize farming with agroforestry systems, which is especially important for NW Vietnam where soil degradation is becoming an eminent threat to the long- term natural resource base (Wezel *et al.*, 2002; Clemens *et al.*, 2010; Tuan *et al.*, 2014; Marohn *et al.*, 2013; and Le Van Lanh, 1994).

The presented combination of qualitative and quantitative methods provides a decision support tool that can derive meaningful implications for land use planning and environmental management. This is important because agricultural development often conflicts with natural resource protection goals (Minh, 2010; Nguyen *et al.*, 2015). Likewise, the combination of qualitative and quantitative data did not only bridge information gaps for the case study area, but also revealed a pragmatic research approach that can operate in data-limited study areas. By this means, the use of mixed approaches was helpful for decision support on how to combat the ongoing pathways of LUC and associated environmental resource degradation in NMR of NW Vietnam.

6.2 Could local stakeholders become key players in mitigating soil degradation?

This study shows that local stakeholders, such as farmers, play an important role in all processes of LUC and contribute either to the preservation or degradation of natural resources. Hence it becomes imperative that local farmers should be understood as key in mitigating soil erosion and further prevent soil degradation, which would lead to more sustainable agricultural production systems over the long term. For example, Lockeretz and Anderson (1990) argued that sustainable agricultural research should involve farmers because farmers originally contributed to improve many agricultural systems, but their activities could be the causes of the deterioration of environmental services. A recent study by Raymond *et al.* (2016) even defined farmers as 'landscape stewards' due to their local understanding and management of natural resources. According to Keil *et al.* (2008) and Wezel *et al.* (2002), the NMR in Vietnam is a good example of a sensitive agro-ecological zone, as this region consists of steep slopes with cleared forest that leads, with the combination of current farming practices, to soil erosion and land degradation. In such a complex and dynamic environment, policies and government agencies play a significant role in supporting financial and market infrastructure in rural areas as well as providing innovative information through extension systems. Although national farming policies in Vietnam serve as a general orientation for local farming practices, farmers are ultimately those who make farm management decisions often based on prevailing soil conditions and the overall local resource availability. To enhance the role of the local stakeholders towards actions in preventing soil degradation, policies could be implemented to allow other organisations such as NGOs and private companies in promoting farming technologies that can offer a basket of (sustainable) management options for farmers. Furthermore, potential future negative long-term impacts must be considered, such as market availability, price volatility, and the overall potential of natural resources for management intensification.

Government initiatives must increase their efforts in supporting local stakeholders by improving current extension service concepts. For example, many extension programmes were launched in Vietnam that implemented 'Farmer Field Schools' to provide farmers with information of new techniques and management systems, such as hybrid crops or direct seeding, to name just two. But these schools must be further acknowledged as important local knowledge transfer centres that can improve ecological understanding and raise awareness of soil degradation processes (Minh, 2010; Diez, 2016). However, most farmer schools were recently closed as international and government funding ended.

Saint Macary *et al.* (2010) indicated that a secured land title could positively influence the decisions of farmers in applying long-term soil conservation techniques. As such, a promising approach would be to combine an increasing share of locally secured land titles in combination with maintaining Farmer Field Schools as a part of governmental extension service tasks.

By this means, rural development policies could be developed that secure local land use rights but also call for farmer's responsibility to implement soil conservation techniques. For instance, farmers who adopt long-term soil conservation techniques could receive, as an incentive, a long- term land title right compared to the current period of twenty years. On the other hand, farmers could lose their land rights if they do not implement soil conservation techniques accordingly. Such measures can be monitored by remote sensing techniques such as drones or satellite images. However, development and implementation of new policies often require long processes.

6.3 Rural agricultural development under a changing environment: From historical experience to future planning

Building on a quote from the philosopher George Santayana (1863 – 1952), it can be argued that "those who cannot remember the past are condemned to repeat it". This may also imply that those who learn from the past will have a better future. When converting this into a science-based approach, by learning from past experiences, research can provide recommendations that avoid mistakes and promote management options that will be successful into the future. Against this background, historical data are important to explore causes and facts of present LUC patterns as well as to estimate potential future patterns (see Chapter 3.4.3). Historical information not only contributes to a better understanding of LUC dynamics and its causes and facts at watershed-level (Chapter 3 and 4), but is also important at regional and national levels too.

Additionally, climate change is becoming a more eminent threat on a global scale and can be regarded as one of the consequences of LUC (Van Noordwijk *et al.*, 2017b; Van der Putten *et al.*, 2016). Climate change impacts are becoming particularly relevant for agricultural development in developing countries due the increasing occurrence of extreme weather events, such as droughts (FAO, 2016). Extreme events may show stronger impacts in rural areas as local livelihoods highly depend on agricultural production. Especially sloping areas in mountainous regions in Asia, which are more vulnerable to soil erosion and flash foods as a result of extreme rainfall events (Wezel *et al.*, 2002; Tuan *et al.*, 2014; Van Noordwijk *et al.*, 2017b). Hence, sustainable agricultural development pathways have to be promoted and implemented as early as possible to ensure the security of farmers' livelihoods and to protect the natural resource base in the future.

Under the threats of global environmental change, which can be understood as an umbrella term of LUC and climate change, questions arise about how to achieve sustainable natural resource management while competing with rural development (Ruten *et al.*, 2014; Illias *et al.*, 2013; Minh *et al.*, 2011; Saint Macary *et al.*, 2010). By using modelling tools, the application of soil conservation techniques can be used for preliminarily testing within several options in mitigating soil degradation towards sustainable agriculture (Marohn *et al.*, 2014). This represents a test for alternative management before applying it to the field. The option confirms the motivation of this study in that modelling tools provide an option for minimising the risk of introducing management alternatives into sensitive regions such as remote mountainous and rural areas. In the future, the Vietnamese government will still play a significant role in the agricultural development by continuing to change the environment (Diez, 2016; Nguyen, 2012). A long-term project (The Upland Program) has provided some recommendations to the government to improve rural infrastructure, market environment, and develop more options for managing risk (Froehlich et al., 2013). Particularly, the detailed findings of this study show a historical overview of LUC, the development of soil fertility, as well as giving a prediction of soil degradation hotspots. Therefore, such information elaborates suggestions considering farmer management and land use decisions for more sustainable ways forward that could be led at the government level:

- Policy should support education in agricultural sectors from university to village levels. At village level, farmer schools should be reopened and integrated as a regular part of local extension services.
- Current promotion approaches to implement soil conservation techniques to mitigate soil degradation must be improved. Most importantly, implementation should focus on local stakeholders at the centre of innovation adoption.
- Best practice concepts that proved successful in other regions should be further promoted, e.g. Vườn- Ao- Chuồng (VAC), which refers to an integrated production system combining farming with livestock, fish-ponds and home gardens. In particular, further engagement of livestock in agricultural systems in NW Vietnam could be an option for a better adaptation of soil conservation techniques in NW Vietnam (Mavrakis, 2012). Furthermore, within a smallholder size with strong and relatively large extended family in NW Vietnam, the VAC system could be combined with Biogas production under farmer family group

management to enhance efficiency.

- Considering the continuing changing environment, policy makers should be prepared and take action to develop approaches for more sustainable agricultural production under the threat of climate change. For example, land use planners should evaluate models such as ‘smart farming adapting with climate change’ which is described in the FAO report on the case of Africa (2016) and CIAT report (2017). These ex-ante tools and approaches could be the first step for adapting agriculture to support more sustainable agricultural developments in the long-term.

6.4 Hypothesis posed

Hypotheses were posed as follows:

- The first hypothesis stated that LUC could be assessed by analysing RS data combined with farmer information. The study proved that the long-term LUC information was able to be captured by using a hybrid land cover classification approach (Chapter 3).
- The second hypothesis presented stated that a newly developed food requirement based model would be able to simulate LUC. This hypothesis was partly proven as the validation showed that the model was able to simulate within the acceptance level of validation. However, the newly developed model was able to simulate the trend of LUC more pronounced than correctly simulating the absolute magnitude of individual land use type transformation (Chapter 4).
- The third hypothesis stated that soil fertility will decrease over the long-term in the study area. This could be confirmed by the reduction of total soil C and N after continuous maize cultivation for 20 years, and was further simulated with the newly developed modelling tool (DyCNDis). Using the outputs from the field survey, the model predicted the same trend of soil fertility, but not the absolute values for the change in total C and N in soils (Chapter 5).

Thus, the developed methods and models are suitable for trend simulations in the limited-date watershed, for example, supporting land use planners and farmers by providing information of hotspots and building future scenarios from that information Next section will provide further information for future research.

6.5 Suggestions for further research

The NMR has a long history of high environmental risks and often provide low profits due to intensive use of tropical soil and landscapes vulnerable to soil degradation (sloping land with large areas of steep slope). This study focused on understanding the past and future areas of dynamic agricultural land and its impacts on natural resources under data-limited conditions. Beside the recommendations to the government level that were already discussed in Section 6.3, further research should:

- *focus on the application of soil fertility mitigation and the adoption of local farmers building on the lessons learned from the recent past.* For example, Saint Macary et al. (2010) and Minh (2010) explained the reason for unsuccessful soil conservation methods, which were already the focus of previous regional development programmes. On the other hand, Tuan et al. (2014) developed soil conservation methods that were partly designed together with local stakeholders and could be applied by local farmers promising a higher adoption rate than the previously implemented government programmes. Minh et al. (2011) further argue that many farmers in NMR Vietnam have introduced different innovations since the 1950s, such as cropping and farm management, but with a stronger orientation towards food security and income generation.
- *focus more intensively on assessing different forms of adoption strategies that would ultimately integrate local farmers in the research process.* Hence, further research should consider different forms of farmers' motivation processes that were described by Minh *et al.* (2011) as:
    - 'Adoption for political and social rewards',
    - 'Adoption for local consumption',
    - 'Adoption for cash income', and
    - 'Adoption for a sustainable environment'.

These could form principal research study guidelines that would be not only be 'environmentally- sound, but would meet farmers' needs', e.g.

- *Improve land right security* (Tuan *et al.*, 2014; Saint Macary *et al.*, 2010) *and responsibilities of farmers to achieve implementation soil conservation techniques.*
- *Integrate a simple model with other models* to simulate erosion and

productivity of crops under alternative systems that could be an option for addressing both positive and normative aspects of the dynamics of LUC (Brown *et al.*, 2013).

- *Improve the database* by enlarging data collection from the first phase of the study period by including historical data collection at plot level. This means enlarging the details and quality rather than quantity of data points. The more detailed the data points, the more they can improve the lack of data for model validation as described in Chapter 5.4.2.
- *Avoid bias during historical data collection*, for example, farmers indicated during PRA that most soil characteristics and weather conditions were much better in the past. For improving and avoiding these factors, questions posed during group discussions should exclude evaluation criteria and comparisons, but rather focus more on the description of events, stories and information, instead of rating or comparing past and current issues.

This study was conducted at commune level. Verburg *et al.* (2013) stated that the local vision of agricultural development can lead to important deviations from regional to global trends. The interaction between local solutions could not only meet their own tasks, but further also provide a better understanding of sustainable intensification on larger scales. The presented results should be considered because sustainable development in fragile rural areas such as NW Vietnam is always challenging for local political decision makers and scientists. This brings insightful knowledge for land use planners and stakeholders to avoid the more serious negative impacts on natural resources in the future.

List of publications

This section presents the overview of publications (including article, book chapter, and conference contributions) which have been done during this PhD study.

1. Article

Title: A software coupling approach to assess low-cost soil conservation strategies for highland agriculture in Vietnam

Abstract

Soil degradation is an environmental process mainly caused by land use decision-makers that has substantial feedback effects on livelihoods and the environment. To capture these feedback effects and the resulting human-environment interactions, we used an agent-based modelling approach to couple two software packages that simulate soil, water and plant dynamics (LUCIA), and farm decision-making (MP-MAS). We show that such a software coupling approach has advantages over hard-coded model integration as applied by most other comparable studies, as it facilitates combining of increasingly sophisticated individual models and can achieve a well-balanced representation of agricultural systems. Using a numerical application for a small mountainous watershed in northwest Vietnam we show the challenges in model coupling, calibration and partial validation, and explore the properties of the coupled model system. Scenario analysis covering the introduction of low-cost soil conservation techniques indicates that some of these techniques would have an impact on soil erosion, maize productivity and household income levels in the study catchment area under current conditions. However, maize yields and the adoption of soil conservation appear to be sensitive to the price of mineral fertilizers, with lower fertilizer prices impeding the adoption of soil conservation measures. The software coupling approach was able to capture interactions between decision-makers and natural resources, as well as the level of spatial variability, in more detail than the individual models. Still, the greater number of endogenous variables and thus degrees of freedom increased the importance of validation and testing parameter sensitivity of the results.

Keywords: Agent-based modelling, Integrated modelling, Land use change, Multi-agent systems, Soil degradation

<u>Published as:</u> Marohn, C., Schreinemachers, P., Quang, D.V., Berger, T., Siripalangkanont, P., **Nguyen, T.T.**, Cadisch, G. 2013.A software coupling approach to assess alternative soil conservation strategies for highland agriculture in Vietnam. Environmental Modelling & Software, 45; S. 116-128. DOI:10.1016/j.envsoft.2012.03.020.

2. Book chapter

Book title: Sustainable Land Use and Rural Development in Southeast Asia: Innovations and Policies for Mountainous Areas

Chapter title: Integrated Modelling of Agricultural Systems in Mountainous Areas

Abstract

People's decisions with respect to agricultural land use and management practices have had a major impact on natural resource degradation in Vietnam and Thailand for centuries. In addition to an ever-increasing population density, economic transformation and market integration have exacerbated the pressure on natural resources in the rural areas of both countries, particularly during recent decades. From its beginning, the Uplands Program has sought to address research questions related to the impacts of land use management on natural resource degradation at the landscape level in Southeast Asian countries, as have researchers linked to the Program in the area. Integrated modelling of land cover and land use change, as a means to simulate effects which extend over various spatial and temporal scales or scientific domains, began to play a more prominent role within the Uplands Program after 2006. This chapter highlights modelling approaches and decision support tools used as part of the Uplands Program to investigate various research questions at the human-biophysical interface, and will compare modelling approaches, looking at the issues of land use and management impacts from different angles, whereby the different focuses used by each model have resulted in different levels of detail and precision in various respects.

Published as: Marohn, Cadisch, Jintrawet, Buddhaboon, Sarawat, Nilpunt, Chinvanno, Pannangpetch, Lippe, Potchanasin, Quang, Schreinemachers, Berger, Siripalangkanont, Thanh Thi Nguyen (2013); Springer, Heidelberg; Sustainable Land Use and Rural Development in Southeast Asia: Innovations and Policies for Mountainous Areas; 490pp; S. 379-449

3. Conferences

In the frame work of this PhD study, eight related topics were presented scientific conferences. Herein, topics are listed combining with abstracts.

Topic 1: Assessing Impacts of Long-Term Maize-Cultivation Using the 'Dynamic of Total Carbon and Nitrogen Distribution' Model

A poster presentation in "Future Agriculture: Social-ecological transitions and bio-cultural shifts" - TropenTag conference in Bonn, Germany in September 2017

Abstract

Ongoing population growth spurred the demand of agricultural land further accompanied by agricultural intensification in Northwest Vietnam. This trend led to an expansion of mono-maize cultivation areas to steep sloping environments with the result of severe soil degradation. Against this background, the presented study evaluated the development of soil fertility under mono-cropped maize cultivation in Northwest Vietnam to offer decision support for natural resource management at watershed level. The specific objectives were: (1) determining the dynamics of total Nitrogen (N_{Tot}) and Carbon (C_{Tot}) under current maize cultivation regimes along selected transect gradients, and (2) developing the spatially-explicit Dynamic of total Carbon and Nitrogen Distribution (DyCNDis) model to assess potential impacts of C_{Tot} and N_{Tot} development after long-term and intensified maize cultivation patterns using Chieng Khoi watershed as an example.

Three transects were delineated to assess N_{Tot} and C_{Tot} content in topsoil along a 25-30 m slope gradient, and to determine crop history focusing particularly on the duration of maize cultivation period. Building on transect results and further auxiliary data, the spatially-explicit DyCNDis model tool was developed using the relationship of cultivation time and C/N_{Tot} content as basic modelling unit. After successful model validation, DyCNDis was used for a soil degradation hotspot analysis, aiming to identify those areas at watershed-level which have the highest risk of soil degradation under the current mono-cropped maize cultivation regime.

DyCNDis identified 134 ha of hotspot areas that are prone to soil degradation after 20 years of continuous maize mono-cultivation, accounting to 19% of the total 708 ha of upland cultivation areas in Chieng Khoi watershed. DyCNDis suggested that particularly those areas require increased attention by government authorities and local farmers, calling for soil conservation measures to retain soil fertility in the long run.

Keywords: Carbon, nitrogen, long-term maize, model.

Published as: Thanh, N.T., Lippe, M., Marohn, C., Vien, D.T., Cadisch,G.. Assessing Impacts of Long-Term Maize-Cultivation Using the 'Dynamic of Total Carbon and Nitrogen Distribution' Model. (2017). “Future Agriculture: Social-ecological transitions and bio-cultural shifts”, September 20 - 22, 2017, Bonn, Germany.

Topic 2: An Integrated Approach to Assess Land Use History in a Watershed in Northwest Vietnam

A poster presentation in "Resilience of agricultural systems against crises” - TropenTag conference in Göttingen,Germany in 2012

Abstract

In the past decades, the introduction and extended cultivation of hybrid maize and hybrid cassava provided higher income for farmers but replaced traditional crops, such as upland rice and local maize and cassava varieties, in the upland area which surrounds a reservoir in Chieng Khoi, Yen Chau district in mountainous Northwest Vietnam. Furthermore, new cultivation areas are still expanding into protected forest, grazing areas and fruit tree plantations. Consequently, primary forest on the upper, steep slopes is illegally cleared for hybrid maize and cassava cultivation.

Detailed Geographic Information System (GIS) based classification of land uses is difficult when crops are planted during the same period of the year and reflect similar spectral bands. Therefore, this study aimed to reconstruct ground cover maps, to distinguish characteristic upland land uses before and after the reservoir was installed and to determine the sediment contribution of different land uses to the reservoir. Hybrid classification combining remote sensing data (aerial photograph 1954, Landsat 1973 and 1993) with farmers' information were used to obtain detailed classification of past land cover.

Compound specific stable isotope (CSSI) analysis of fatty acid methyl ester (FAME) and fallout radionuclide (FRN) measurements were chosen to support and match the data obtained by remote sensing - GIS and farmer interviews. The integration of FRNs and CSSI-FAME markers enables apportioning sediment bodies to land use specific erosion rates. This is achieved through the following steps: 1. FRN are used to distinguish sediment strata at the deposition sites. To receive an estimate of sediment volumes, a statistical analysis of sediment strata is based on spatially distributed sediment profiles. The approach is capable of converting measurements of FRN soil inventories to estimate soil erosion and deposition rates. 2. The land use specific mass accumulation represented within a stratum is estimated by multiplying the mass of the

stratum (FRN) by the land use specific soil proportion (CSSI-FAME). 3. Linking the land use specific mass accumulation to land use information from GIS allows the evaluation of land use specific erosion dynamics corresponding to the sediment strata.

Keywords: Compound specific stable isotopes, fallout radionuclides, GIS, land use history, remote sensing

Published as: Thanh, N.T., Brandt, C., Marohn, C., Rasche, F., Lam, T.N, Vien, D.T., Cadisch, G. (2012). An Integrated Approach to Assess Land Use History in a Watershed in Northwest Vietnam. "Resilience of agricultural systems against crises". Tropentag, September 19 - 21, 2012 in Göttingen, Germany.

Topic 3: Assessing role of farmers' decisions on land use change and its impacts on long term soil fertility in North West Vietnam using a reverse modelling approach

An oral presentation in "International Scientific Conference on Sustainable Land Use and Rural Development in Mountain Areas", Hohenheim University, Stuttgart, Germany in 2012

Abstract

Since the end of the French war in 1954, landscapes in Northwest Vietnam have seen drastic changes in land use. Increased food demand by a rapidly developing population, migration from lowland to upland areas, agricultural innovations, shifting consumption patterns and policy changes induced large-scale changes in land cover. Main trends were de- and later re-forestation and illegal logging as well as agricultural intensification on sloping land, expressed mainly as reduced fallow periods. Consequences of these practices were increased rates of soil erosion and continuous decline of soil fertility, particularly in organic matter and nitrogen contents. With 75% of the total area being sloping land and given a subtropical climate with intensive rainfall, soils in mountainous Northwest Vietnam are particularly sensitive to rapid degradation.

The overall objective of this study was to assess the impact of land use change (LUC) on soil fertility in Chieng Khoi commune, Yen Chau district, Northwest Vietnam, since 1954, and to reconstruct this process using a landscape modelling approach. This would show, whether the model is able to capture the relevant processes in the soil over a longer period and at the same time serve as a calibration and validation of the model for further projections into the future. To achieve this, we needed to (1) reconstruct land use/land cover history since 1954, (2) gather/reconstruct data on soil fertility in different landscape positions, (3) calibrate and validate the model.

To reconstruct land use/and cover history since 1954, hybrid classification of remote sensing data combined with socio-economic data was used. Aerial photographs in 1954 and 1999 , LANDSAT 1973, 1993 and 1999 (US Geological Survey) and LISS III 2007 shaped with a PAN (Panchromatic from National Remote Sensing Agency - NRSA, India) were classified. LUC during years not covered by remote sensing data was reconstructed through cartographic modelling based on expansion algorithms using aggregated agricultural statistical data combined withfarmer decision rules and information on crop rotations obtained during interviews in 2011. Focus group discussions with young and old farmers, transect walks and individual household interviews (n=22) were conducted to collect information on crop rotations and farmers' preferences. Along four transects from the forest into cultivated fields, soil samples were taken and analysed for organic C, total N, available P and texture to assess soil fertility. A georeferenced dataset of soil data taken in 1998 (Wezel *et al* 2002a) was used as a reference point in history, while the original state of soil fertility under forest in 1954 was assumed to have been similar to current soil fertility in untouched forest areas in the watershed. Further validation will be obtained from repeated sampling in 2011 at the data points used in 1998.

Our results show the expansion of agricultural areas from village cores into the surrounding forests, crop rotations on the newly converted fields during later years and changing cropping patterns over time. Transect data from the forest into agricultural areas, used as false time series that reflect the decline of soil fertility over time, confirmed assumptions of declining Corg and Nt. Land conversion rules and algorithms, and the resulting land cover maps are presented and linked to soil fertility data.

Published as: **Thanh, N.T.,** Marohn, C., Chukwumah, I., Lam, T.N, Cadisch, G.. (2012). Assessing role of farmers' decisions on land use change and its impacts on long term soil fertility in North West Vietnam using a reverse modelling approach. International Scientific Conference on Sustainable Land Use and Rural Development in Mountain Areas 16-18 April 2012, University of Hohenheim, Stuttgart, Germany.

Topic 4: Assessing impacts of farmers' land use change decisions on long term soil fertility in North West Vietnam using a reverse modelling approach

A poster presentation in "Development on the margin: -TropenTag conference in University Bonn, Germany 2011

Abstract

During the last two decades, farmers in Son La province, North West Vietnam, have reduced and finally omitted fallow periods when replacing the traditional swidden system with intensive maize monocropping. Land use in upland areas has been in a transition from upland rice, cassava and local maize varieties as staple crops towards hybrid fodder maize as cash crop. Despite higher expenses for seeds, synthetic fertilizer, pesticides and draft power, a hybrid maize boom has been observed in the region since 2007, which can be explained by the high productivity, revenues and direct cash income related to this crop. At the same time farmers are aware that intensification is not sustainable and soils are heavily degraded, mainly through water erosion when cultivating on steep slopes.

The study assesses impact of land use and management on soil fertility during 20 years under known land use change using a landscape model. Based on field information on land use, history trends of soil fertility are reconstructed in the simulations and model outcomes are validated against recent field measurements of soil fertility related parameters.

Aerial photos (1954, 1999) and satellite imagery (1999, 2007, 2010) were used to create land use maps using visual interpretation and supervised classification, past ground truth points supplemented by transect walks and key person interviews. More detailed information on cropping history and farmers' decisions were obtained from semi-structured household interviews and focus group discussions. Soil samples were collected along transects that reflect expansion of cultivation areas over time. Soil carbon, texture, available N and P were analyzed and used for validation of the LUCIA (Land Use Change Impact Assessment) model.

Results of this study will serve as model validation and a basis to assess alternative land use options. Assessment of soil fertility changes under land use change will support land development agencies at local and national level when planning sustainable development in the area under current challenges, e.g. the rubber boom. In a second instance, data on land use history and farmers' decisions will be used to develop a decision-making module for the LUCIA model.

Key words: Farmers' decisions, soil fertility, Vietnam, maize, LUCIA.

Published as: **Thanh, N.T.,** Marohn, C., Chukwumah, I., Lam, T.N., and Cadisch, G.

(2011). Assessing impacts of farmers' land use change decisions on long term soil fertility in North West Vietnam using a reverse modelling approach. In Tropentag 2011. University Bonn, Germany.

Topic 5: Assessment of soil conservation strategies in upland agriculture: Interdisciplinary case study in Tat hamlet, Da Bac district, Hoa Binh province, Northern Vietnam

An oral presentation in "The Soil and Water Conservation Society - SWCS 65th Annual International Conference". Topic *Ecosystem Services: Applications for Conservation Science, Policy and Practice* in St. Louis, Missouri, USA 2010

Abstract

Due to the rapid economic growth and the demographic pressure in Northern Mountainous Region (NMR) of Vietnam, traditional slash-and-burn farming has been replaced by more profitable land use systems. This has increasingly led to problems of soil degradation and hydrological processes. The implementation of soil conservation measures (SCMs) is becoming an important issue for sustainable agriculture. Considering that implementation of SCMs has rarely been a long-term success, so in this study, two models were used in order to suggest the suitable SCMs in the NMR. The data used to parameterize the models were derived from previous studies in Tat Hamlet, Northern Vietnam. After calibrating, WaNuLCAS (Water, Nutrient, Light Capture in Agroforestry Systems) was used to assess biophysical outputs (soil erosion, runoff) and financial profitability of four scenarios. The Land Use Change Impact Assessment (LUCIA) model was used to see the consequence of land use change at the watershed level including runoff and water balance. The results from LUCIA showed that land use in the upland changed runoff and hydrological processes in the lowlands. At landscape level, effect of increased rainfall variability under a scenario of climate change exceeded that of land use change. WaNuLCAS could, to a certain extent, predict the consequence of the different scenarios. A no-tillage system seemed to be the most appropriate strategy, however, farmers' perception towards this system could become a barrier. In order to come to a successful adoption of SCMs, all aspects of the implementation (environment, financial profitability and suitability) have to be considered.

Published as: **Thanh, N.T,** Ayanu, Y., Nugruho, E., Ikenoue,S., Marohn, C., Cadisch, G. (2010). Assessment of soil conservation strategies in upland agriculture: Interdisciplinary case study in Tat hamlet, Da Bac district, Hoa Binh province, Northern Vietnam. SWCS 65th Annual International Conference. 18-21 July 2010, St. Louis, Missouri, USA.

Topic 6: CDM and mitigation of land use change: Potential for densely populated watersheds in northwest Vietnam?

A poster presentation in “International Symposium Sustainable Land Use and Rural Development in Mountainous Regions of Southeast Asia” in Hanoi 2010

Abstract

In Northwest Vietnam, increasing population density and economic development have forced people to expand agricultural production into upland areas. This resulted in decreasing natural forest area with a conjoint increase of tree-based plantations and a replacement of upland rice-based swidden farming systems with continuous maize cropping systems. In context with climate change, the aims of our study were to reconstruct past land cover by classifying land cover changes based on remote sensing imagery, combining this information with primary quantitative biomass and C-stocks data of perennial vegetation to quantify and evaluate communal CO2 sequestration potential. This research was conducted within the framework of the Uplands Program SFB 564, subproject C4, in cooperation with GTZ and ICRAF Vietnam. To map the change of land cover in Chieng Khoi commune, remote sensing and interview historical local knowledge data, in combination with the development of hybrid classification method, using ENVI 4.3 and ArcGIS 9.3, was used. A decision-tree based on land suitability and cropping season for different annual crops, participatory soil maps and local stakeholder interviews, LANDSAT 1993, 1999 and LISS III 2007 were used to classify five land cover types. To quantify C-stocks, 10 perennial land-use systems were surveyed using a nested sampling plot design. Aboveground biomass parameters of overstorey trees were measured non-destructively, parameters of mid-, understorey vegetation and coarse litter were sampled destructively.

Additionally, allometric equations for Melastoma sanguineum Sims, Chromolaena odorata (L.) and local bamboo species were developed. Thus land cover maps for years 1993, 1999 and 2007 were generated, with the hybrid classification method rendering land cover maps with overall accuracies of 81.1% (1993), 98.5% (1999) and 82.5% (2007). Even though there was a decrease in forested area of ‘only‘ 36%, based on the generated map of 2007 our study results showed a reduction of 61% in total communal carbon stocks during last 50 years. This shows the different carbon storing capacities of natural forest vegetation and tree based plantation systems and the limited usefulness of C stock estimates based on rough land cover categories without proper ground measurements. Looking at above-ground Cstocks of timber and fruit tree plantations, stand ages of 12 and 20 years showed significant differences. Two scenarios showed that Clean Development Mechanism (CDM) projects may provide

new income opportunities for local farmers. In summary, our results provide land cover maps that allow a spatial and temporal extrapolation of the quantified biomass and carbon stocks of different terrestrial vegetation in Chieng Khoi commune; additionally they provide crop management options that may lead to both ecological and economic benefits for local farmers and international stakeholders. Moreover, the generated data can be used as input data for the spatially explicit and dynamic LUCIA (Land use Change Impact Assessment) tool. The results generated from LUCIA model will be applied to assist local land use planning authorities seeking for possibilities to mitigate climate change and hereby may improve the management of natural resources for a more sustainable development.

Published as: Thanh, N.T., Zemek, O., Marohn, C., Hilger, T., Lam, N. T., Vien, T.D., Hoang, H.M.T., Cadisch, G. (2010). CDM and mitigation of land use change: Potential for densely populated watersheds in northwest Vietnam? International Symposium Sustainable Land Use and Rural Development in Mountainous Regions of Southeast Asia. 21-23 July 2010, Hanoi, Vietnam.

Topic 7: Estimating CO2 Sequestration Potential in Northwest Vietnam: Combination of Field Measurements and Remote Sensing Analysis

A poster presentation in “World Food System - A Contribution from Europe” – TropenTag conference in Zurich, Switzerland in 2010

Abstract

Increasing population density and economic development have forced people to expand agricultural production into upland areas in Vietnam. This resulted in decreasing natural forest cover with a conjoint increase of tree-based plantations and a replacement of traditional swidden farming systems with commercial cropping systems. Our study aimed at reconstructing past land cover based on remote sensing imagery, and combined this information with primary quantitative biomass and C stocks data of perennial vegetation to quantify and evaluate communal CO2 sequestration potential.

To generate land cover maps of Chieng Khoi commune, Northwest Vietnam, LANDSAT 1993, 1999 and IRS LISS III 1C 2007 were used. 262 Ground Truthing Points (GTP) were collected, and farmer interviews and group discussions were conducted to gather information per GTP in past times. Hybrid classification methods were applied to classify land cover maps. Land suitability information, cropping season calendar, participatory soil maps and local stakeholder interviews were used to classify crop cover. To quantify C stocks, 10 perennial land-use systems were surveyed using a nested sampling plot design. Aboveground biomass parameters of overstorey trees were measured non-destructively, parameters of mid-, understorey vegetation and coarse litter were sampled destructively. Allometric equations for early succession species were developed.

Land cover maps for 1993, 1999 and 2007 were generated, overall accuracies were 81.1 %, 98.5% and 82.5 %, respectively. Even though forest areas decreased by ‘only’ 36%, based on the map of 2007, our results showed a reduction of 61% in total communal carbon stocks during the last 50 years. This shows the different carbon storing capacities of natural forest vegetation and tree based plantation systems and limited usefulness of C stock estimates based on rough land cover categories without site-specific ground measurements.

The study combined methods to quantify biomass and carbon stocks over time at landscape scale. It also provided input data for a spatially explicit and dynamic Land use Change Impact Assessment tool, which can be applied to assist land use planners to mitigate climate change and improve the management of natural resources.

Keywords: Allometric equation, carbon stocks, land cover maps, remote sensing, Vietnam

Published as: Thanh, N.T., Zemek, O., Marohn, C., Hilger, T., Nguyen,T.L., Vien, T.D., Hoang, H.M.T., Cadisch, G. (2010). Estimating CO2 Sequestration Potential in Northwest Vietnam: Combination of Field Measurements and Remote Sensing Analysis, Tropentag “World Food System - A Contribution from Europe”, September 14-16, 2010, Zurich Switzerland.

Topic 8: Simulating resource dynamics of highland agriculture in northern Vietnam by coupling biophysical and economic models

A presentation in “International Symposium Sustainable Land Use and Rural Development in Mountainous Regions of Southeast Asia” in Hanoi 2010

Abstract

Agriculture in northern Vietnam has much intensified in the past two decades. Fallow periods have shortened and farmers grow maize on sloping lands year after year. Because soil conservation methods are little used, large amounts of soil are eroded from sloping lands annually. Farmers have been able to compensate for the loss in soil nutrients by using mineral fertilizers and planting higher yielding varieties, but these practices are unsustainable if not combined with methods to conserve the topsoil. Farmers are well aware of the danger that erosion poses for their future farm revenues.

Yet farmers need cash to support their household and to buy farm inputs every year. By depleting the soil, farmers tend to trade future crop revenues for higher current crop revenues. Exploring strategies to promote sustainable resource use therefore requires knowledge about the biophysical as well as the economic system and its dynamics. By coupling two models, one representing the biophysical dynamics and the other representing the economic decision-making, this study seeks to get a better understanding of the resource use of farmers. It aims at quantifying the impact of unsustainable land use and at identifying under which conditions soil conservation methods would be economically attractive for farmers to use. The Land Use Change Impact Assessment (LUCIA) model is a spatially explicit dynamic model which simulates watershed functions, soil fertility and plant growth. The hydrological part combines elements of SPAW, KINEROS 2, and algorithms from PCRaster. Plant growth is simulated based on CGMS-WOFOST and was amended for perennial crops and natural vegetation. Residue and soil organic matter decomposition are carbon-driven and follow the Century model. Mathematical Programming-based Multi Agent Systems (MP-MAS) is an agent-based model simulating the land use decisions of large numbers of farm households using whole farm mathematical programming. Agents make decisions about what crops to grow and the amount of inputs to apply based on their expectations about prices and crop yields. By adjusting these expectations, trade-offs between future and current income can be analyzed and quantified. The models are dynamically linked using the Typed Data Transfer library. MP-MAS simulates the crop choice and input use for each pixel in the catchment on a yearly basis and transfers these data to LUCIA, which computes crop yields and resource dynamics on a daily time step. Crop yields are then returned to MP-MAS and agents evaluate their farm revenues and update their crop yield expectations. The coupled model was calibrated to one catchment in northern Vietnam comprising five villages and 471 farm households. Farmers grow paddy rice in the valleys and mostly maize and cassava on the slopes while keeping small numbers of livestock. Using scenario analyses, the study analyzed how crop yields change over time in response to changes in input use and changes in soil fertility. By imposing a sustainability constraint on the agent decision-making in the coupled model, it quantifies the current cost of sustainable land use. The implications for promoting soil conservation methods are discussed.

Published as: Marohn, C., Schreinemachers, P., Siripalangkanont, P., Quang, D.V., **Thanh, N.T.,** Berger, T., Cadisch, G. (2010). Simulating resource dynamics of highland agriculture in northern Vietnam by coupling biophysical and economic models. International Symposium "Sustainable Land Use and Rural Development in Mountainous Regions of Southeast Asia". 21-23 July 2010, Hanoi, Vietnam.

Appendix

Appendix 3.1

Plot and transect history sheet

Transect sheet

Purposes:

- Indentify the training sets for aerial photo 1954
- Indentify the land use history along the transect (with slope)
- Indentify the trend of changing the cropping type
- Indentify the impact of land use change base on indigenous knowledge
- Indentify the future plan for certain area (cropping or tree plantation)

Date: ……………………………………… Transect number:……………………….

Participants: ………………………………………………………………………………

(1) …………………………………...

(2) …………………………………..

(3) …………………………………..

(4) …………………………………..

(5) …………………………………..

(6) …………………..……………

Start: ……………………………………… End:…………..……………………………..

Photo number:……………………………....

Recorder number:..

Local name:……………………………………………………………..……………

Soil type:…………………………………………………………………………………

Land use history and other information:………………………………………………

Land use in 1950s: Describe land use history (let the farmers tell themselves, record the story)

…………………………………………………………………………………………

…………………………………………………………………………..………………

………………………………………………………………….………………………

Land covers type dominants:

………………………….………………………………………………………………

……….……………………………………………………………………………………

.……………………………………………………………………………………………

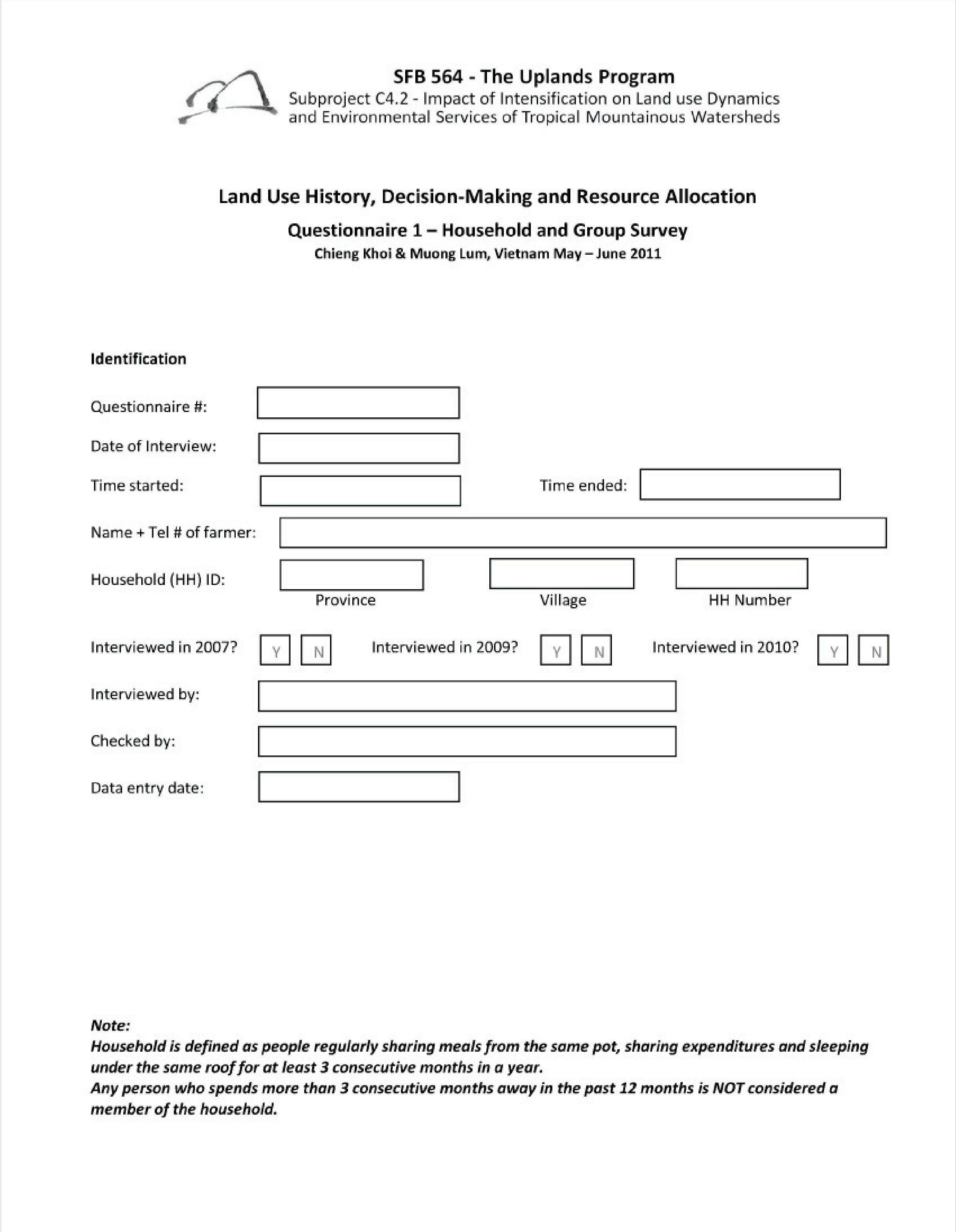
……………..………………………………………………………………………………

LU1:……………………………………
LU2:……………………………………
LU3:……………………………………
LU4:……………………………………
LU5:……………………………………
LU6:……………………………………
LU7:……………………………………
LU :……………………………………
LU :……………………………………
LU :……………………………………

Note: Download GPS and record after the transect walk.

	1950					1960					1970					1980				1990				2000					2010		
LU1																															
LU2																															
LU3																															
LU4																															
LU5																															
LU6																															
LU7																															
LU8																															
LU9																															

Appendix 3.2 Household questionnaire (short version) was developed and conducted in cooperation with Irene Chukwumah, PhD student in the project C4.2 in The Upland Program. This study analyzed the general crop decision and crop history at watershed level in Chieng Khoi commune. Ms. Irene Chukwumah focused more detailed at plot level.



SFB 564 - The Uplands Program
Subproject C4.2 - Impact of Intensification on Land use Dynamics
and Environmental Services of Tropical Mountainous Watersheds

Land Use History, Decision-Making and Resource Allocation

Questionnaire 1 – Household and Group Survey

Chieng Khoi & Muong Lum, Vietnam May – June 2011

Identification

Questionnaire #: ☐

Date of Interview: ☐

Time started: ☐ Time ended: ☐

Name + Tel # of farmer: ☐

Household (HH) ID: ☐ Province ☐ Village ☐ HH Number

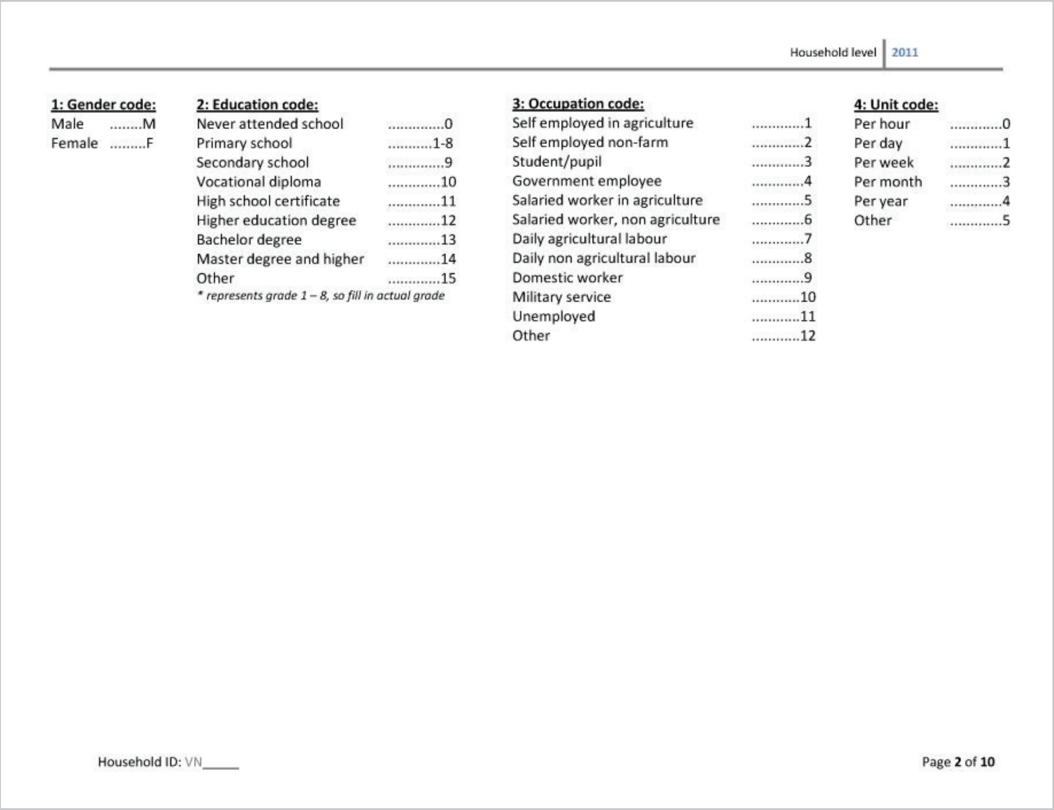
Interviewed in 2007? ☐ Y ☐ N Interviewed in 2009? ☐ Y ☐ N Interviewed in 2010? ☐ Y ☐ N

Interviewed by: ☐

Checked by: ☐

Data entry date: ☐

Note:
Household is defined as people regularly sharing meals from the same pot, sharing expenditures and sleeping under the same roof for at least 3 consecutive months in a year.
Any person who spends more than 3 consecutive months away in the past 12 months is NOT considered a member of the household.



Household level | 2011

1: Gender code:

Male	........M
Female	........F

2: Education code:

Never attended school	0
Primary school	1-8
Secondary school	9
Vocational diploma	10
High school certificate	11
Higher education degree	12
Bachelor degree	13
Master degree and higher	14
Other	15

** represents grade 1 – 8, so fill in actual grade*

3: Occupation code:

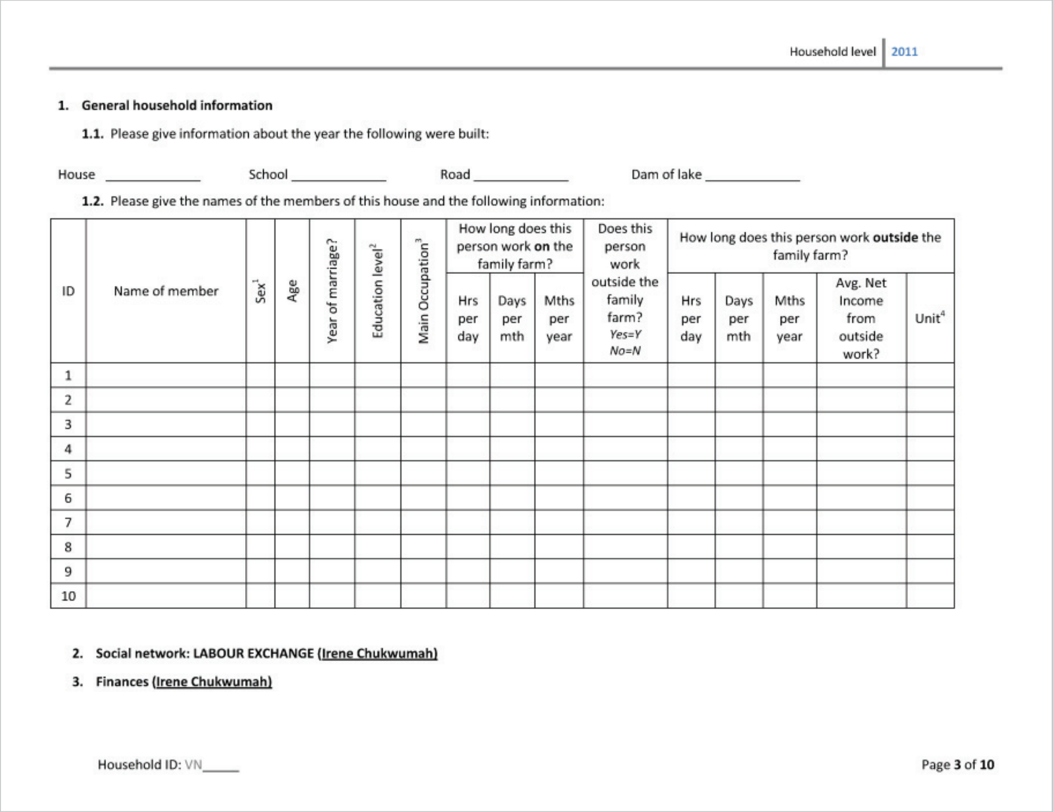
Self employed in agriculture	1
Self employed non-farm	2
Student/pupil	3
Government employee	4
Salaried worker in agriculture	5
Salaried worker, non agriculture	6
Daily agricultural labour	7
Daily non agricultural labour	8
Domestic worker	9
Military service	10
Unemployed	11
Other	12

4: Unit code:

Per hour	0
Per day	1
Per week	2
Per month	3
Per year	4
Other	5

Household ID: VN_____

Page **2** of **10**



Household level | 2011

1. General household information

1.1. Please give information about the year the following were built:

House ____________ School ____________ Road ____________ Dam of lake ____________

1.2. Please give the names of the members of this house and the following information:

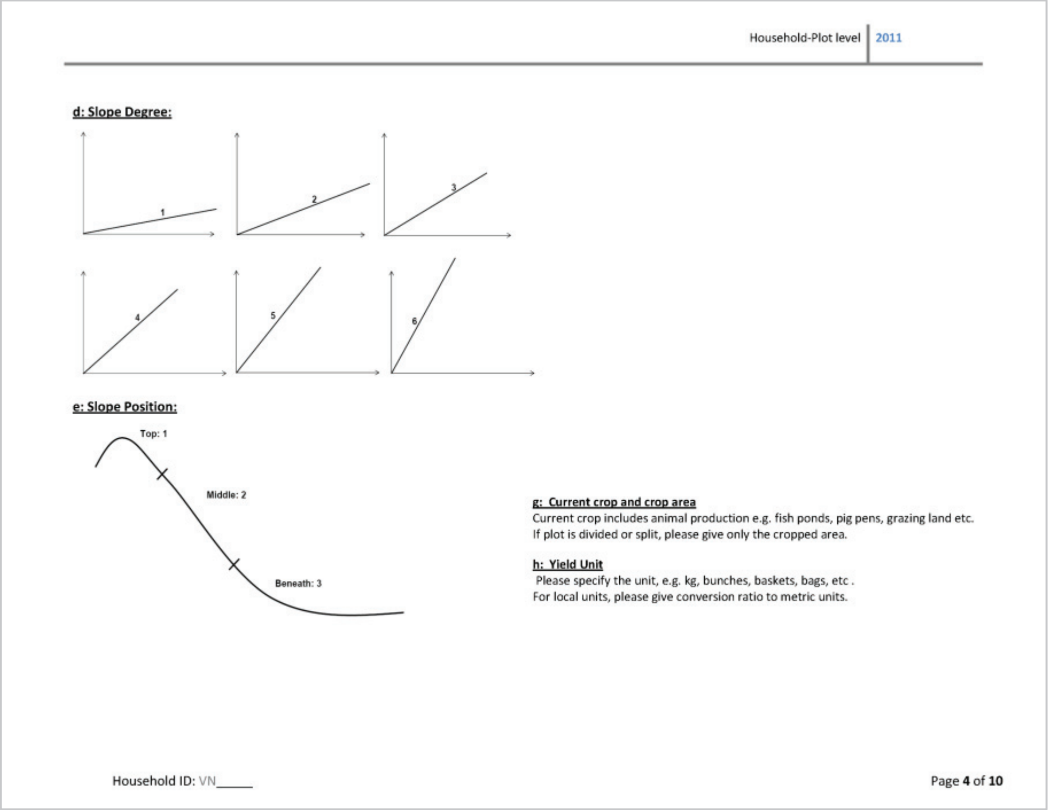
ID	Name of member	Sex[1]	Age	Year of marriage?	Education level[2]	Main Occupation[3]	How long does this person work **on** the family farm?			Does this person work outside the family farm? *Yes=Y No=N*	How long does this person work **outside** the family farm?				
							Hrs per day	Days per mth	Mths per year		Hrs per day	Days per mth	Mths per year	Avg. Net Income from outside work?	Unit[4]
1															
2															
3															
4															
5															
6															
7															
8															
9															
10															

2. Social network: LABOUR EXCHANGE (<u>Irene Chukwumah</u>)

3. Finances (<u>Irene Chukwumah</u>)

Household ID: VN_____

Page **3** of **10**



Household-Plot level | 2011

d: Slope Degree:

e: Slope Position:

g: Current crop and crop area

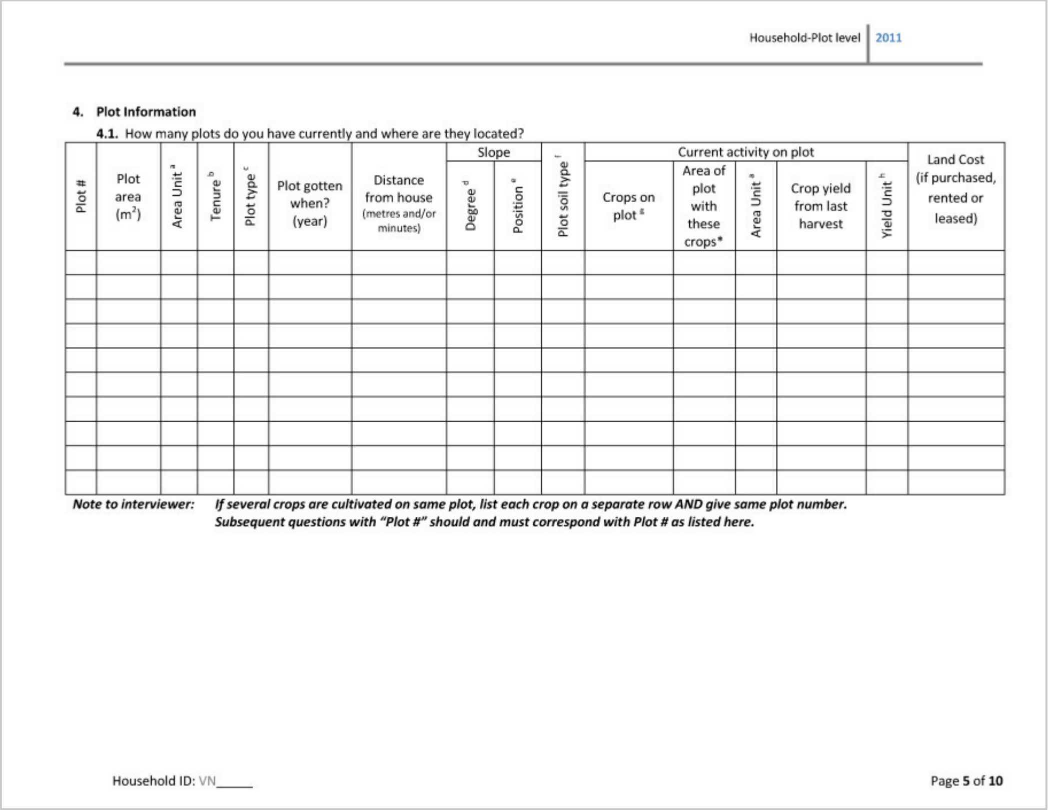
Current crop includes animal production e.g. fish ponds, pig pens, grazing land etc.
If plot is divided or split, please give only the cropped area.

h: Yield Unit

Please specify the unit, e.g. kg, bunches, baskets, bags, etc .
For local units, please give conversion ratio to metric units.

Household ID: VN_____

Page **4** of **10**



Household-Plot level | 2011

4. Plot Information

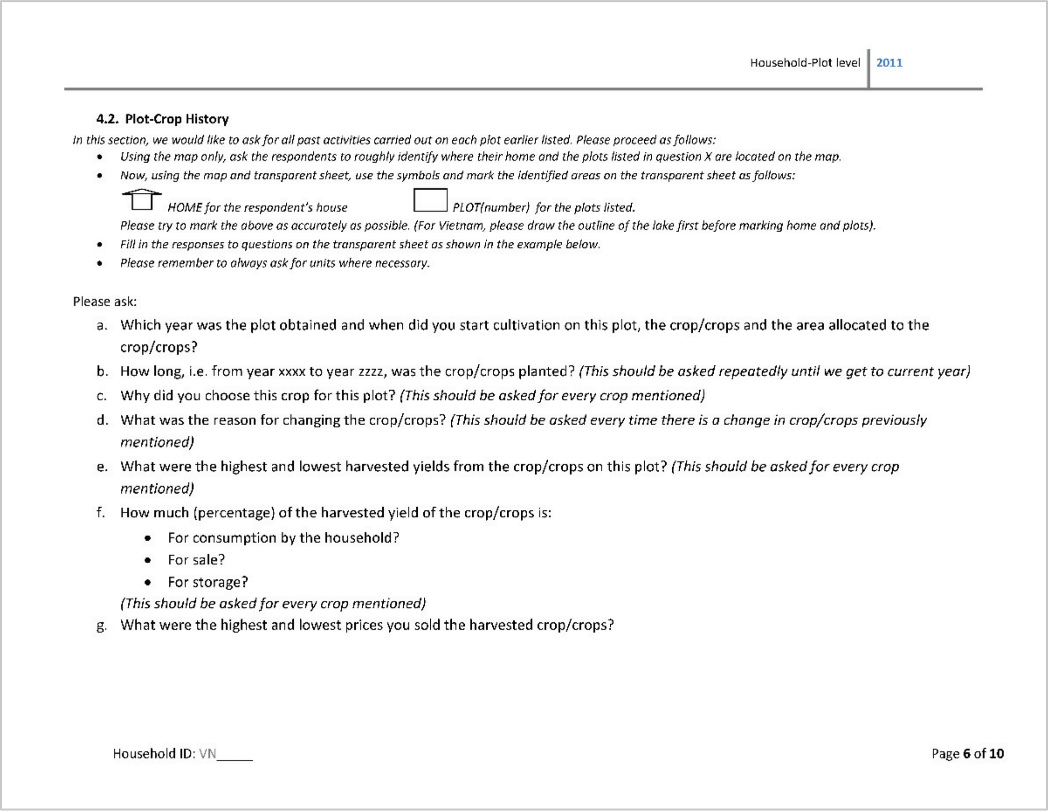
4.1. How many plots do you have currently and where are they located?

Plot #	Plot area (m^2)	Area Unit [a]	Tenure [b]	Plot type [c]	Plot gotten when? (year)	Distance from house (metres and/or minutes)	Slope		Plot soil type [f]	Current activity on plot					Land Cost (if purchased, rented or leased)
							Degree [d]	Position [e]		Crops on plot [g]	Area of plot with these crops*	Area Unit [a]	Crop yield from last harvest	Yield Unit [h]	

Note to interviewer: ***If several crops are cultivated on same plot, list each crop on a separate row AND give same plot number.***
Subsequent questions with "Plot #" should and must correspond with Plot # as listed here.

Household ID: VN_____

Page **5** of **10**



Household-Plot level | 2011

4.2. Plot-Crop History

In this section, we would like to ask for all past activities carried out on each plot earlier listed. Please proceed as follows:

- *Using the map only, ask the respondents to roughly identify where their home and the plots listed in question X are located on the map.*
- *Now, using the map and transparent sheet, use the symbols and mark the identified areas on the transparent sheet as follows:*

  ⌂ *HOME for the respondent's house* ☐ *PLOT(number) for the plots listed.*

  Please try to mark the above as accurately as possible. (For Vietnam, please draw the outline of the lake first before marking home and plots).
- *Fill in the responses to questions on the transparent sheet as shown in the example below.*
- *Please remember to always ask for units where necessary.*

Please ask:

a. Which year was the plot obtained and when did you start cultivation on this plot, the crop/crops and the area allocated to the crop/crops?

b. How long, i.e. from year xxxx to year zzzz, was the crop/crops planted? *(This should be asked repeatedly until we get to current year)*

c. Why did you choose this crop for this plot? *(This should be asked for every crop mentioned)*

d. What was the reason for changing the crop/crops? *(This should be asked every time there is a change in crop/crops previously mentioned)*

e. What were the highest and lowest harvested yields from the crop/crops on this plot? *(This should be asked for every crop mentioned)*

f. How much (percentage) of the harvested yield of the crop/crops is:

- For consumption by the household?
- For sale?
- For storage?

(This should be asked for every crop mentioned)

g. What were the highest and lowest prices you sold the harvested crop/crops?

Household ID: VN_____ Page **6** of **10**

Household-Plot level | 2011

Example: Plot 1 - 1967

Years	*Crops*	*Reason – crop on this plot*	*Reason - change*	*High and low yield*	*Yield use*	*High and low price*
1967 - 1980	*Rice (0.5ha)*	*Food*	-	*H. 5t/ha; L 1.5t/ha*	*100% consumed*	-
	Cabbage (0.3ha)	*Fertile soil, near water*	-	*H. 3t/ha; L. 1t/ha*	*70% sold, 30% cons.*	*H. 300B/kg; L. 100B/kg*
1980 - 1985	*Fallow*			*Normal to improve soil*		
1985 - date	*Chrysanthemums(1ha)*	*Easy to manage, near road*	*Good price*	*H. 3000basket/ha;L.1000bask*	*100% sold*	*H.500B/basket;L.120B/basket*

5. Decision Making

5.1. Plot-crop decisions:

a. If you were allowed only one plot, which plot # would you choose to plant on **first** and what crop? Why? Rank the reasons.

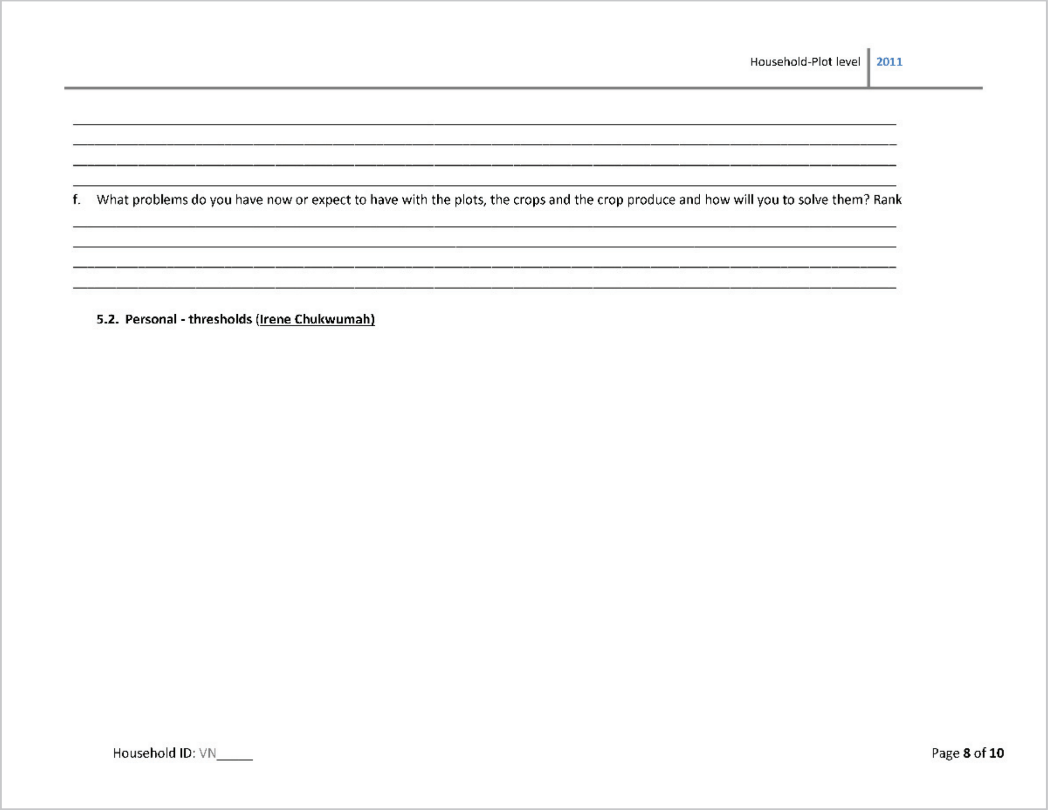
b. Which are the next plot #s you would choose to plant on and what crops - in order of preference - and why? Rank the reasons.

c. If resources for only one plot were available, which plot # and/or crop would you put these resources (e.g. labour, capital, fertilizer, etc) **first** and why? Rank the reasons.

d. Which are the next plot #s and/or crops in line for resource allocation - in order of preference - and why? Rank the reasons.

e. In the past, what were the problems you had with your farms, crops and the crop produce and how did you solve them? Rank the problems

Household ID: VN_____ Page **7** of **10**



____

____

____

____

f. What problems do you have now or expect to have with the plots, the crops and the crop produce and how will you to solve them? Rank

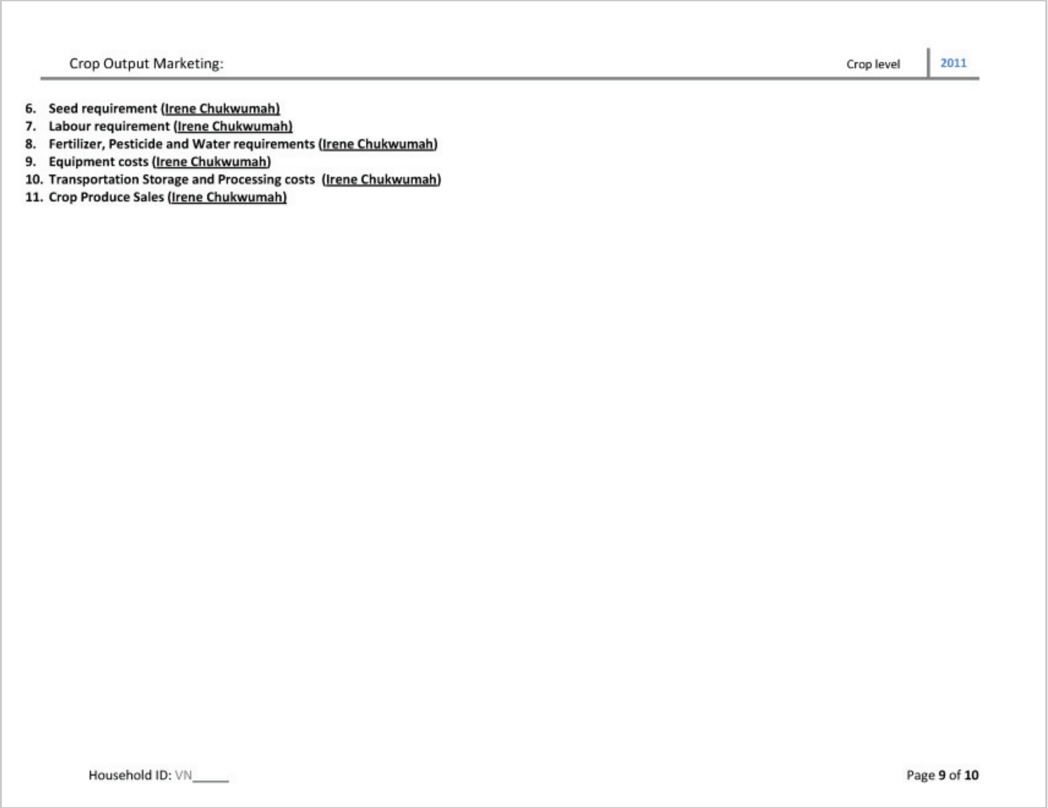
____

____

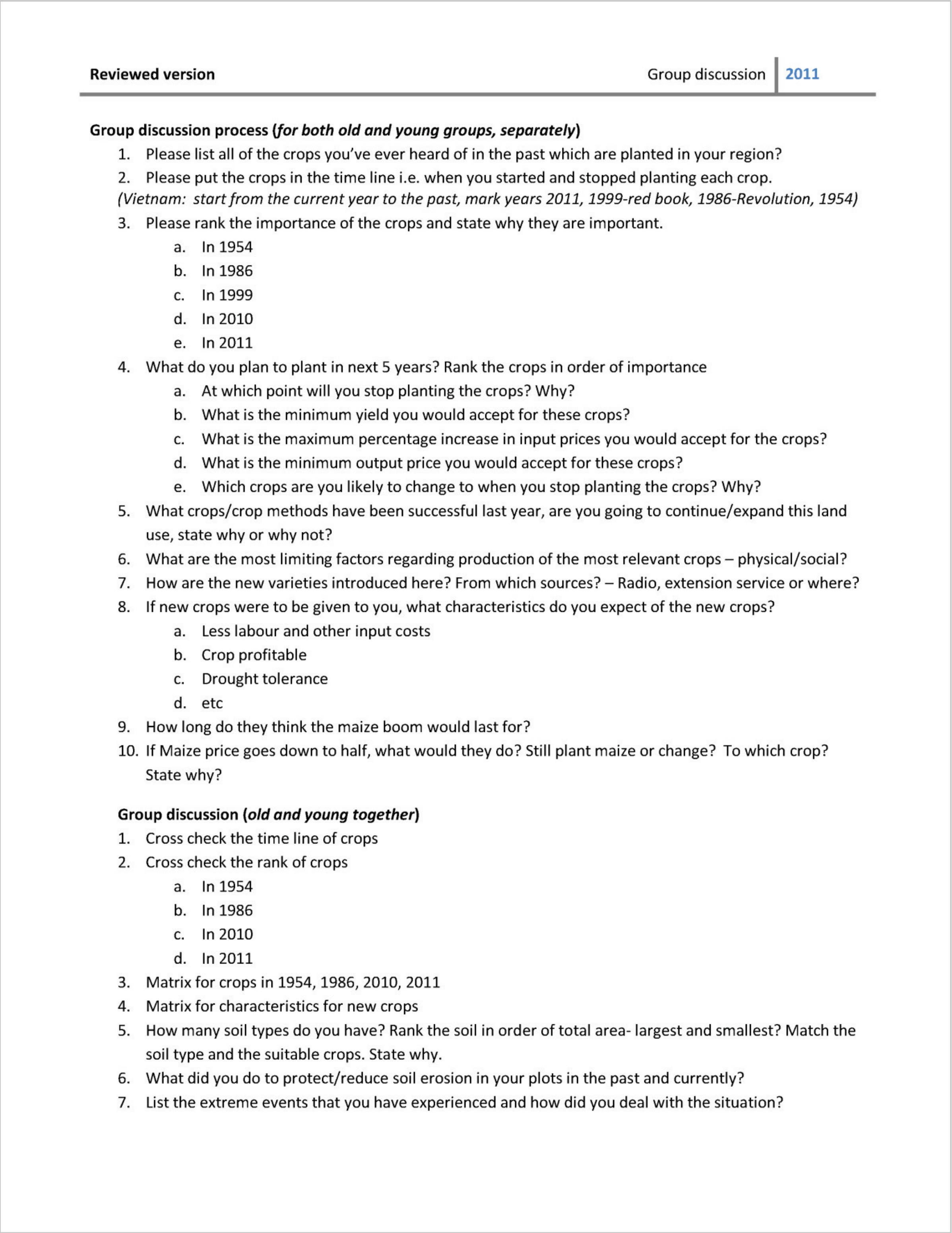
____

____

5.2. Personal - thresholds (Irene Chukwumah)



6. **Seed requirement (Irene Chukwumah)**
7. **Labour requirement (Irene Chukwumah)**
8. **Fertilizer, Pesticide and Water requirements (Irene Chukwumah)**
9. **Equipment costs (Irene Chukwumah)**
10. **Transportation Storage and Processing costs (Irene Chukwumah)**
11. **Crop Produce Sales (Irene Chukwumah)**



Reviewed version Group discussion | 2011

Group discussion process (*for both old and young groups, separately*)

1. Please list all of the crops you've ever heard of in the past which are planted in your region?
2. Please put the crops in the time line i.e. when you started and stopped planting each crop.

(Vietnam: start from the current year to the past, mark years 2011, 1999-red book, 1986-Revolution, 1954)

3. Please rank the importance of the crops and state why they are important.
    a. In 1954
    b. In 1986
    c. In 1999
    d. In 2010
    e. In 2011
4. What do you plan to plant in next 5 years? Rank the crops in order of importance
    a. At which point will you stop planting the crops? Why?
    b. What is the minimum yield you would accept for these crops?
    c. What is the maximum percentage increase in input prices you would accept for the crops?
    d. What is the minimum output price you would accept for these crops?
    e. Which crops are you likely to change to when you stop planting the crops? Why?
5. What crops/crop methods have been successful last year, are you going to continue/expand this land use, state why or why not?
6. What are the most limiting factors regarding production of the most relevant crops – physical/social?
7. How are the new varieties introduced here? From which sources? – Radio, extension service or where?
8. If new crops were to be given to you, what characteristics do you expect of the new crops?
    a. Less labour and other input costs
    b. Crop profitable
    c. Drought tolerance
    d. etc
9. How long do they think the maize boom would last for?
10. If Maize price goes down to half, what would they do? Still plant maize or change? To which crop? State why?

Group discussion (*old and young together*)

1. Cross check the time line of crops
2. Cross check the rank of crops
    a. In 1954
    b. In 1986
    c. In 2010
    d. In 2011
3. Matrix for crops in 1954, 1986, 2010, 2011
4. Matrix for characteristics for new crops
5. How many soil types do you have? Rank the soil in order of total area- largest and smallest? Match the soil type and the suitable crops. State why.
6. What did you do to protect/reduce soil erosion in your plots in the past and currently?
7. List the extreme events that you have experienced and how did you deal with the situation?

Appendix 3.3 Crop choice matrixes, the abbreviations in the cell are the choice-crop by pair wise ranking, the crop with higher score indicates the more prefer crop by farmers' choice.

Ban Ngoang

1986	Paddy Rice	Upland Rice	Maize	New Cassava	Old Cassava	Sweet potato	Sesame	**Rank**
Paddy Rice	X	PR	PR	PR	PR	PR	PR	**7**
Upland Rice		X	UR	UR	UR	UR	UR	**6**
Maize			X	NC	OC	SP	M	**4**
New Cassava				X	OC	SP	NC	**1**
Old Cassava					X	OC	OC	**5**
Sweet Potato						X	SP	**3**
Seasame							X	**2**

1954	Paddy Rice	Upland Rice	Old Cassava	Sticky Maize	Sweet potato	C/Silkworm	**Rank**
Upland Rice	X	UR	UR	UR	-	UR	**5**
Paddy Rice		X	PR	PR	-	PR	**4**
Old Cassava			X	OC	-	OC	**3**
Sticky Maize				X	-	C/S	**1**
Sweet potato					X	-	**-**
Cotton/Silkworm						X	**2**

In Ban Hiem

2011	Paddy Rice	Sticky Maize	New Maize	3yr Cassava	1yr Cassava	Sesame	Peanut	Soybean	**Rank**
Paddy Rice	X	PR	PR	PR	PR	PR	PR	PR	**8**
Sticky Maize		X	NM	3YC	1YC	SM	PN	SM	**3**
New Maize			X	3YC	NM	NM	NM	NM	**7**
3YR Cassava				X	1YC	3YC	PN	3YC	**5**
1YR Cassava					X	1YC	1YC	1YC	**7**
Sesame						X	PN	SS	**2**
Peanut							X	PN	**5**
Soybean								X	**1**

There was no information for 1986 and 1954, farmers did not remember

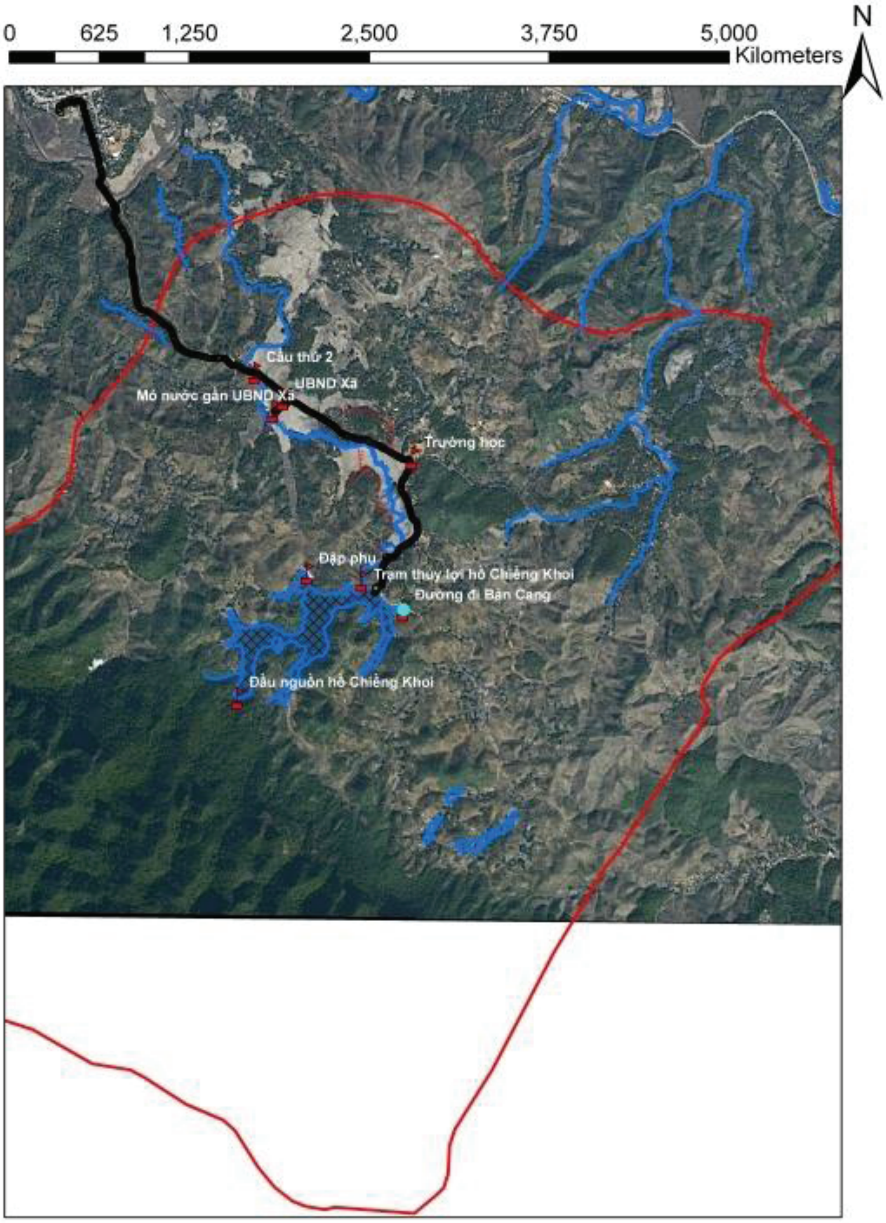
Ban Me

2011	Paddy rice	1yr Cassava	New maize	Banana	2yr Cassava	Sticky Maize	Mango	Tamarind	**Rank**
Paddy rice	**X**	PR	PR	PR	PR	PR	PR	PR	**8**
1yr Cassava		**X**	1YC	1YC	1YC	1YC	1YC	1YC	**7**
Maize			**X**	M	M	M	M	M	**6**
Banana				**X**	2YC	BN	BN	BN	**4**
2yr Cassava					**X**	2YC	2YC	2YC	**5**
Sticky Maize						**X**	SM	SM	**3**
Mango							**X**	TM	**1**
Tamarind								**X**	**2**

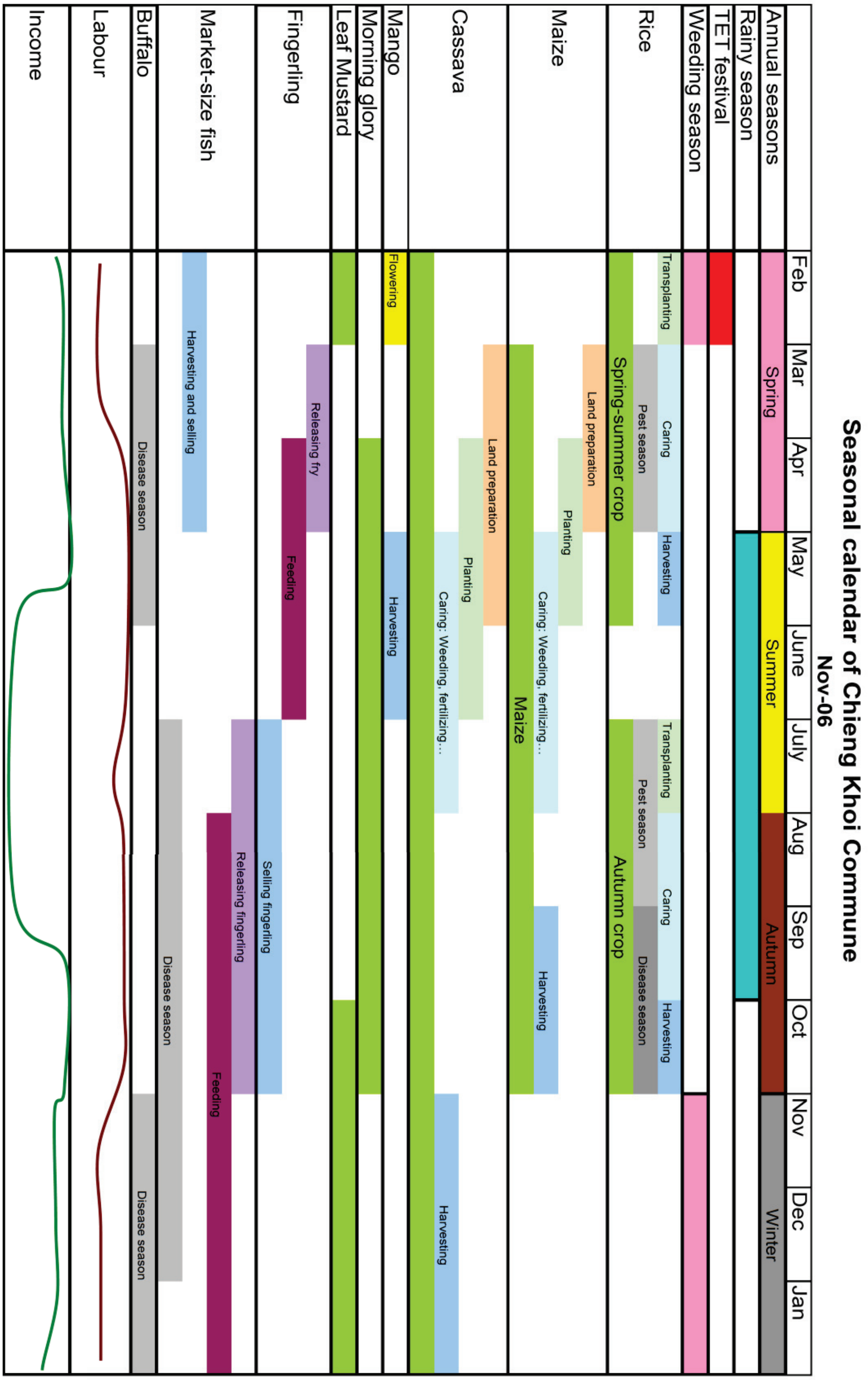
1999 and 1986	Paddy Rice	Maize	2 yr Cassava	Banana	Vegetable	Mango	Sticky Maize	**Rank**
Paddy Rice	**X**	PR	PR	PR	PR	PR	PR	**7**
Maize		**X**	2YC	M	M	M	M	**5**
2 yr Cassava			**X**	2YC	2YC	2YC	2YC	**6**
Banana				**X**	BN	BN	BN	**4**
Vegetable					**X**	MG	SM	**1**
Mango						**X**	SM	**2**
Sticky Maize							**X**	**3**

Before stages were similar to stage 1999 and1986

Appendix 3.4 GoogleEarth image presents Chieng Khoi commune (Retified)



Appendix 3.5 Harvesting calendar (From Upland program database)



Appendix 3.6 Separability of land cover classes in 2007, 1999 and 1993

From LISS III in 2007, Input File: yenchau_liss3_panshaped431

ROI Name: (Jeffries-Matusita, Transformed Divergence)

Pair Separation (least to most);
forest2 [Cyan] 188 points and tree [Maroon] 58 points - 1.69456135
tree [Maroon] 58 points and upland [Red] 17 points - 1.75554417
tree [Maroon] 58 points and upland 1 [Green] 25 points - 1.88786479
upland [Red] 17 points and upland 1 [Green] 25 points - 1.90700469
forest1 [Yellow] 139 points and water [Magenta] 275 points - 1.99759823
forest1 [Yellow] 139 points and tree [Maroon] 58 points - 1.99976721
paddy [Blue] 166 points and tree [Maroon] 58 points - 1.99997569
forest1 [Yellow] 139 points and forest2 [Cyan] 188 points - 1.99998800
paddy [Blue] 166 points and upland [Red] 17 points - 1.99999650
paddy [Blue] 166 points and water [Magenta] 275 points - 1.99999781
paddy [Blue] 166 points and upland 1 [Green] 25 points - 1.99999979
paddy [Blue] 166 points and forest2 [Cyan] 188 points - 1.99999996
paddy [Blue] 166 points and forest1 [Yellow] 139 points - 1.99999999
water [Magenta] 275 points and tree [Maroon] 58 points - 1.99999999
forest2 [Cyan] 188 points and water [Magenta] 275 points - 2.00000000
forest2 [Cyan] 188 points and upland 1 [Green] 25 points - 2.00000000
forest1 [Yellow] 139 points and upland 1 [Green] 25 points - 2.00000000
forest2 [Cyan] 188 points and upland [Red] 17 points - 2.00000000
water [Magenta] 275 points and upland 1 [Green] 25 points - 2.00000000
water [Magenta] 275 points and upland [Red] 17 points - 2.00000000
forest1 [Yellow] 139 points and upland [Red] 17 points - 2.00000000

From Landsat in 1999, ROI Name: (Jeffries-Matusita, Transformed Divergence)

Pair Separation (least to most);
tree [Green] 58 points and forest2 [Cyan] 109 points - 1.88197583
upland [Red] 27 points and tree [Green] 58 points - 1.91396955
forest1 [Yellow] 85 points and forest2 [Cyan] 109 points - 1.99962266
paddy rice [Blue] 47 points and water1 [Maroon] 65 points - 1.99981943

tree [Green] 58 points and paddy rice [Blue] 47 points - 1.99987420
upland [Red] 27 points and forest2 [Cyan] 109 points - 1.99995634
upland [Red] 27 points and forest1 [Yellow] 85 points - 1.99999892
tree [Green] 58 points and forest1 [Yellow] 85 points - 1.99999937
tree [Green] 58 points and water1 [Maroon] 65 points - 1.99999939
upland [Red] 27 points and paddy rice [Blue] 47 points - 1.99999971
paddy rice [Blue] 47 points and forest2 [Cyan] 109 points - 1.99999999
paddy rice [Blue] 47 points and forest1 [Yellow] 85 points - 2.00000000
forest2 [Cyan] 109 points and water1 [Maroon] 65 points - 2.00000000
upland [Red] 27 points and water1 [Maroon] 65 points - 2.00000000
forest1 [Yellow] 85 points and water1 [Maroon] 65 points - 2.00000000

From Landsat in 1993, Input File: yenchau_landsat93 . ROI Name: (Jeffries-Matusita, Transformed Divergence)

Pair Separation (least to most);
upland [Red] 64 points and tree [Blue] 51 points - 1.71042598
paddy rice [Green] 63 points and tree [Blue] 51 points - 1.98912538
water1 [Maroon] 62 points and tree [Blue] 51 points - 1.99951237
forest2 [Magenta] 142 points and tree [Blue] 51 points - 1.99996865
forest2 [Magenta] 142 points and forest1 [Yellow] 164 points - 1.99998010
paddy rice [Green] 63 points and water1 [Maroon] 62 points - 1.99999340
tree [Blue] 51 points and forest1 [Yellow] 164 points - 1.99999697
upland [Red] 64 points and paddy rice [Green] 63 points - 1.99999731
upland [Red] 64 points and forest2 [Magenta] 142 points - 2.00000000
paddy rice [Green] 63 points and forest2 [Magenta] 142 points - 2.00000000
upland [Red] 64 points and water1 [Maroon] 62 points - 2.00000000
water1 [Maroon] 62 points and forest1 [Yellow] 164 points - 2.00000000
upland [Red] 64 points and forest1 [Yellow] 164 points - 2.00000000
forest2 [Magenta] 142 points and water1 [Maroon] 62 points - 2.00000000
paddy rice [Green] 63 points and forest1 [Yellow] 164 points - 2.00000000

Appendix 3.7 Crop scientific names in Table 3.11

Upland rice, paddy rice (*Oryza sativa* L.), maize (*Zea mays* L.), cassava (*Manihot esculenta)*, cotton (*Gossypium hirsutum)*. Peanut (Arachis hypogaea L.). Mulberry for silkworm (*Morus indica* L), black bean (*Vigna unguiculata)*, plump (*Prunus salicina)* and Apricot (*Prunus persica)*, litchi (*Litchi chinensis*), Orange (*Citrus sinensis)*, potato (*Solanum tuberosum)*, sorghum (*Sorghum bicolor* L.), cucumber *(Cucumis sativus)*, sweet potatoes (*Ipomoea batatas)*, dye plant (*Wrightia laevis in* Apocynaceae*,* Co mụ in Thai*),* soybean (Glycine max

L.), sesame (*Sesamum indicum* L.), banana *(Musa spp.)*, mango *(Mangifera indica)*, longan (*Dimocarpus longan)*, jackfruit (*Artocarpus heterophyllus*), pineapple (*Ananas comosus)*, taro (*Colocasia esculenta* L.), pumpkin (*Cucurbita pepo L.)*, squash (*Benincasa hispida)*, ginger (*Zingiber officinale)* , tamarind (*Tamarindus indica)*, sugar cane *(Saccharum offcinarum L.)*, melon (*Cucumis melo)*, climbing beans (*Vigna unguiculata* subsp. *Sesquipedalis and Phaseolus vulgaris*), egg plants (*Solanum macrocarpon*), pomelo (*Citrus maxima)*, key lime (*Citrus aurantifolia)*, and chili *(Capsicum frutescens)*

Appendix 3.8 Check list of group discussion

Uplands Program: C4.2 – prepared by Thanh Nguyen

Date: 31 March 2012

Group discussion: Use for Chieng Khoi comune

Selected farmers: old farmers who are older than 60 years old (were born before 1954)

- How many households and villages were in Chieng Khoi? Let the famer estimate the expansion of residential by themselves using land mark tools with google earth map.
- Decision in the past:
  - where extend residential area, choice by ranking
    - Paddy rice
    - Water body
    - Primary forest
    - Secondary forest
    - Crop land
    - Fruit tree plantation
    - Other
  - Ranking the criteria for extending residential area:
    - Close to other houses
    - Close to water source
    - Close to paddy rice area
    - Close to forest
    - Close to relatives
    - Close to market
    - Other reason
  - where to extend crops: choice by ranking
    - Paddy rice
    - Water body
    - Primary forest
    - Secondary forest
    - Cropping area in upland
    - Fruit tree plantation
    - Other
  - Ranking the criteria for extending crop area:
    - Close to other houses
    - Close to water source
    - Close to paddy rice area
    - Close to forest
    - Close to relatives
    - Close to market
    - Other reason
  - How to extend and why?
  - What crop you decision to plan in one field: Choice by ranking
    - Food security
    - Market orientation/good price/easy to sell
    - Long time storage
    - Recommend from extension service

  - Time line when and which village and how it established in Chieng Khoi? Draw the line.
  - Draw the soil fertility line since 1954 to now (from 100% = after clear the forest to 0% = no crop planted) – can draw the line and/or can give the grades by years.
  - Draw the erosion problem (From 0 = forest to 100) and/or give the grades
- Draw the population increase (from 1954 –now)

Tools: PRA tools: Chieng khoi map from google earth with landmarks. Other tools are required

Prepare: Farmers gifts, A0 and color papers, maps, pens, recorder, camera, beer caps for ranking and grading, note.

Appendix 4.1 Documentation the Goodness-of-fit validation processes using the multiple resolution from Costanza (1989) using PCRaster and Arc GIS 9.3

Formulas were used:

$$F_w = \frac{\sum_{s=1}^{t_w} \left[1 - \frac{\sum_{i=1}^{p} |a_{1i} - a_{2i}|}{2w^2} \right]_s}{t_w}$$

F_w is the fit for sampling window size w, w the dimension of one side of the (square) sampling window, a_{ki} the number of cells of category i in scene k in the sampling window, p the number of different categories (i.e., land use types) in the sampling windows, s the sampling window of dimension w by w which slides through the scene one cell at a time and t_w the total number of sampling windows in the scene for window size w.

$$F_t = \frac{\sum_{w=1}^{n} F_w e^{-k(w-1)}}{\sum_{w=1}^{n} e^{-k(w-1)}}$$

F_t is a weighted average of the fits over all window sizes, F_w the fit for sampling windows of linear dimension w, k a constant, and w the dimension of one side of the (square) sampling window. The value of k determines how much weight is to be given to small versus large sampling windows. A default value for k = 0.1.

1. Calculate Fw

There were two comparisons: (1) compare actual land use map 1973 with land use map 1973 simulated, (2) compare actual land use map 1973 with actual land use map 1954.

Choose the window size: with pixel 20m, window size selected: 3 (3 pixels per window=60m), 5 (5 pixels =100m), 7 (7pixels=140m), 10 (10 pixels=200m), 13 (13 pixels=260m), 20 (20 pixels =400m), 30 (30pixels=600m), 50(50 pixels=1000m), 80 (80 pixels=1600 m).

In this case, the comparison was made for the expansion of upland cultivation areas, the maps to compare contain two classes: Upland and Other classes. The output simulated map and actual maps converted to 2 classes in PCRaster using map edit.

Create match maps: The match map is the map if in that pixel are the same land use type, cite value 1 and if it is not the same land use type, cite value 0. Using if then else in PCRaster

There were two matched maps created in PCRaster:

Vs.map (or Vs_boolean.map is in boolean): Is the match map of actual land use map 1973 and simulate map 1973,

Vsnor.map: is the match map of actual map 1973 and actual 1954

Increase the window size: The increasing window processes made in PCRaster using majority function with selected windows above, the output maps named by the window size: from vs3.map. vs5.map, vs7.map to vs100.map are maps for first comparison 1973 simulated and 1973 actual. From vsno3.map to vsno100.map are maps for second comparison 1973 actual and 1954 actual. (As the results from window 50 to 100 are coarse and the agreement was very high and the same in both comparisons excluded those window sizes at the end).

After increase the window size process, the resolution was the same, 20x20m, but the pixel is aggregated due to majority processes. Aggregate mean function in ArcGIS 9.3 had made two works:

-Increase the size of the pixel base on multiply the pixels

-With code 1 is matched land use type and 0 is not matched land use type, aggregate mean function cited the value of the multiplied pixel by the average of all pixels in the window.

Below is the example of aggregated by 3 using mean.

1	1	0
1	1	0
0	0	1

=>

0.55555556 or 5/9

Using the aggregate function in ArcGIS, Fw automatic calculated for each window, maptotal function in PCRaster will sum all windows from the multiplied maps and divide by total pixels to get Fw. The aggregated maps name: vs3m.map to vs30m.map for first comparison, vsno3m.map to vsno30m.map for second comparison, the number in the names mean the value for each window size of pixel (window sampling).

This code calculate Fw each window size FwSiVSAc3a.txt to FwVSAc30a.txt for fist comparison land use map 1973 simulated and actual, and from FwSiVSno3a.txt to FwVSAcno30a.txt for second comparison land use map 1973 actual and 1954 actual.

All the support maps: area, clone, nonspat made for each resolution for all calculations and conversion from ArcGIS to PCRaster format.

2. Calculate Ft: In Excel file FtCalculationMajority_finalfinal.xlxs based on all results from all windows in PCRaster: fit3.text for window 3 to fit30.txt for window 30 for 1973 actual compare with 1973 simulated. Fitno3.txt for window 3 to fitno30.txt for window 30 for 1973 actual compare with 1954 actual.

3. Calculate Figure of Merit

These values were calculated by determined the observed change and simulate change (as change detection maps) at different resolutions. Some maps were actually existed from previous calculations.

Vs.map (or Vs_boolean.map is in boolean): Is the match map of actual land use map 1973 and simulate map 1973 – not use for this case

Vsnor.map: is the match map of actual map 1973 and actual 1954 = actual change.

Need to do more: The simulated change is the addition need to consider match map between land use 1954 and land use map simulated 1973**: vsnull.map**

Using the windowmajrotity function in PCRaster to increase the window size then use aggregation in ArcGIS as the step to calculate Fw to produce different maps at different window size .Below are the codes using for window 3 (pixel =60m2) to calculate Fw, Intersection, Union, simulated change and actual change.

```
#Fw in difference window size, here at 5
NonSpatno5=nonspat5.map;
VSno5MA=boolean(vsno5ma.map);
Areano5=if( VSno5MA eq 1 or VSno5MA eq 0,1,0);
report areano5.map=boolean(Areano5);
Areano5a=maptotal(scalar(Areano5));
report areano5.txt=timeoutput(NonSpatno5,Areano5a);
------
Matchno5=maptotal(vsno5m.map);
report matchno5.txt=timeoutput(NonSpatno5,Matchno5);# Actual change or observed change
Fitno5=Matchno5 div maptotal(scalar(Areano5));
report fitno5.txt=timeoutput(NonSpatno5,Fitno5);
-------
 # Calculate Figure of merit
Intersection5=if( scalar(vsnull5.map) eq 1 and scalar(vsno5ma.map) eq 1, 1, 0);
report Intersection5.map=boolean(Intersection5);
Inter5=maptotal(scalar(Intersection5.map));
report Intersection5.txt=timeoutput(NonSpatno5,Inter5);
```

```
Union5=if( scalar(vsnull5.map) eq 1 or scalar(vsno5ma.map) eq 1, 1, 0);
report Union5.map=boolean(Union5);
Union5=maptotal(scalar(Union5.map));
report Union5.txt=timeoutput(NonSpatno5,Union5);
------
 # calculate area of simulate change
vsnull5a=boolean(vsnull5.map);
report vsnull5a.map=scalar(vsnull5a);
Match5nul=maptotal(vsnull5a.map);
report match5nul.txt=timeoutput(NonSpatno5,Match5nul);# Simulated change
```

The FOM by (Intersection/Union)x100%

The FOM figure:

- Persistence simulated as change (Yellow)= watershed - Observed change
- Change simulated as persistence (Blue)=watershed - Simulated change
- Change simulated as change to wrong category (Green) =

  Observed change – intersection - Blue
  Or Simulated change – Intersection- Yellow
- Persistence simulated correctly (Grey) =watershed area – Union
- Change simulated correctly (Red) = Intersection

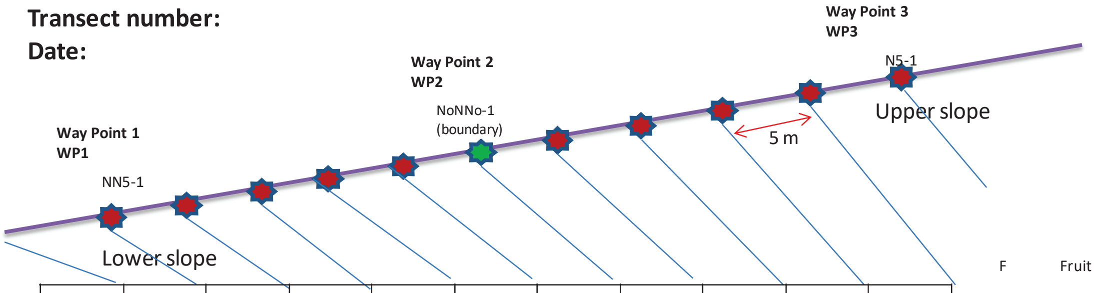
Appendix 4.2 Population in Chieng Khoi from 1955 to 2011, data collected from the Statistics Department in Yen Chau 2012

Years	Population of Chieng Khoi (persons)	Years	Population of Chieng Khoi (persons)
1958	1022	1985	1968
1959	1028	1986	2088
1960	1087	1987	2119
1961	1130	1988	2128
1962	1152	1989	2189
1963	1173	1990	2208
1964	1185	1991	2217
1965	1200	1992	2347
1966	1256	1993	2403
1967	1262	1994	2462
1968	1280	1995	2517
1969	1318	1996	2547
1970	1369	1997	2569
1971	1401	1998	2577
1972	1475	1999	2644
1973	1486	2000	2682
1974	1522	2001	2710
1975	1541	2002	2760
1976	1608	2003	2818
1977	1614	2004	2870
1978	1651	2005	2879
1979	1721	2006	2893
1980	1767	2007	2906
1981	1757	2008	2911
1982	1795	2009	2896
1983	1876	2010	2948
1984	1903	2011	2999

Appendix 5.1 History along transect sheet

Transect number:

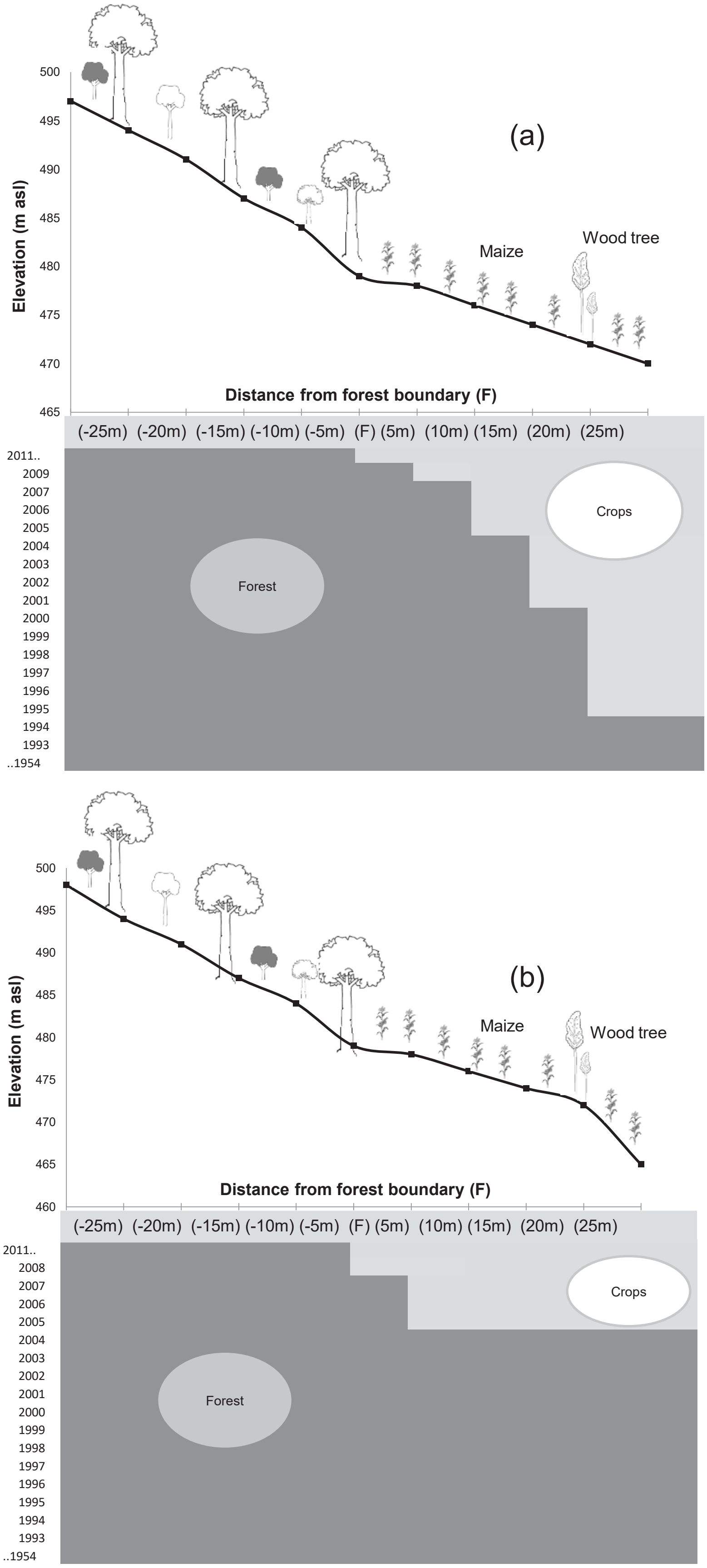
Date:



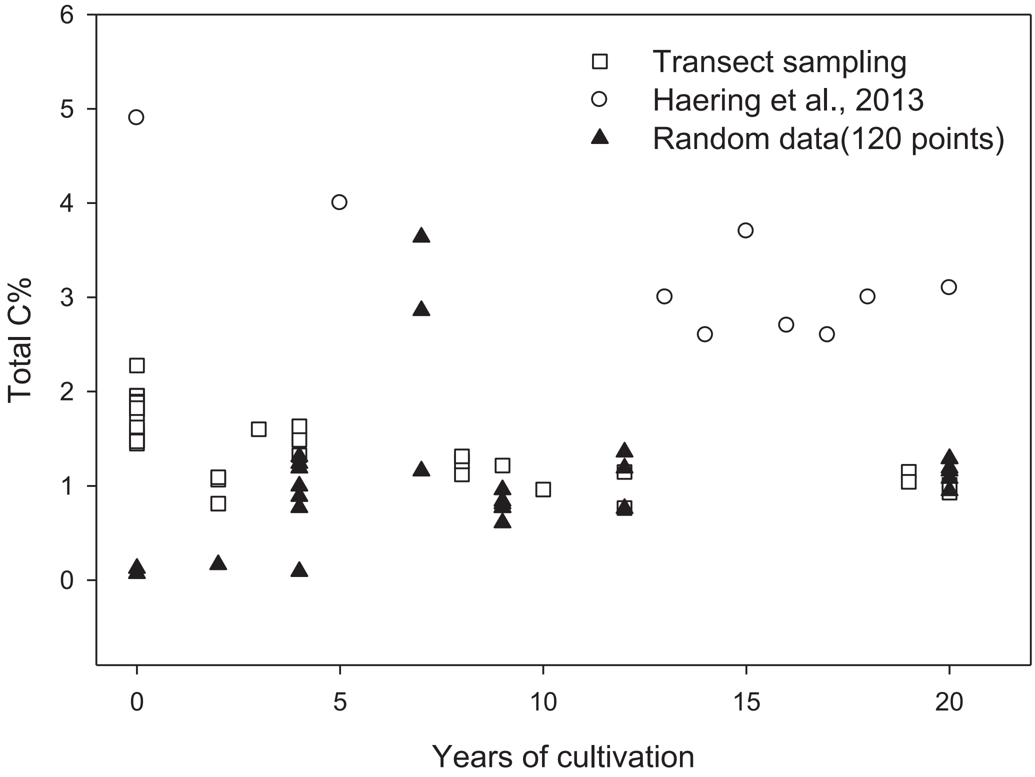
F	Fruit tree
C	Cassava
C&M	Cassava and maize
PF	Production forest
NF	Natural forest
SF	Secondary forest
Bb	Bamboo
UR	Upland rice
Other	Specify

	X	Y	E
WP1			
WP2			
WP3			

Appendix 5.2 Crop history and elevation of Transect 1 (a) and 3 (b)



Appendix 5.3 Cloud data in three datasets from soil sampling (transect and random sampling) and secondary data from Haering *et al*. (2013), comparison data three sources: Haering *et al*. (2013), transect sampling, and available historical data from 120 points



References

Abbott L.K. and D.V. Murphy (Eds). (2003). ‘Soil biological fertility. A key to sustainable land use in agriculture.’ (Kluwer Academic Publishers: Dordrecht, The Netherlands).

Adriaenssens, V., De Baets, B., Goethals, P.L.M., De Pauw, N. (2004). Fuzzy rule-based models for decision support in ecosystem management. Science of the Total Environment, 319 (1-3), pp. 1-12.

Agarwal C., Green G.M., Grove J.M., Evans T.P. and Schweik C.M. (2001). A Review and Assessment of Land-Use Change Models. Dynamics of Space, Time, and Human Choice. Bloomington and South Burlington, Center for the Study of Institutions, Population, and Environmental Change, Indiana University and USDA Forest Service. CIPEC Collaborative Report Series 1.

Ahmed, B., Ahmed, R., Zhu, X. (2013). Evaluation of model validation techniques in land cover dynamics. ISPRS International Journal of Geo-Information, 2 (3), pp. 577-597.

Arshad, M., Coen, G. (1992). Characterization of soil quality: Physical and chemical criteria. American Journal of Alternative Agriculture, 7(1-2), 25-31.

Ashraf M. Dewan, Yasushi Yamaguchi. (2009). Land use and land cover change in Greater Dhaka, Bangladesh: Using remote sensing to promote sustainable urbanization, Applied Geography, Volume 29, Issue 3, July 2009, Pages 390-401, ISSN 0143-6228..

Bechstedt, H.D. 2000. Socioeconomic diagnosis for the evaluation of sustainable land management. Global Tool Kit No. 4. Bangkok, Thailand: IBSRAM

Beeson, K.C., and G.M. Matrone. (1976). The Soil Factor in Nutrition. Animal and Human. New York: Marcel Dekker.

Bellocchi, G., Rivington, M., Donatelli, M., Mathews, K. (2010) Validation of biophysical models: issues and methodologies. A review. Agron. Sustain. Dev. (2010) 30: 109.

Berger, T., 2001. Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. Agric. Econ. 25, 245.

Berger, T., Schreinemachers, P., 2006. Creating agents and landscapes for multiagent systems from random samples. Ecol. Soc. 11, 10 –19.

Beuchelt, T., 2008. Support networks of rural households. A case study of Risk-Management in Northern Vietnam. Margraf Publishers, Weikersheim, Germany.

Brandt, C., Cadisch, G., Nguyen, L.T., Vien, T.D., Rasche, F. (2016). Compound-specific δ13C isotopes and Bayesian inference for erosion estimates under different land use in Vietnam. Geoderma Regional, 7 (3), pp. 311-322.

Brown, D.G., Verburg, P.H., Pontius, R.G., Lange, M.D. (2013). Opportunities to improve impact, integration, and evaluation of land change models Current Opinion in Environmental Sustainability, 5 (5), pp. 452-457.

Bui, H.H., Dao. T.A., Le, V.T., Mai, V.T., Nguyen M.T. (1995). Etude sur la durabilité de l’agriculture d’une commune de montagne du Nord-Ouest Vietnam. In: INSA and CIRAD-URPA (eds), Durabilité du développement agricole au Nord-Vietnam. Etudes de cas, pp. 114–172. Maison d’édition de l’agriculture, Hanoi.

Bui, L.V., Stahr, K., Clemens, G. (2017). A fuzzy logic slope-form system for predictive soil mapping of a landscape-scale area with strong relief conditions Catena, 155, pp. 135-146.

Bui, T.M.H., Schreinemachers, P. (2011). Resettling Farm Households in Northwestern Vietnam: Livelihood Change and Adaptation, International Journal of Water Resources Development, 27:4, 769-785.

Buringh, P., Dudal, R. (1987). Agricultural land use in space and time. Land Transformation in Agriculture, pp. 9-43.

Burkett, V.R., A.G. Suarez, M. Bindi, C. Conde, R. Mukerji, M.J. Prather, A.L. St. Clair, and G.W. Yohe. (2014). Point of departure. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken,P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 169-194 (p190).

Castella, J.C., Boissau, S., Trung, T.N., Quang, D.D. (2005a). Agrarian transition and lowland-upland interactions in mountain areas in northern Vietnam: Application of a multi-agent simulation model Agricultural Systems, 86 (3), pp. 312-332.

Castella, J.C., Pheng Kam, S., Dinh Quang, D., Verburg, P.H., Thai Hoanh, C. (2007). Combining top-down and bottom-up modelling approaches of land use/cover change to support public policies: Application to sustainable management of natural resources in northern Vietnam Land Use Policy, 24 (3), pp. 531-545.

Castella, J.C., Trung, T.N., Boissau, S. (2005). Participatory simulation of land-use changes in the northern mountains of Vietnam: The combined use of an agent-based model, a role-playing game, and a geographic information system. Ecology and Society, 10 (1), art. no. 27, 32 p.

Castella, J.C., Verburg, P.H., 2007. Combination of process-oriented and pattern-oriented models of land use change in a mountain area of Vietnam. Ecological modeling 202, 410-420.

Chambers, R. (1994). Participatory rural appraisal (PRA): analysis of experience. World Development 22 (9), 1253-1268.

Chambers, Robert. (1992). Rural appraisal: rapid, relaxed and participatory. IDS Discussion Paper No. 331, Institute of Development Studies, University of Brighton, Sussex, United Kingdom.

Chand, R. (2008). The global food crisis: Causes, severity and outlook. Economic and Political Weekly, 43 (26-27), pp. 115-123.

Chi, V.K. (2007). Land use change in the Suoi Muoi catchment, Vietnam: disentangling the role of natural and cultural factors, PhD Dissertation Leuven University.

Chi, V.K., Van Rompaey, A., Govers, G., Vanacker, V., Schmook, B., Hieu, N. (2013). Land Transitions in Northwest Vietnam: An Integrated Analysis of Biophysical and Socio-Cultural Factors. Human Ecology, 41 (1), pp. 37-50.

CIAT's Partnership with Germany. (2017). Reducing hunger and poverty through sustainable and climate-smart agriculture. Stewardship Report: Achieving Food Security and Rural Prosperity.

Clemens, G., Sabine Fiedler, S., Cong, N.D., Dung, N.V., Schuler, U., Stahr, K. (2010). Soil fertility affected by land use history, relief position, and parent material under a tropical climate in NW-Vietnam. Catena.

Clement, F., Amezaga, J. M. (2008). Linking reforestation policies with land use change in Northern Vietnam: Why local factors matter. Geoforum, 39(1), 265-277. DOI: 10.1016/j.geoforum.2007.05.008.

Conforti, M., Buttafuoco, G., Leone, A.P., Aucelli, P.P.C., Robustelli, G., Scarciglia, F. (2013). Studying the relationship between water-induced soil erosion and soil organic matter using Vis-NIR spectroscopy and geomorphological analysis: A case study in southern Italy. Catena, 110, pp. 44-58.

Cong, N.D. (2011). SOTER database for land evaluation procedure: A case study in two small catchments of Northwest Vietnam. PhD thesis, Institute of Soil Science and Land Evaluation (310a), Universität Hohenheim, Stuttgart, Germany.

Cook, B.D., Corp, L.A., Nelson, R.F., Middleton, E.M., Morton, D.C., McCorkel, J.T., Masek, J.G., Ranson, K.J., Ly, V., Montesano, P.M. (2013). NASA goddard's LiDAR, hyperspectral and thermal (G-LiHT) airborne imager. Remote Sensing, 5 (8), pp. 4045-4066.

Costanza, R. (1989). Model goodness of fit: a multiple resolution procedure. Ecol. Model. 47, 199–215.

Cousins, S.A.O. (2001). Analysis of land-cover transitions based on 17th and 18th century cadastral maps and aerial photographs. Landscape Ecology, 16 (1), pp. 41-54.

Cox, A., Le, V. (2014). Governmental influences on the evolution of agricultural cooperatives in Vietnam: an institutional perspective with case studies. Asia Pacific Business Review, 20 (3), pp. 401-418.

Dao Minh, T., Yanagisawa, M., Kono, Y. (2017). Forest transition in Vietnam: A case study of Northern mountain region. Forest Policy and Economics, 76, pp. 72-80.

Dawes, W.R., Walker, G.R., Stauffacher, M. (2001). Practical modelling for management in data-limited catchments. Mathematical and Computer Modelling, 33 (6-7), pp. 625-633.

Dieu, P.Q. (2016). Agriculture growth after 30 years of renovation - necessity for a new thought on rice cultivated land for exports and food security. Ikonomicheski Izsledvania, 25 (4), pp. 145-157.

Diez, J.R. (2016). Vietnam 30 years after Doi Moi: Achievements and challenges. Zeitschrift fur Wirtschaftsgeographie, 60 (3), pp. 121-133.

Donahue, R.L. (1965). Soils: An Introduction to Soils and Plant Growth, 2nd Edition, Prentice Hall, Englewood Cliffs, N.J.

Edwards J.H., C.W. Wood, D.L. Thurlow, and M.E. Ruf. (1999). Tillage and crop rotation effects on fertility status of a Hapludalf soil. Soil Sci. Soc. Am. J. 56:1577-1582.

Ellis, E.C., Kaplan, J.O., Fuller, D.Q., Vavrus, S., Goldewijk, K.K., Verburg, P.H. (2013). Used planet: A global history. Proceedings of the National Academy of Sciences of the United States of America, 110 (20), pp. 7978-7985.

Endo, I., Magcale-Macandog, D.B., Kojima, S., Johnson, B.A., Bragais, M.A., Macandog, P.B.M., Scheyvens, H. (2017). Participatory land-use approach for integrating climate change adaptation and mitigation into basin-scale local planning. Sustainable Cities and Society, 35, pp. 47-56.

ESRI. (2015). http://desktop.arcgis.com/en/desktop/latest/tools/environments/resampling-method.htm (assessed date 12:00 on 28.12.2015).

Fagerstroem, H. M, D.T. Tran, H. Sodarak, M. v. Noordwijk and L. Joshi. (2004). How to combine scientific and local knowledge to develop sustainable land use practices in the Upland - A case study from Vietnam and Laos. Proceedings of the workshop: Poverty reduction and shifting cultivation stabilization in the uplands of Lao PDR: Technologies, approaches and methods for improving upland livelihoods. Luang Prabang, Lao, 27-30/1/2004.

FAO and ITPS. (2015). Status of the World’s Soil Resources (SWSR) – Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy.

FAO. (2002a). Sustainable rice production for food security Proceedings of the 20th Session of the International Rice Commission (Bangkok, Thailand, 23–26 July 2002).

FAO. (2002b). http://www.fao.org/forestry/country/57478/en/vnm/. Assessed 06.05.2013.

FAO. (2003). Report of a technical workshop in Rome 2002, 2003. Food energy – methods of analysis and conversion factors. ISSN 02254-4725, FAO Food and Nutrition paper 77, pp 25-26, Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. (2006). Guidelines for soil description (Fourth Edi.). Rome: FAO.

FAO. (2009). Case Studies on Measuring and Assessing Forest Degradation Community Measurement of Carbon Stock Change for REDD Margaret M. Skutsch, Michael K. McCall, Bhaskar Karky, E. Zahabu, Graciela Peters-Guarin, Rome, December, 2009.

FAO. (2011a). Representation in Viet Nam, 2011. Viet Nam and FAO Achievements and success stories. http://www.fao.org/docrep/015/an165e/an165e00.pdf

FAO. (2011b). Soil test: assessed at 10.00 on 10.05. ftp://ftp.fao.org/fi/cdrom/fao_training/FAO_Training/General/x6706e/x6706e06.htm.

FAO. (2013). http://teca.fao.org/technology/improved-fallows Fallow definition. Assessed 14.01.2013.

FAO. (2015). Global Forest Resources Assessment, desk reference. Rome.

FAO. (2016). 11 mitigation of climate change in agriculture series, 2016. Planning, implementing and evaluating Climate-Smart Agriculture in Smallholder Farming Systems The experience of the MICCA pilot projects in Kenya and the United Republic of Tanzania. Janie Rioux, Marta Gomez San Juan, Constance Neely, Christina Seeberg-Elverfeldt, Kaisa Karttunen, Todd Rosenstock, Josephine Kirui, Erasto Massoro, Mathew Mpanda, Anthony Kimaro, Thabit Masoud, Morgan Mutoko, Khamaldin Mutabazi, Geoff Kuehne, Anatoli Poultouchidou, Armine Avagyan, Marja-Liisa Tapio-Bistrom, and Martial Bernoux. Rome, Italy.

FAO. (2017a). The future of food and agriculture – Trends and challenges. Rome.

FAO. (2017b). Soil degradation. Accessed on [11/10/2017]. Available: www.fao.org/soils-portal/soil-degradation-restoration/en.

FAOSTAT, (2017a). http://www.fao.org/faostat/en/#data/QL. assessed 10.20 on 30.06.2017.

FAOSTAT, (2017b). http://www.fao.org/faostat/en/#data/QL. assessed 13.00 on 28.07.2017.

FAOSTAT. (2013). http://www.fao.org/faostat/en/#data/QL. assessed 14.20 on 07.07.2013.

Fox, J. and Vogler, J.B. (2005). Land-Use and Land-Cover Change in Montane Mainland Southeast Asia. Environmental Management Vol. 36, No. 3, pp. 394–403.

Fox, J., Fujita. Y., Ngidang, D., Peluso, N., Potter, L., Sakuntaladewi, N., Sturgeon, J., Thomas, D. (2009). Policies, Political-Economy, and Swidden in Southeast Asia, Hum Ecol, 37:305–322.

Friederichsen, J.R.; and Neef, A. (2010). Variations of Late Socialist Development: Integration and Marginalization in the Northern Uplands of Vietnam and Laos. European Journal of Development Research 22(4): 564-581.

Froehlich. L.F., Schreinemachers, P., Stahr, K., Clemens, G. (eds.). (2013). Sustainable Land Use and Rural Development in Southeast Asia: Innovations and Policies for Mountainous Areas, Springer Environmental Science and Engineering, DOI 10.1007/978-3-642-33377-4_1, # Springer-Verlag Berlin Heidelberg, pp. 487-488.

General Statistic Office. (2011). http://www.gso.gov.vn/default.aspx?tabid=386&idmid=3&ItemID=12816 06.05.2013.

Giang. Le Thi. (2002). Assessing the land use changes on agro forestry lands in Yen Chau district, Son La province using remote sensing data analysis. (Tim hieu nhung thay doi su dung dat Lam Nong nghiep tai huyen Yen Chau, tinh Son La qua viec su dung ky thuat giai doan anh vien tham). Master thesis in Khoa Quan Ly Ruong Dat and Khoa Sau dai hoc, Hanoi University of Agriculture. (in Vietnamese).

Goldshleger, N., Ben-Dor, E., Lugassi, R., Eshel, G. (2010). Soil degradation monitoring by remote sensing: Examples with three degradation processes. Soil Science Society of America Journal, 74 (5), pp. 1433-1445.

Grekousis, G., Mountrakis, G., Kavouras, M. (2015). An overview of 21 global and 43 regional land-cover mapping products. International Journal of Remote Sensing, 36 (21), pp. 5309-5335.

Ha, D.T, T. Thao, N.D., Khiem, M.T., Trieu, X., Gerpacio, R.V., Pingali, P.L. (2004). Maize in Vietnam: Production Systems, Constraints, and Research Priorities. Mexico, D.F. CIMMYT.

Haering, V., Clemens, G., Sauer, D., Stahr, K. (2010). Human-induced soil fertility decline in a mountain region in northern vietnam. Erde, 141(3), 235-253.

Haering, V., Fischer, H., Cadisch, G., Stahr, K. (2013). Implication of erosion on the assessment of decomposition and humification of soil organic carbon after land use change in tropical agricultural systems. Soil Biology and Biochemistry, 65, 158-167.

Haering, V., Fischer, H., Stahr, K. (2014). Erosion of bulk soil and soil organic carbon after land use change in northwest Vietnam Catena, 122, pp. 111-119.

Hagel, H. (2011). Local soil knowledge in Vietnam's northern mountainous region: A case study among different ethnic groups. Master thesis, Management in landwirtschaftlichen Unternehmen, Institute for Social Sciences of the Agricultural Sector, Department of Rural Communication and Extension, University Hohenheim, pp.2-14, pp 26-32, 46-47, 67, 73-78.

Hanh, H.Q., Azadi, H., Dogot, T., Ton, V.D., Lebailly, P. (2017). Dynamics of Agrarian Systems and Land Use Change in North Vietnam. Land Degradation and Development, 28 (3), pp. 799-810.

Hazell, P., Wood, S. (2008). Drivers of change in global agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences, 363 (1491), pp. 495-515.

Hoogenboom, G., J.W. Jones, P.W. Wilkens, C.H. Porter, K.J. Boote, L.A. Hunt, U. Singh, J.I. Lizaso, J.W. White, O. Uryasev, R. Ogoshi, J. Koo, V. Shelia, and G.Y. Tsuji. 2015. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.6 (http://dssat.net). DSSAT Foundation, Prosser, Washington.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, and J.T. Ritchie. (2003). DSSAT Cropping

System Model. European Journal of Agronomy 18:235-265.

Kadmon, R., Harari-Kremer, R. (1999). Studying long-term vegetation dynamics using digital processing of historical aerial photographs. Remote Sensing of Environment, 68 (2), pp. 164-176.

Keil, A., Saint-Macary, C., Zeller, M. (2008). Maize boom in the uplands of Northern Vietnam: economic importance and environmental implications. Department of Agricultural Economics and Social Sciences in the Tropics and Subtropics (Ed.), Forschung zur Entwicklungsökonomie und -politik – Research in Development Economics and Policy, Discussion Paper No. 4/2008.

Keil, A., Saint-Macary, C., Zeller, M. (2013). Intensive commercial agriculture in fragile uplands of vietnam: How to harness its poverty reduction potential while ensuring environmental sustainabiliry? Quarterly Journal of International Agriculture, 52 (1), pp. 1-25.

Kerr, T.J., Cihlar, J. (2003). Land use and cover with intensity of agricultural for Canada from satellite and census data. Global Ecology and Biogeography 12, 167-172

Kibret, K.S., Marohn, C., Cadisch, G.(2016. Assessment of land use and land cover change in South Central Ethiopia during four decades based on integrated analysis of multi-temporal images and geospatial vector data. Remote Sensing Applications: Society and Environment, 3, pp. 1-19.

Kok, K., Farrow, A., Veldkamp, A., Verburg, P.H. (2001). A method and application of multi-scale validation in spatial land use models. Agriculture, Ecosystems and Environment, 85 (1-3), pp. 223-238.

Krueger, T., Page, T., Hubacek, K., Smith, L., Hiscock, K. (2012). The role of expert opinion in environmental modeling. Environmental Modelling and Software, 36, pp. 4-18.

Lal, R., Blum, W.H., Valentine, C., Stewart B.W. (2000). Methods for assessment of soil degradation. CRC press.

Lambin E.F., B.L. Turner, Helmut J. Geist, Samuel B. Agbola, Arild Angelsen, John W. Bruce, Oliver T. Coomes, Rodolfo Dirzo, Günther Fischer, Carl Folke, P.S. George, Katherine Homewood, Jacques Imbernon, Rik Leemans, Xiubin Li, Emilio F. Moran, Michael Mortimore, P.S. Ramakrishnan, John F. Richards, Helle Skånes, Will Steffen, Glenn D. Stone, Uno Svedin, Tom A. Veldkamp, Coleen Vogel, Jianchu Xu. (2001).The causes of land-use and land-cover change: moving beyond the myths, Global Environmental Change, Volume 11, Issue 4, December 2001, Pages 261-269, ISSN 0959-3780.

Le, V.L. (1994). Establishment of ecological models for rehabilitation of degraded barren Midland land in northern Vietnam. Journal of Tropical Forest Science, 7 (1), pp. 143-156.

Leisz, S. J., N.T.T. Ha, N.T.B. Yen, N.T. Lam and T.D. Vien. (2005). Developing a methodology for identifying, mapping and potentially monitoring the distribution of general farming system types in Vietnam's Northern Mountain Region. Agricultural Systems, 85(3) Spec,340-363. (p.352).

Lentz, C.C. (2011). Mobilization and state formation on a frontier of Vietnam The Journal of Peasant Studies. Vol. 38, No. 3, July 2011, 559–586. (578- 581).

Lentz, C.C. (2017). Cultivating Subjects: Opium and rule in post-colonial Vietnam. Modern Asian Studies, pp. 1-40. Article in Press.

Lewis, S.L. (2006). Tropical forests and the changing earth system. Philosophical Transactions of the Royal Society B: Biological Sciences, 361 (1465), pp. 195-210.

Lillesand, T.M and R.W. Kiefer. (2000). Remote sensing and image interpretation Wiley&Sons. West Sussex, England.

Lippe , M. (2015). Simulating the impact of land use change on ecosystem functions in data-limited watersheds of Mountainous Mainland Southeast Asia. PhD dissertation, Faculty of Agricultural Sciences, Hohenheim University, pp. 130-139.

Lippe, M., Marohn, C., Hilger, T., Dung, N.V., Vien, T.D., Cadisch, G. (2014). Evaluating a spatially-explicit and stream power-driven erosion and sediment deposition model in Northern Vietnam. Catena, 120, pp. 134-148.

Lippe, M., T. T Minh, A. Neef, T. Hilger, V. Hoffmann, N.T. Lam, G. Cadisch. (2011). Building on qualitative datasets and participatory processes to simulate land use change in a mountain watershed of Northwest Vietnam, Environmental Modelling & Software.

Lockeretz, W., Anderson, M.D. (1990). Farmers' role in sustainable agriculture research. American Journal of Alternative Agriculture, 5 (4), pp. 178-182.

Loi, N.K., Huyen, N.T., Tu, L.H., Quynh Tram, V.N., Liem, N.D., Tan Dat, N.L., Nhat, T.T., Minh, D.N. (2016). Sustainable land use and watershed management in response to climate change impacts: Case study in srepok watershed, central highland of Vietnam. Environmental Sustainability and Climate Change Adaptation Strategies, pp. 255-295.

Longley, P.A., M.F. Goodchild, D.J. Maguire and D.W. Rind (2005). Geographical information systems and science. John Wiley &Sons, Ltd, West Sussex, England.

Lusiana, B. (2015). Salience, credibility and legitimacy in land use change modeling: model validaiton as product or process? Bogor, Indonesia. World Agroforestry Centre (ICRAF) Southeast Asia Regioonal Program and University of Hohenheim. 165p.

Lusiana, B., Noordwijk, M., Cadisch, G. (2012). Land sparing or sharing? Exploring livestock fodder options in combination with land use zoning and consequences for livelihoods and net carbon stocks using the FALLOW model. Agriculture, Ecosystems and Environment 159, 145– 160.

Lusiana, B., van Noordwijk, M., Suyamto, D., Mulia, R., Joshi, L., and Cadisch, G. (2011). Users' perspectives on validity of a simulation model for natural resource management," International Journal of Agricultural Sustainability, 2, 37-41.

Lynch, J.P. (2007). Turner review no. 14. Roots of the second green revolution. Australian Journal of Botany, 55 (5), pp. 493-512.

Magcale-Macandog, D.B., Balon, J.L., Engay, K.G., Nicopior, O.B.S. (2011). Understanding the patterns, drivers and impacts of land use change in sta. Rosa subwatershed using participatory approaches Journal of Environmental Science and Management, 14 (2), pp. 1-12.

Marchini, A. (2011). Modelling ecological processes with fuzzy logic approaches. Modelling Complex Ecological Dynamics: An Introduction into Ecological Modelling for Students, Teachers & Scientists, pp. 133-145.

Marohn C. and G. Cadisch. (2011). Documentation and manual of the LUCIA model. https://lucia.uni-hohenheim.de/.

Marohn, C., Schreinemachers, P., Quang, D.V., Berger, T., Siripalangkanont, P., Nguyen, T.T., Cadisch, G. (2013). A software coupling approach to assess alternative soil conservation strategies for highland agriculture in Vietnam. Environmental Modelling & Software.

Mavrakis, Dorothea Kalliopi. (2012). Livelihood strategies: Potential of cattle rearing by improved feed production to increase households` income and to decrease soil erosion in rural communities in Northwest Vietnam. Diploma Thesis, Department of Geosciences , Institute of Geography, Eberhard-Karls University of Tübingen, Germany.

Mazzarino, M.J., Szott, L., Jimenez, M. (1993). Dynamics of soil total C and N, microbial biomass, and water-soluble C in tropical agroecosystems. Soil Biology and Biochemistry, 25 (2), pp. 205-214.

Mertz, O., C. Padoch, J. Fox, R. A. Cramb, S. J. Leisz, N. T. Lam, and T. D. Vien. (2009a). Swidden change in Southeast Asia: understanding causes and consequences. Human Ecology 37**:**259–264.

Mertz. O. (2009b). Trends in shifting cultivation and the REDD mechanism. Current Opinion in Environmental Sustainability **1:**156–160.

Minh, T.T., 2010. Agricultural innovation systems in Vietnam’s Northern Mountainous Region - six decades shift from a supply-driven to a diversification-oriented system. Margraf Publishers, Weikersheim, Germany, pp. 32-34.

Minh, T.T., Neef, A., Hoffmann, V. (2011). Agricultural knowledge transfer and innovation processes in Vietnam's northwestern uplands: State-governed or demand-driven? Southeast Asian Studies, 48 (4), pp. 425-455.

Mitchell, A.L., Rosenqvist, A., Mora, B. (2017). Current remote sensing approaches to monitoring forest degradation in support of countries measurement, reporting and verification (MRV) systems for REDD+. Carbon Balance and management, 12 (1), art. no. 9.

Mui, N.T. (2006). Country pasture/Forage Resource Profiles Vietnam. FAO report. http://www.fao.org/ag/AGP/AGPC/doc/Counprof/PDF%20files/Vietnam.pdf. Accessed 06.05.2013, pp7-12.

Müller, D. and M. Zeller. (2002). Land use dynamics in the central highlands of Vietnam: A spatial model combining village survey data with satellite imagery interpretation. Agricultural Economics, 27(3):333-354.

Munsell Colour (1994). Munsell Soil Colour Charts. Kollmorgen Instruments, New York, United States.

Corporation.Nagabhatla, N., Padmanabhan, M., Kühle, P., Vishnudas, S., Betz, L., Niemeyer, B. (2014). LCLUC as an entry point for transdisciplinary research - Reflections from an agriculture land use change study in South Asia. Journal of Environmental Management . Article in Press.

Newman, M.E., McLaren, K.P., Wilson, B.S. (2014). Assessing deforestation and ragmentation in a tropical moist forest over 68 years; the impact of roads and legal protection in the Cockpit Country, Jamaica. Forest Ecology and Management, 315, pp. 138-152.

Nga, D.T., Thao, T.T., van Tu, V., Phuc, P.D., Nguyen-Viet, H. (2016). Development of nutrient cycle through agricultural activities of a rural area in the North of Vietnam. Journal of Material Cycles and Waste Management, pp. 1-9. Article in Press.

Nguyen, T.T. (2009). Assessment of land cover change in Chieng Khoi Commune, Northern Vietnam, by combining remote sensing tools and historical local knowledge. MSc thesis, Institute for Plant Production and Agroecology in the Tropics and Subtropics (380a), Universität Hohenheim, Stuttgart, Germany.

Nguyen, T.T. (2012). Land Reform and Farm Production in the Northern Uplands of Vietnam. Asian Economic Journal, 26 (1), pp. 43-61.

Nguyen, T.T., Do, T.L., Bühler, D., Hartje, R., Grote, U. (2015). Rural livelihoods and environmental resource dependence in Cambodia. Ecological Economics, 120, pp. 282-295.

Nikolic, N., Kostic, L., Djordjevic, A., Nikolic, M. (2011). Phosphorus deficiency is the major limiting factor for wheat on alluvium polluted by the copper mine pyrite tailings: A black box approach. Plant and Soil, 339 (1), pp. 485-498.

Nyssen, J., Petrie, G., Mohamed, S., Gebremeskel, G., Seghers, V., Debever, M., Hadgu, K.M., Stal, C., Billi, P., Demaeyer, P., Haile, M., Frankl, A. (2016).

Recovery of the aerial photographs of Ethiopia in the 1930s. Journal of Cultural Heritage, 17, pp. 170-178.

Pansak, W., Hilger, T., Lusiana, B., Kongkaew, T., Marohn, C., Cadisch, G. (2010). Assessing soil conservation strategies for upland cropping in Northeast Thailand with the WaNuLCAS model Agroforestry Systems, 79 (2), pp. 123-144.

Parker, D.C., Manson, S.M., Janssen, M.A., Hoffmann, M.J., Deadman, P. (2003). Multi-agent systems for the simulation of land-use and land-cover change: A review. Annals of the Association of American Geographers, 93 (2), pp. 314-337.

PCRaster Team. (2011). PCRaster Documentation. http://pcraster.geo.uu.nl/

PLA. (2001). Participatory Learning and Action. Notes. Issue 33, pp.35–39, IIED London.

Pontius J.R, Boersma, W., Castella, J.C., Clarke, K., Nijs T., Dietzel,C., Duan, Z., Fotsing, E., Goldstein, N., Kok, K., Koomen, E., Lippitt, C.D., McConnell, W., Sood, A.M., Pijanowski, B., Pithadia, S., Sweeney, S., Trung, T.N., Veldkamp, A.T., Verburg, P.H. (2008). Comparing the input, output, and validation maps for several models of land change. Ann Reg Sci. 42:11–37.

Pontius, J.R.G., Peethambaram, S., and Castella, J.C. (2011). Comparison of Three Maps at Multiple Resolutions: A Case Study of Land Change Simulation in Cho Don District, Vietnam', Annals of the Association of American Geographers, 101: 1, 45-62, First published on: 27 October 2010 (iFirst).

Putten, v.d.W.H., Bradford, M.A., Pernilla Brinkman, E., van de Voorde, T.F.J., Veen, G.F. (2016). Where, when and how plant–soil feedback matters in a changing world. Functional Ecology, 30 (7), pp. 1109-1121.

Quang, D.V. (2012). An agent-based simulation model of human-environment interactions as applied to soil fertility management practices in northwestern Vietnam, PhD dissertation in institute of agricultural economics and social sciences in the Tropics and Subtropics, faculty of Agricultural sciences, Hohenheim University, pp 13. Printed by Culvillier Verlag Goetingen.

Quang, D.V., Schreinemachers, P., Berger, T. (2014). Ex-ante assessment of soil conservation methods in the uplands of Vietnam: An agent-based modeling approach Agricultural Systems, 123, pp. 108-119.

Rambo, A. T. (1998). The composite swiddening agroecosystem of the Tay Ethnic Minority of the Northwestern Mountains of Vietnam. In Patanothai, A. (ed.), Land Degradation and Agricultural Sustainability: Case Studies from Southeast and East Asia, Regional Secretariat, The Southeast Asian Universities Agroecosystem Network (SUAN). Khon Kaen University, Khon Kaen, pp. 43–64.

Ramboo. Terrry A. (1997). Development Trends in Vietnam's Northern Mountain Region: Overview and analysis. National Political Publishing House, Vietnam.

Ranzi, R., Le, T.H., Rulli, M.C. (2012). A RUSLE approach to model suspended sediment load in the Lo river (Vietnam): Effects of reservoirs and land use changes. Journal of Hydrology, 422-423, pp. 17-29.

Raymond, C.M., Bieling, C., Fagerholm, N., Martin-Lopez, B., Plieninger, T. (2016). The farmer as a landscape steward: Comparing local understandings of landscape stewardship, landscape values, and land management actions. Ambio, 45 (2), pp. 173-184.

Rosenfield, G. H., Fitzpatrick-Lins, K. (1986). A coefficient of agreement as a measure of thematic classification accuracy. Photogrammetric Engineering & Remote Sensing, 52(2), 223–227.

Rounsevell, M.D.A., Annetts, J.E., Audsley, E., Mayr, T., Reginster, I. (2003). Modelling the spatial distribution of agricultural land use at the regional scale. Agriculture, Ecosystems and Environment, 95 (2-3), pp. 465-479.

Rutten, M., Van Dijk, M., Van Rooij, W., Hilderink, H. (2014). Land use dynamics, climate change, and food security in Vietnam: A global-to-local modeling approach. World Development, 59, pp. 29-46.

Saha, A.K., M.K. Arora, E. Csaplovics and R.P. Gupta. (2005). Land cover classification using IRS LISS III image and DEM in a rugged terrain: A case study in Himalayas. Geocarto International 20:33-40. Geocarto International Center, Hong Kong.

Saint-Macary, C., Keil, A., Zeller, M., Heidhues, F., My Dung, P.T. (2010). Land titling policy and soil conservation in the northern uplands of Vietnam. Land Use Policy 27, 617–627 621.

Saraf, A.K. (1999). IRS-1C-LISS-III and PAN data fusion: An approach to improve remote sensing based mapping techniques. International Journal of Remote

Sensing 20(10):1929-1934.

Satellite. (2017) http://www.satimagingcorp.com, accessed latest on 06.07.2017.

Schad, I., Schmitter, P., Saint-Macary, C., Neef, A., Lamers, M., Nguyen, L., Hilger, T., Hoffmann, V. (2012). Why do people not learn from flood disasters? evidence from vietnam's northwestern mountains. Natural Hazards, 62(2), 221-241.

Schmidt-Vogt, D., Leisz, S., Mertz, O., Heinimann, A., Thiha, T., Messerli, P., Eppreacht, M., Cu, PV., Hardiono, N. (2009). An assessment of trends in extent of swidden in Southeast Asia. Humen Ecology, 37: 269-280.

Schmitt, L.K. (2009). Developing and applying a soil erosion model in a data-poor context to an island in the rural Philippines. Environment, Development and Sustainability, 11 (1), pp. 19-42.

Schmitter, P., Dercon, G., Hilger, T., Hertel, M., Treffner, J., Lam, N., Duc Vien, T., Cadisch, G. (2011). Linking spatio-temporal variation of crop response with sediment deposition along paddy rice terraces. Agriculture, Ecosystems and Environment, 140 (1-2), pp. 34-45.

Schmitter, P., Dercon, G., Hilger, T., Thi Le Ha, T., Huu Thanh, N., Lam, N., Duc Vien, T., Cadisch, G. (2010). Sediment induced soil spatial variation in paddy fields of Northwest Vietnam. Geoderma, 155 (3-4), pp. 298-307.

Schmitter, P., Fröhlich, H.L., Dercon, G., Hilger, T., Huu Thanh, N., Lam, N.T., Vien, T.D., Cadisch, G. (2012). Redistribution of carbon and nitrogen through irrigation in intensively cultivated tropical mountainous watersheds. Biogeochemistry, 109 (1-3), pp. 133-150.

Schoenholtz, S.H., Miegroet, H.V., Burger J.A. (2000). A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities, Forest Ecology and Management, Volume 138, Issue 1, Pages 335-356, ISSN 0378-1127.

Schreinemachers, P., Berger, T., 2011. An agent-based simulation model of human – envi- ronment interactions in agricultural systems. Environ. Model Softw. 26, 845 – 859.

Schuler, U., Clemens, G., Cong, N.D., Stahr, K. (2007). Awareness raising for soil erosion by elicitation of local (soil) knowledge. International Agroforestry

Education Conference – Integrating Conservation in the Upland Agriculture in Southeast Asia. Chiang Mai, Thailand.

Schweizer, S.A., Fischer, H., Häring, V., Stahr, K. (2017). Soil structure breakdown following land use change from forest to maize in Northwest Vietnam. Soil and Tillage Research, 166, pp. 10-17.

Seto, K.C., Shepherd, J.M. (2009). Global urban land-use trends and climate impacts. Current Opinion in Environmental Sustainability, 1 (1), pp. 89-95.

Sikor T., 1995: Decree 327 and the restoration of barren land in the Vietnamese Highlands. In: Rambo, A.T., Reed, R.R., Le Trong Cuc and DiGregorio, M.R. (eds), The challenges of highland development in Vietnam, East-West Center, Honolulu, Hawaii, Center for Natural Resources and Environmental Studies, Hanoi University, Center for Southeast Asis Studies, University of California, Berkley, pp. 143–156.

Sikor, T., Truong, D.M. (2002). Agricultural policy and land use changes in a Black Thai commune of northern Vietnam, 1952-1997. Mountain Research and Development, 22 (3), pp. 248-255.

Sims, J.T., A. N. Sharpley, A.N., (editors). (2005). Phosphorus: Agriculture and the Environment. Agron. Monogr. 46. ASA, CSSA, and SSSA, Madison, WI. Number 8 Section II p. 353-262.

Slaets, J.I.F., Schmitter, P., Hilger, T., Duc Vien, T., Cadisch, G. (2016a). Sediment trap efficiency of paddy fields at the watershed scale in a mountainous catchment in northwest Vietnam. Biogeosciences, 13 (11), pp. 3267-3281.

Slaets, J.I.F., Schmitter, P., Hilger, T., Hue, D.T.T., Piepho, H.P., Vien, T.D., Cadisch, G. (2016b). Sediment-associated organic carbon and nitrogen inputs from erosion and irrigation to rice fields in a mountainous watershed in Northwest Vietnam. Biogeochemistry, 129 (1-2), pp. 93-113.

Slaets, J.I.F., Schmitter, P., Hilger, T., Lamers, M., Piepho, H.-P., Vien, T.D., Cadisch, G. (2014). A turbidity-based method to continuously monitor sediment, carbon and nitrogen flows in mountainous watersheds. Journal of Hydrology, 513, pp. 45-57.

Sohl, T.L., Claggett, P.R. (2013). Clarity versus complexity: Land-use modeling as a practical tool fordecision-makers Journal of Environmental Management, 129, pp. 235-243.

Staalhl, G., Ringvall, A., Laamaas, T. (1997). Guided Transect Sampling - An Outline of the Principle ISSN 1401-1204.

Steinbronn, S. 2009. A case study: Fish production in the integrated farming system of the black Thai in Yen Chau district (Son La province) in mountainous North-western Vietnam – current state and potential. PhD dissertation, Faculty of Agricultural Sciences, Hohenheim University pp 30-48

Tang, Z., Engel, B. A., Pıjanowskı, B. C., Lim, K. J. (2005). Forecasting land use change and its environmental impact at a watershed level. Journal of Environmental Management, 76, 35–45.

Tao, F., Yokozawa, M., Liu, J., Zhang, Z. (2009). Climate change, land use change, and China's food security in the twenty-first century: An integrated perspective. Climatic Change, 93 (3-4), pp. 433-445.

Tottrup, C. (2004). Improving tropical forest mapping using multi-date landsat TM data and pre-classification image smoothing. International Journal of Remote Sensing 25(4):717-730.

Tottrup, C. (2007). Forest and land cover mapping in a tropical highland region. Photogrammetric Engineering and Remote Sensing 73(9):1057-1065.

Tottrup, C., M.S. Rasmussen. (2004). Mapping long-term changes in savannah crop productivity in Senegal through trend analysis of time series of remote sensing data. Agriculture, Ecosystems and Environment 103(3):545-560.

Tuan, V.D., Hilger, T., Cadisch, G. (2016). Identifying resource competition in maize-based soil conservation systems using ^{13}C and ^{15}N isotopic discrimination. Archives of Agronomy and Soil Science, 62 (5), pp. 688-707.

Tuan, V.D., Hilger, T., MacDonald, L., Clemens, G., Shiraishi, E., Vien, T.D., Stahr, K., Cadisch, G. (2014). Mitigation potential of soil conservation in maize cropping on steep slopes. Field Crops Research, 156, pp. 91-102.

Tuan, V.D., Hilger, T., Vien, T.D., Cadisch, G. (2015). Nitrogen recovery and downslope translocation in maize hillside cropping as affected by soil conservation. Nutrient Cycling in Agroecosystems, 101 (1), pp. 17-36.

Tugel, Arlene J., Skye A. Wills, and Jeffrey E. Herrick. (2008). Soil Change Guide: Procedures for Soil Survey and Resource Inventory, Version 1.1. USDA, Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Van Noordwijk, M., Tanika, L., Lusiana, B. (2017b). Flood risk reduction and flow buffering as ecosystem services - Part 2: Land use and rainfall intensity effects in Southeast Asia. Hydrology and Earth System Sciences, 21 (5), pp. 2341-2360.

van Vliet, J., Magliocca, N.R., Büchner, B., Cook, E., Rey Benayas, J.M., Ellis, E.C., Heinimann, A., Keys, E., Lee, T.M., Liu, J., Mertz, O., Meyfroidt, P., Moritz, M., Poeplau, C., Robinson, B.E., Seppelt, R., Seto, K.C., Verburg, P.H. (2016). Meta-studies in land use science: Current coverage and prospects. Ambio, 45 (1), pp. 15-28.

Vancutsem, C., Marinho, E., Kayitakire, F., See, L., Fritz, S. (2013). Harmonizing and combining existing land cover/land use datasets for cropland area monitoring at the African continental scale. Remote Sensing, 5 (1), pp. 19-41.

Veldkamp, A., and L. O. Fresco. (1996). CLUE-CR: an integrated multi-scale model to simulate land use change scenarios in Costa Rica. Ecological modelling 91:231–248.

Veldkamp, A., Verburg, P.H. (2004). Modelling land use change and environmental impact. Journal of Environmental Management, 72 (1-2), pp. 1-3.

Verburg, P. H., A. Veldkamp and J. Bouma. (1999b). Land use change under conditions of high population pressure: the case of Java. Global Environmental Change 9:303–312.

Verburg, P. H., A. Veldkamp, G. H. J. de Koning, K. Kok, and J. Bouma. (1999a). A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. Ecological modelling 116:45–61.

Verburg, P.H. Simulating feedbacks in land use and land cover change models (2006) Landscape Ecology, 21 (8), pp. 1171-1183.

Verburg, P.H., Mertz, O., Erb, K.-H., Haberl, H., Wu, W. (2013). Land system change and food security: Towards multi-scale land system solutions. Current Opinion in Environmental Sustainability, 5 (5), pp. 494-502.

Verburg, P.H., Schot, P.P., Dijst, M.J., Veldkamp, A. (2004). Land use change modelling: Current practice and research priorities. GeoJournal, 61 (4), pp. 309-324.

Verburg, P.H., Soepboer, W., Veldkamp, A., Limpiada, R., Espaldon, V., Mastura, S.S.A. (2002). Modeling the spatial dynamics of regional land use: The CLUE-S model. Environmental Management, 30 (3), pp. 391-405.

Vezina, K., Bonn, F., Van, C.P. (2006). Agricultural land-use patterns and soil erosion vulnerability of watershed units in Vietnam's northern highlands. Landscape Ecology, 21 (8), pp. 1311-1325.

Viet, P.V., Phuong, N.M. (1993). Natural resources evaluation by the use of remote sensing and GIS technology for agricultural development. Adv.Space Res. Vol.13. No11 pp 117-121. Printed in Great Britain.

Vongvisouk, T., Broegaard, R.B., Mertz, O., Thongmanivong, S. (2016). Rush for cash crops and forest protection: Neither land sparing nor land sharing. Land Use Policy, 55, pp. 182-192.

Wezel, A. (2000). Weed vegetation and land use of upland maize fields in north-west vietnam. GeoJournal., 50(4), 349-357. DOI.org/10.1023/A:1011090214532

Wezel, A., A. Luibrand and L.Q. Thanh. (2002a). Temporal changes of resource use, soil fertility and economic situation in upland Northwest Vietnam. Land Degradation and Development 13(1):33-44.

Wezel, A., Steinmüller, N., Friederichsen, J. R. (2002b). Slope position effects on soil fertility and crop productivity and implications for soil conservation in upland northwest vietnam. Agriculture, Ecosystems and Environment, 91(1-3), 113-126.

Wilkie, D.S., J.T. Finn (1996). In Pearl, M.C. (ed.). Remote sensing imagery for natural resources monitoring. Columbia University Press, USA.

Wright, S.J. (1992). Seasonal drought, soil fertility and the species density of tropical forest plant communities. Trends in Ecology and Evolution, 7 (8), pp. 260-263.

Yang, X., Blagodatsky, S., Lippe, M., Liu, F., Hammond, J., Xu, J., Cadisch, G. (2016). Land-use change impact on time-averaged carbon balances: Rubber expansion and reforestation in a biosphere reserve, South-West China. Forest Ecology and Management, 372, pp. 149-163.

Yang, X., Lo, C.P. (2002) Using a time series of satellite imagery to detect land use and land cover changes in the Atlanta, Georgia metropolitan area, International Journal of Remote Sensing, 23:9, 1775-1798.

Yen, B.T., Visser, S.M., Hoanh, C.T., Stroosnijder, L. (2013). Constraints on agricultural production in the northern uplands of Vietnam. Mountain Research and Development, 33 (4), pp. 404-415.

Zhang, W., Qi, Y., Zhang, Z. (2006). A long-term forecast analysis on worldwide land uses. Environmental Monitoring and Assessment, 119 (1-3), pp. 609-620

Zhu, A.X., Hudson, B., Burt, J., Lubich, K., Simonson, D. (2001). Soil mapping using GIS, expert knowledge, and fuzzy logic. Soil Science Society of America Journal, 65 (5), pp. 1463-1472.

Zhu, A.X., Qi, F., Moore, A., Burt, J.E. (2010). Prediction of soil properties using fuzzy membership values. Geoderma, 158 (3-4), pp. 199-206.

Ziegler, A., Fox, J., Webb, E., Padoch, C., Leisz, S., Cramb. R., Mertz, O., Bruun, T., Vien, TD. (2011). Recognizing Contemporary Roles of Swidden Agriculture in Transforming Landscapes of Southeast Asia, Conservation Biology, Volume 25, No. 4, 846–848.