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Using Farmer Decision Rules for Mapping Historical Land Use Change Patterns from 1954 to 2007 in Rural Northwestern Vietnam

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Abstract: The present study revealed how local socioecological knowledge elucidated during participatory rural appraisals and historical remote sensing data can be combined for analyzing land use change patterns from 1954 to 2007 in northwestern Vietnam. The developed approach integrated farmer decision rules on cropping preferences and location, visual and supervised classification methods, and qualitative information obtained during various forms of participatory appraisals. The integration of historical remote sensing data (aerial photo, Landsat, LISS III) with farmer decision rules showed the feasibility of the proposed method to explain crop distribution patterns for the assessment period of 53 years. Our approach is beneficial for data-limited environments, which is a prevalent situation for many developing regions. The derived land use and crop type dataset was used for understanding how anthropogenic activities altered the study area of the Chieng Khoi commune during the assessment period of five decades, and what potential impact this can have on the natural resource base. The newly developed approach offers a methodological pathway that can be easily transferred to local government authorities for a better understanding of cropping transitions and agricultural expansion trends in data-limited rural landscapes. The detected land use change patterns and upland cropping expansion of more than two hundred percent in 53 years not only revealed the consequences of the interactions and feedback between farmers and their land, but further highlighted the urgent need for implementing sustainable land management practices in the case study watershed of the Chieng Khoi commune and northwestern Vietnam in general.

Keywords: land use mapping; farmer decision rules; remote sensing; participatory rural appraisals; local knowledge

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1. Introduction

Land use classification and mapping out detailed crop system patterns requires in-depth knowledge of the area of interest, and are often accompanied by ground truthing field campaigns [1]. Detailed crop type maps are becoming important components for landscape management and as a planning tool for agricultural development in rural regions such as mountainous mainland Southeast Asia [2,3]. This mountainous region has faced tremendous changes over the past decades fostered by growing populations, increasing road networks, and changing agricultural policies that pushed for stronger rural–urban market connectivity [1,3,4]. Remote sensing information obtained from satellite sensors or airborne instruments are widely used to monitor and analyze land use patterns and for determining land use change trajectories [4]. The derived data quality, however, can be affected by the employed analysis technique, available ground truthing information, and data-limited constraints, among others [5]. Remote sensing data are widely used to interpret land use patterns by comparing two (or more) stages in time for analyzing land use change [4,6]. However, the lack of long-term historical ground truthing information often hinders thorough map validation, especially when focusing on the analysis of past land use change patterns [7,8]. While land cover describes the natural and anthropogenic features on the Earth's surface, such as forests, water bodies, agricultural areas or grassland, land use describes the human activities taking place on the land describing its current use form, such as secondary forest or maize cropping. For the purpose of this study, land use is used as the main term which includes land cover.

Participatory research methods have a long application record in natural resource management and land use planning [9]. Participatory mapping is among the most prominent methods and it is widely used in rural appraisals [8–12]. Qualitative data, such as local farmer knowledge, is an alternative source to compensate for the challenge of lack of historical ground truthing information and remote sensing data [1,9–11]. Kibret et al. [12] used local knowledge to enhance a multitemporal land use classification approach in South Central Ethiopia. The incorporation of local knowledge was useful input for mapping and successfully improving misclassification errors by 18%. However, local knowledge also can be used as a ground truthing source for land use classification at the crop type level, and also can serve other aspects of a classification workflow. For example, using participatory appraisals for elucidating farmers' local knowledge and decisions on crop management practices could be an alternative option for assessing land use change [13–15]. This can be especially interesting for data-limited environments such as rural northwestern Vietnam [9].

Against this background, the present study developed a methodological approach that integrated local farmers' knowledge, participatory elicitations, and remote sensing information for detecting land use change patterns up to the crop type level from 1954 to 2007 for a case study watershed in northwestern Vietnam. Especially for developing regions which are characterized by data-limited conditions, the combination of qualitative information and quantitative mapping analysis can be a powerful tool for examining spatial patterns of human–environment interactions. Such information is not only important for fostering sustainable landscape management practices locally, but also to support decision-making processes at the regional level and eventually to provide empirical evidence for policy design. Hence, the aims of the present study were the following: (1) Build on participatory procedures and qualitative data focusing on farmer decision rules for assessing historical land use change and crop type patterns, (2) develop a crop type specific classification approach that allows for analyzing remote sensing data from 1954 to 2007, and (3) subsequently, assess land use change dynamics from 1954 to 2007 for a case study watershed in northwestern Vietnam to obtain long-term social-ecological knowledge for deriving implications for landscape management.

2. Materials and Methods

2.1. Study Site

The study was carried out in Chieng Khoi commune, which is one of the 14 communes in Yen Chau district, Son La province (Figure 1). Elevation in the study area ranges from 400 m in the valley bottom to more than 1000 m above sea level on the high karst mountains in the southeastern part of the commune. Chieng Khoi covers about 3100 ha and consists of five villages (Ngoang, Hiem, Put, Tum, and Na Dong). The region is governed by a tropical monsoon climate with an average annual precipitation of 1250 mm. The average annual temperature is 24 °C, with hot summers occurring during May to October, and dry and cold winters from November to April [9,16,17].

The resident Black Thai belong to one of the largest ethnic minorities in Vietnam and have been living in this region for several hundred years [9,16]. The main income comes from smallholder farming activities practiced on an average farm size of 1.7 ha [18] without further mechanization;

indeed, the first handle tractor was introduced in 2007. All households connect strongly with the extended family in the same village or commune. Education level has improved since the 1970s, however, still only a few inhabitants graduated from colleges or universities [17,19].

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 without fertilization or pruning.

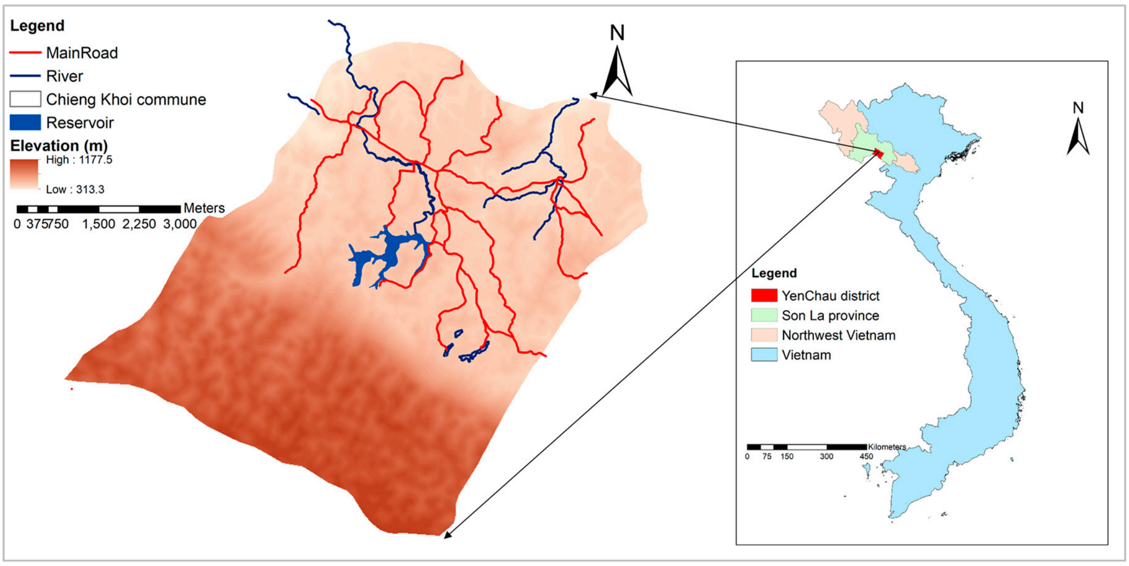

Figure 1. Location of Chieng Khoi commune in Yen Chau district, Son La province, northwestern Vietnam, showing topographic and infrastructure features.

2.2. *Participatory Appraisals and Stakeholder Elicitations*

2.2.1. Farmer Decision Rules on Crop Choices and Crop Rotation

Farmers from three out of five villages in the Chieng Khoi commune were invited to a series of participatory rural appraisals and focus group discussions to determine their decision processes on crop choice and crop rotations. Ban Ngoang, Ban Me, and Ban Hiem villages were selected as they were regarded representative of the biophysical and socioeconomic conditions in the commune.

In each village, 7–10 farmers joined the focus group discussions. Discussions were conducted in an age-sensitive manner by separating participants into a young group aged less than 50 years, and an elder group with participants aged above 50 years. Hagel [20] 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 elder farmers would remember their traditional cultivation systems as they had lived in Chieng Khoi since their childhood. A semi-structured interview format was chosen during focus group elicitations to ensure that participants focused on the outlined discussion topics and to reduce the influence of dominant participants [21]. Separating farmers into two groups further reduced the influence of cultural factors, such as respect by younger farmers to older ones, as also pointed out by Hagel [20].

For each village, three focus group discussions of farmers' decisions on crop choice and crop rotation practices were conducted. Discussion rounds began with the elder farmer group, followed by the young farmer group, and completed by a common elder and young farmer group discussion round. The agreements that were reached in the mixed age group were considered as the final focus group results. The issues and decisions that differed between both groups were considered as "past" decisions (from elder groups) or "present" decisions (from young groups). A pairwise ranking approach was used to elicit the past crop choice patterns as described by the elder participants [22], while matrix tables were created for describing crop preference of present farming systems [23]. By using a crop choice matrix, farmers were requested to choose one crop from every pair following the assumption that "if a farmer has only one plot to cultivate, which crop will he choose from every pair". The ranking exercise was conducted to elucidate the farmer crop decisions. For this purpose, farmers had to rank crops according to their planting preference (Table S1). Subsequently, crops that referred to low yielding local crop varieties and cropped without the input of chemical fertilizer, required a larger cultivation area as compared with high yielding crop varieties for meeting the local food consumption demands.

2.2.2. Participatory Mapping

In addition to the focus group discussions, participatory mapping exercises were conducted with local key informants in five villages—Ban Me, Ban Put, Ban Ngoang, Ban Na Dong, Ban Hiem to estimate the expansion of residential areas in the five villages of the Chieng Khoi commune for the assessment period from 1954 to 2007. In each village, 3–5 key informants were invited to represent farmers who were 50 years or older and other key informants such as village headmen. In addition, at least two respondents were required to be older than 70 years with proven knowledge of the historical land use patterns based on recommendations from local village headmen.

Key informants received color A0 printouts of Google Earth images that referred to the Chieng Khoi commune (coordinates: 21°02′45″ N and 104°18′03″ E; accessed: 18 September 2010) including landmarks such as roads or stream networks, and other important landscape features such as public buildings, among others. Interviews began by requiring every respondent to identify the location of their own houses on the Google Earth image. The next step focused on drawings of the residential boundaries, starting in 1954, and if possible, sequentially for a period of ten years until 2007. Key informant discussions were aligned with historical events, e.g., 1954 when the French army was defeated by the Vietcong during the Indo China War, 1974 referring to the completion of an irrigation reservoir, the implementation of land use reforms, etc. Furthermore, the number of households and estimated population for each village were recorded for each time period if possible to crosscheck the sketched residential boundary. The resulting sketches of the residential area were digitized using Google Earth, and the settlement area expansion was calculated subsequently for each period (Figure 2). Due to the lack of other information, data from annual statistical records on residential areas and population available at the Yen Chau district level were used to substantiate the estimation of the identified residential expansion [24] as elucidated by the focus group discussions.

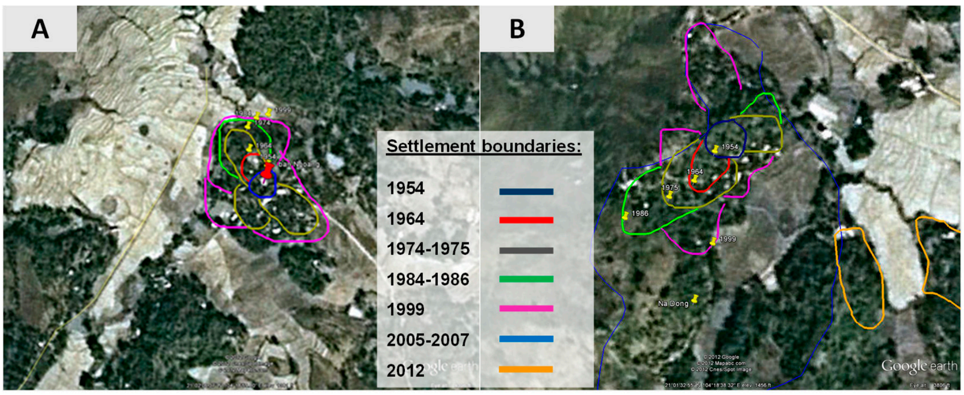

Figure 2. Examples of residential expansion in the villages of Ban Ngoang (**A**) and Ban Na Dong (**B**). Expansion lines were generated based on farmer group discussions combined with sketchings on Google Earth with time and landmarks.

2.3. Ground Truthing, Transect Walks and Plot History

Ground truthing data collection was done separately for present and past land use conditions. A total of 328 ground truthing points was collected in 2009 and 2010 using a handheld GPS device

(Garmin CSX60) to determine present and land use types in 2007 for a specific location. The considered crop type related land use classes (Table 2) did not exhibit changes during a 3–4 year period based on farmer interviews. Moreover, with the exception of the upland cultivation land use classes, ground truthing information was collected together with farmers who owned and managed a respective plot, with each collected ground truthing point subsequently containing information on plot history. Field locations were chosen randomly within the Chieng Khoi commune building on the information obtained from focus group discussions and key informant interviews.

A total of 102 ground truthing points referring to past landscape conditions (1954, 1993, and 1999) were obtained during four transect walks that were conducted with a group of up to five elder farmers. Elders were approached who had grown up in the study region, were more than 60 years of age, and were recommended as knowledgeable by the village headmen. 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 each other to answer questions provided from a checklist related to crop history, field boundaries, important events, and causes and consequences considering crop choice decisions.

Furthermore, semi-structured household interviews were conducted with farmers managing the upland plots surrounding the Chieng Khoi reservoir in 2012. These farmers were selected because the construction of the reservoir was regarded as one of most important events in Chieng Khoi history [17]. Interviews referred to general socioeconomic household characteristics (e.g., education and occupation) and agricultural activities. All plots belonging to the interviewed farmers were assessed for their crop history and the crop-related decisions in a two-stage exercise. Firstly, individual house location, main roads, and land marks were identified by interviewers together with farmers using similar A0 Google Earth image printouts of Chieng Khoi commune (coordinates: 21°02′45′′ N and 104°18′03′′ E; accessed: 18 September 2010). Secondly, locations, size, and current crops of each plot were determined and crop types of previous years were investigated in retro perspective starting in 2012 as the initial year (household interview period) and 1954 as the final assessment year, with the latter one referring to the oldest available remote sensing data source (see also the next section for more information). Famers were further asked to describe the factors which influenced plot level crop decisions. The obtained information was cross-checked and consolidated with the results from the focus group discussion on farmers' decision rules.

2.4. Earth Observation Data

Various earth observation data sources were drawn for producing historical land use maps of Chieng Khoi commune (Table 1). Aerial photographs of 1954 were taken by the French army and obtained from the Data and Map Archive Center, the Ministry of Resources and Environment, Vietnam. Thematic Mapper-TM 1993 and Enhanced Thematic Mapper ETM+ 1999 were downloaded 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) image were obtained from the National Remote Sensing Agency (NRSA), India.

Table 1. List of remote sensing data sources used in this study.

Source	Aerial photograph 1954	Landsat TM 1993	Landsat ETM+ 1999	IRS LISS III 2007
Pixel (m)	5	30	30	5.8 [1]
Date	na [2]	1 February 1993	27 December 1999	4 March 2007
Season	na	dry	dry	late dry season
Sensor	na	TM	ETM+	self-scanning

[1] pan-sharpened to 5.8m; [2] not applicable.

2.5. Integrating Local Knowledge in Land Use Classification Workflow

Various sources of local knowledge and ground truthing information were used in a two-stage approach for mapping the historical land use patterns of the Chieng Khoi commune during the period of available remote sensing data (1954 to 2007) [1]. The first stage was built on a supervised classification approach [23] to produce land use maps for the reference years 1954, 1993, 1999, and 2007 based on the available aerial photos, Landsat TM and ETM, and LISS III images, respectively. The resolutions of the satellite image in 1993 (30 m × 30 m), and 1999 (30 m × 30 m) were rather low which resulted in a spectral confusion as one-pixel size was larger than the average field size in the commune (about 400–500 m^2) [25]. Additionally, no soil map of Chieng Khoi for the reference years 1993 and 1999 existed and farmers were not able to adequately identify ground truthing points during the interviews. This lack of information made it impossible to distinguish the different annual upland crops for the periods 1993 and 1999, respectively. In a second stage, produced land use maps of 1954 and 2007 were overlaid to identify the location of upland cropping patterns through a more detailed crop type level classification procedure. This step was done using the determined farmer decision rules and crop rotation information obtained during focus group discussions to estimate the change of upland cropping areas during 1954 and 2007. While the classification workflow of the first classification stage yielded six land use classes (Table 2), i.e., forest, residential area, open canopy vegetation (not determined in 1954), paddy rice, water body, and upland cultivation, outcomes of the second classification step further separated the upland cultivation systems into maize, upland rice, cassava, and maize-cassava intercropping types in 1954 and 2007, respectively. The detected crop types were defined based on the outcomes of crop choice ranking exercises and the period of the land use map classification exercise (for further details see below). Figure 3 presents the developed classification workflow using the land use map of 1954 as an example.

Table 2. Main land use types for all considered periods (1954, 1993, 1999, and 2007) in the Chieng Khoi commune.

No	LU Type	Description
1	Forest	Dense primary forest and dense secondary forest, fallow *, 7 years or older with medium and large trees (≥10 m)
2	Residential area	Location of farmers' houses **
3	Open canopy vegetation	Mixture of small trees, bush, fruit trees, and planted forests that resemble less dense canopy vegetation (not in 1954)
4	Paddy rice	Low elevation and flat areas where water level is low and that become dry during dry season
5	Water body	Lake or ponds larger than 2500 m^2 (excluding small streams and rivers of ≤10 m width)
6	Upland cultivation	Crop areas cultivated on areas with slopes >5° and elevation >300 m above sea level, also including young fallow stages (1–6 years of age), 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.

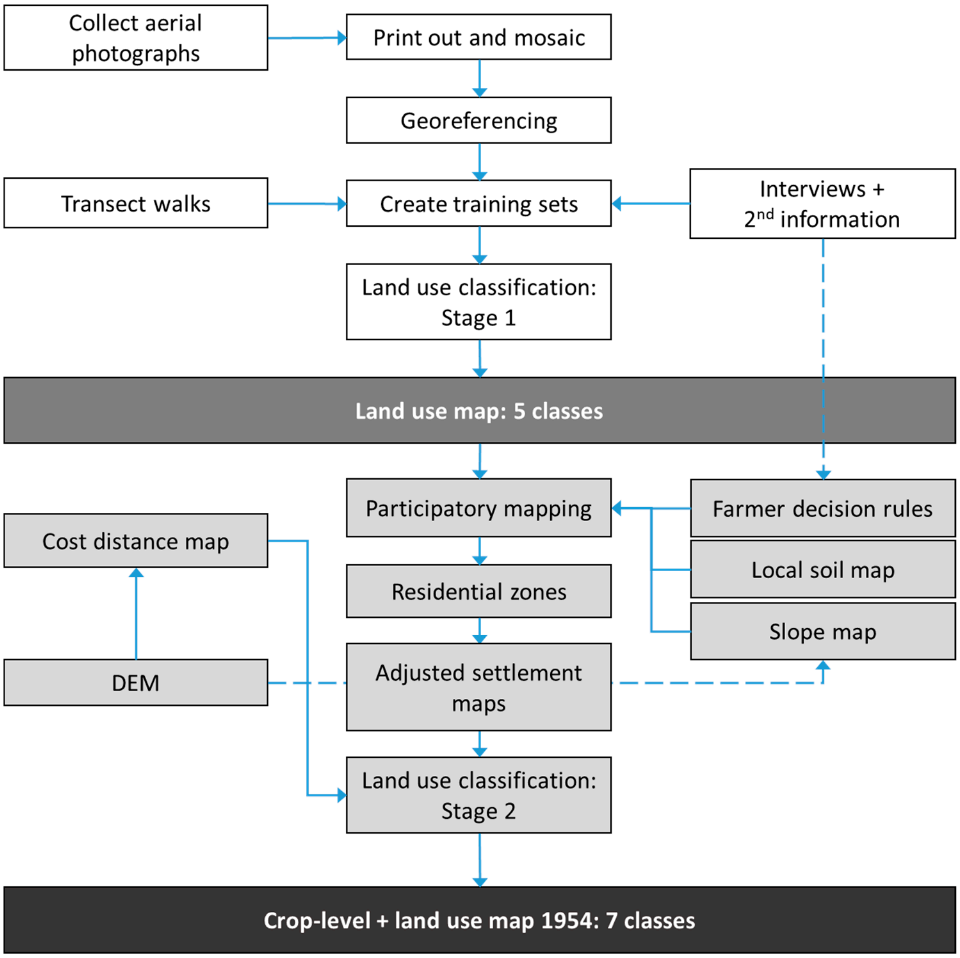

Figure 3. Workflow to classify LU 1954 map at the crop-level classification from aerial photographs combined with historical information from farmers. (Note: In case of 1954, only five land use classes were classified at stage 1, while for all other stages, 6 classes were separated).

2.5.1. Stage 1: Land Use Mapping 1954, 1993, 1999, and 2007

Remote sensing data were cut out based on the study site boundary and preprocessed before executing the supervised classification. Aerial photographs were rectified by geometric correction random distortions [2] and then mosaicked from six black and white colored photographs. Landsat images were radian and geometrically corrected. LISS III 2007 was enhanced with high resolution panchromatic (PAN) data [26].

The land use map 1954 was produced by using a visualization classification approach [4,6], based on image texture, patterns, lightness, and darkness based on the given features of the aerial photos [27]. Training sets for inspection were derived from Giang [27] referring to land use types determined in aerial photographs of the same reference year for selected communes in Yen Chau District. The resulting land use map 1954 was classified into five classes, namely, forest, water body, paddy rice, residential area, and upland cultivation (Table 2), respectively.

The separation of land use classes for 1993, 1999, and 2007 was done visually before the supervised classification was executed with ENVI software 4.3. For this purpose, qualitative information from the participatory rural appraisals (focus group discussions and transect walks), as well as ground truthing data collected in 2009 and 2010 were used. From the obtained ground truthing points, one third were used as the training set for land use classification and two thirds were used for the accuracy assessment of the Landsat 1993 and 1999, and LISS III 2007 satellite images [28,29]. Land use history information referring to transects and plot history was treated as past ground truthing information, and by this means as a further information source to identify past land use types, and for verifying the accuracy of classified land use patterns at a later stage of analysis [29]. A separability analysis of the six classes was applied using transformed divergence (TD) and Bhattacharya distance (BD) statistic parameters [30]. Afterwards, a maximum likelihood procedure was applied to determine the shape of the spatial distribution of six classes from the 328 ground truth points collected during the fieldwork periods in 2009 and 2010. Two forest subclasses were used during the supervised classification for avoiding misclassification caused by shade and slope effects in high rugged terrain in the northwestern part of the study area. Forest subclasses were then merged into one forest class at the final stage of land use classification. As compared with unsupervised classification methods, which are often based on clustering of pixels into sets of classes, such a method is more sufficient to classify land use or vegetation dynamics [26,29,31]. A pixel resolution of 20 x 20 m was chosen for all classified maps to approximate the minimum crop field size of 500 m^2 in the Chieng Khoi commune [24]. A nearest neighbor cell algorithm (ArcGIS 9.3) was implemented to harmonize the spatial resolution of produced land use maps, which is one of the most suitable methods to retain the information for discrete data such because the classes of land use maps [32]. This pixel size refers to the pixel size of the produced land use maps after the supervised classification stage, and not to the original data source resolution as presented in Table 1.

2.5.2. Stage 2: Adjusting for Residential Area Expansion and Upland Crop Types in 1954 and 2007

The second stage of land use classification combined a more detailed upland crop type classification for 1954 and 2007 with a post-classification adjustment process to take the expansion of residential areas in the land use maps 1954, 1993, 1999, and 2007 into account. Map adjustments followed the outcomes of the participatory mapping exercises described above and revealed a more realistic representation of residential area expansion as compared with the supervised classification approach caused by detected misclassification between settlement areas and the open canopy vegetation class. In the case of land use maps for 1954 and 2007, a more detailed upland crop type classification was conducted additionally, aiming to adjust for the outcomes of the participatory elicitations.

As a prerequisite, a historical soil map referring to 1954, a slope map, and a distance map were created based on available secondary data to support the second stage of land use classification procedure. The soil map 1954 was modified from an existing local soil map of Clemens et al. [33] which included twelve soil classes. This map was produced using local farmer knowledge and soil profile information. For this study, the originally described twelve soil classes by Clemens et al. [33] were reduced to a historical "black and non-black soil" and a "stony soil" map building on the outcomes of the aforementioned focus group discussion. Therefore, soil classes with common characteristics, such as soils with a black color, were grouped into one class, and so forth. Subsequently, a "black and non-black soil" map was created containing only two classes: black soil and non-black soil; a "stony soil" map was further created referring to the four classes: black soil non-stony, sandy soil, poor soil, and a combination of red and yellow soil (Figure S1). These classes followed the farmers' descriptions based on their decisions on crop choice and crop allocation concerning soil types.

A slope map was created from a digital elevation model (DEM) derived from contour lines from the National Geodatabase, Data and Map Archive Center, Ministry of Resources and Environment of Vietnam. The distance map was produced using the Cost Distance toolbox of ArcGIS 9.3. Cost distance tools calculate the least accumulative cost for each cell to specified source locations (i.e., residential areas) over a cost surface (i.e., slope map). Cost distance is the prerequisite for finding the least cost path or corridor (Esri 2017). In this case, the distance from homestead to all potential crop locations in the Chieng Khoi commune was calculated (Figure S2).

In the case of land use in 1954, the specific location and area of the main upland crops upland rice, cassava, and maize could be further separated, building on outcomes of the participatory mapping exercises. Because these crops served as basic subsistence crops during the assessment period, elder farmers (>50 years) were asked to define the proportion of preference crops to fulfill food security for a household in 1954 referring to the upland cultivation area from the supervised land use classification process per crop type (maize, cassava, and upland rice) accordingly. For this purpose, the first choice of farmer crop location was adjusted during the mapping exercise by increasing the distance from resident areas on farmer appreciated soil types and slopes. The increasing distance adjustments were halted once the defined areas of the first choice crop by the farmer were reached and the quantity of the defined areas were determined by the historical crop rotations building on the focus group discussions described above. The same procedure was applied for the remaining crops, ranked as second and so forth choice. The adjustment process outcomes were digitized using ArcGIS 9.3 and PCRaster [34]. Figure 4 shows the adjustment processes as done in ArcGIS and PCRaster software, 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 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, the first crop choice area was deemed a potential crop area. Otherwise, the distance from residential areas to upland fields was increased by 100 m intervals during the participatory mapping exercise until the potential crop area fulfilled the defined area requirements for the first crop choice. The following second, third, and fourth crop choice was accordingly spatially adjusted using the same approach, however, excluding the area of previous crop choice selection.

After the completion of the land use mapping workflow, a "fuzzy logic" approach was employed for achieving a better fit of upland crop type distributions as compared to a rule-based classification approach which uses information such as local knowledge. For this purpose, identified crop types in the land use map 1954 were randomly distributed using weighted fuzzy membership values as representative crop types, building on a concept by Zhu et al. [35,36].

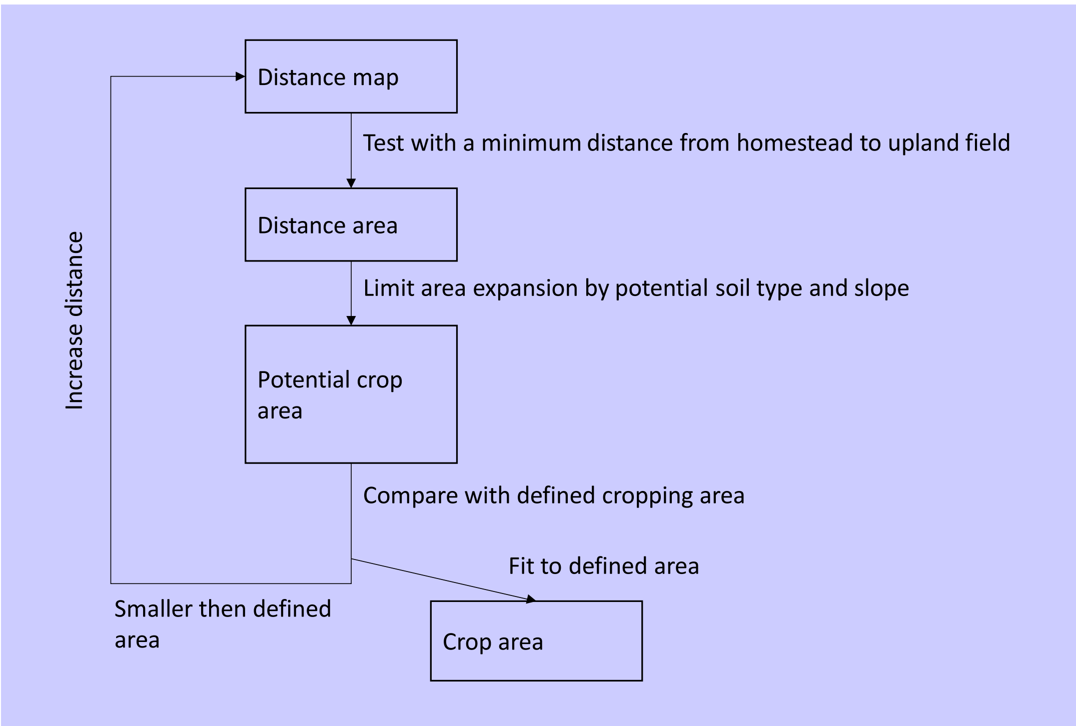

Figure 4. Adjustment processes to define the cropping area from first to fourth choice crops in upland areas of the Chieng Khoi commune in 1954. Crop area boundary was set up when the potential crop area equals the defined areas from the crop rotation and the farmer decision rules.

For the case of land use in 2007, information of available harvesting calendars [28], a local soil map [33], and a crop decision tree retrieved from farmer interviews were used to distinguish the different upland crop types, respectively. For this purpose, upland areas as classified in the land use map 2007 were first converted into vector files. These polygons were then used to mask and extract upland crop areas from the LISS III images as regions of interest (ROI) for further crop-level classification using ArcGIS 9.3. The detailed 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 an available local soil map [36] using ENVI 4.3 and ArcGIS 9.3. Suitability per crop type was used as the indicator in this case to assign the crop location using the crop choice decision tree derived from the participatory rural appraisals as described above.

2.6. Accuracy Assessment

The validity of the produced LU map 1954 was cross-checked by an independent focus group discussion with farmers who did not participate in the previous elicitations. Cross-checks were done by presenting the LU 1954 map to the "independent farmer group". The percentage of the independent farmer group agreeing with the produced map of 1954 was used as an accuracy proxy due to the lack of other independent information. Hence, the comparison between calculated and defined areas by crop rotation and farmer decision rules (see Table S2 for further explanations) was treated as a form of validation which was considered acceptable for such a historical land use mapping exercise [37].

For the case of the maps of 1993, 1999, and 2007, Kappa coefficient was used for accuracy assessment. 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, a value greater than 0.4 is acceptable [38,39].

2.7. Upland CroppingAarea Change Detection 1954 and 2007

The cropping area change was analyzed by overlaying the crop type specific land use maps of 1954 and 2007 to distinguish between upland areas that were under permanent cultivation since 1954 (upland rice, maize, cassava, and intercropping), were cultivated in 1954 but used for other purposes in 2007, or were not under cultivation in 1954 but were used for cropping in 2007, respectively.

3. Results

3.1. Farmer Decision Rules and Crop Rotations

3.1.1. Plot-Level Decision Rules

Focus group participants gave high priority to staple crops for the period from 1950 to 1960, which was explained by their lower productivity as to modern hybrid and fertilized crop varieties (see Table 3). Subsequently, highest priority was attributed to upland rice and paddy rice, followed by a three-year cassava variety which was introduced during the Indo China War in the 1950s. From 1954 onwards, cassava became an important staple crop with its cropping area further expanding in the 1960s. Vegetables and minor crops such as herbs and medicinal plants were only used for home consumption and were grown in home gardens or intercropped with the major crops during that period (Table 3). Only the most common crops were considered by participants during the focus group exercises, while crops with a cropping area of <1 ha were excluded from the pairwise ranking list. In addition, crops such as cotton, mulberry, and potato, which were planted only for a short period of up to two years, were also excluded by focus group participants (Table S1).

Table 3. Results of farmers' ranking on crop choice from 1950s to 1990s based on focus group discussions, carried out in the Chieng Khoi commune, Yen Chau district, Son La province, northwestern Vietnam.

Rank	Name of Crops *	Reasons
1st	Paddy rice and upland rice	Staple crop, both paddy rice and upland rice were the first choice as both revealed no area competition. Paddy rice was planted on flat land or terraces while upland rice was planted in upland areas without irrigation.
2nd	Three years cassava **	Staple crop which was not common before 1950s, but became more frequent and important after 1954 until 1990s. Crop served as important starch source in the household.
3rd	Maize ***	Additional food for home consumption with low crop yields (>0.5 Mg per ha), grown in upland fields following upland rice and often used as livestock feed
4th	Peanut	Additional food source and added as a flavor for household meals

* Name of crops varied, for example in some villages, farmers used crop characteristics as indicator. ** Crop was named as local cassava or high cassava. *** Crop was also named as sticky, local maize or white maize.

Paddy rice requires a consistent and large irrigation supply, thus this crop was planted close to water sources (rivers, springs) or terraced on sloping lands, while rain-fed crops such as upland rice, maize, and cassava were planted on hills surrounding the villages during the described periods. As a result, there was no highlighted 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. Total area and location of paddy rice production plots were almost constant until 1973, when an artificial reservoir was established and irrigation management improved as revealed during the focus group mapping exercises.

The location of upland crops was determined by the focus group participants using period-dependent criteria. For example, from the 1950s to 1990s the importance of crop, distance to transport products from fields to house, convenience of harvesting, weeding and soil management, slope, and soil properties (soil color and texture) were chosen during the participatory exercises. In the past, shifting cultivation required the clearing of forest and fallow areas on an annual basis. Subsequently, these areas were called "1st year", while already cultivated land was named "2nd year (+)". As a priority crop for upland fields, upland rice was chosen predominantly for "1st year" areas (Figure 5). "2nd year (+)" fields were either prioritized for second year upland rice cropping followed by maize or cassava cultivation. Fields within a relatively short walking distance of <1 h to homesteads, being of good soil quality as indicated by black topsoil color, and of non-stony character were further prioritized for three-year cassava cropping, while maize was cropped on black soils with a stony topsoil character. Participants further described that topsoil color changed after a two- to three-year cropping cycle from black to grey, reddish or yellowish color, with those fields of changing soil color left fallow thereafter. In the case of areas characterized by good soil quality (i.e., black soils) and walking distances of greater than 1 h to homesteads, fields were additionally characterized by their level of stoniness. Fields which were defined as non-stony were used for maize and cassava intercropping, whereas, stony soils were used for maize and "bad" soils (also named as non-black soils in the local soil map in Figure S1) were left fallow (Figure 5).

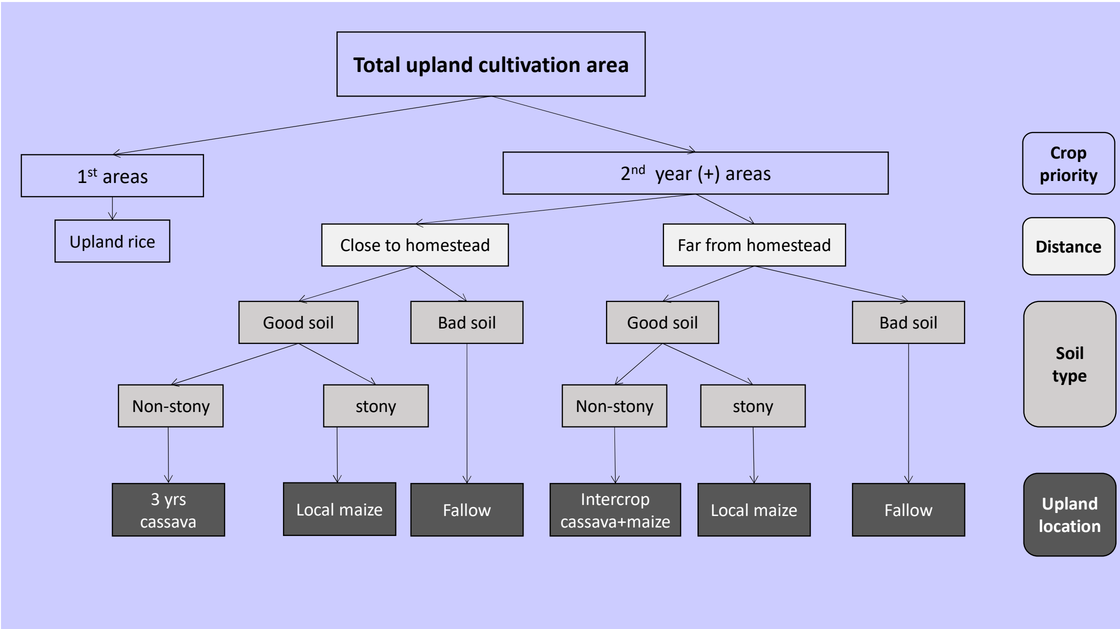

Figure 5. Farmers' decision tree on the location of upland crops during 1950s and 1990s in the Chieng Khoi commune as determined by a combination of distance from homestead and local soil type.

In the assessment stage of 2007, farmer decisions were different, and cropping area expansion to natural forests was officially banned while road infrastructure had improved significantly. Access to distant upland plots was further facilitated by the increasing availability of motorbikes, with the results that distance from homesteads to fields became a less important crop allocation selection criteria. In this period, farmers stated that good soil types could be used for all crops while poor soil types were considered suitable for cassava only. In the case of soils with an intermediate fertility level, maize cultivation requires fertilizer inputs, which were, however, often unaffordable due to a household's financial constraints. Therefore, farmers preferred to grow cassava or intercropped maize and cassava. Focus group participants further described that earlier harvesting of hybrid maize varieties, as compared to the local varieties, led to longer periods of bare soil exposure, while cassava or the intercropping system still provided sufficient soil coverage. In the case of high soil stone contents, farmers planted maize, or inter alia, intercropped maize with cassava. Locally observed changes in topsoil color (still black or becoming brownish) gave further indications in deciding which crop to plant. The outcomes of the focus group discussions revealed the continuous relationship between topsoil quality, cropping calendar, soil characteristics, and crop cover, as described by Lippe et al. [9] among others for the case of northwestern Vietnam.

3.1.2. Crop Rotations

A further outcome of the focus group discussions and key informant interviews was the identification of the crop rotation systems for the investigation period of 53 years. In the case of northwestern Vietnam and Chieng Khoi commune, composite swidden cultivation systems were common and popular until the 1990s integrating upland rotating crop and 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 from middle February to June, and then from July to November. Livestock manure was applied annually to compensate nutrient export and to enhance topsoil properties. Pest and weed control were conducted manually. In the upland areas, farmers slashed and burned fields after harvesting and planted their rain-fed crops at the beginning of the rainy season. As a result, upland crop rotations were grouped into 3 major periods:

- 1954 to 1973, due to the completion of the reservoir in 1974 (establishment started in 1968);

- 1973 to 1993, a transition period where new land laws provided farmers long-term land use rights;
- 1993 to 2007, sub-grouped into:
    - 1993 to 1999, land title rights for agricultural land provided (also referred to as Red Book) was applied in 1999 in Chieng Khoi commune;
    - 1999 to 2007, due to available remote sensing data (here: LISS III).

In the first period of 1954 to 1973, upland rice was planted for two years after removing and slashing forest areas (or older fallow areas). In areas with low productivity, upland rice was planted only for one year. Intercropped maize or three-year cassava followed upland rice in the crop rotation cycle because cassava was introduced at the beginning of the 1950s, and commonly planted after 1954, while maize had been always cultivated by farmers in case of Chieng Khoi (Figure 6). During the period 1973–1993, fallow duration was shortened from seven to three or four years, while maize and cassava intercropping followed a two-year upland rice cultivation cycle. With the introduction of hybrid maize varieties in 1993, upland rice cultivation was gradually abandoned and fallow periods lasted only two years before the next cropping cycle of hybrid maize was started again. However, after the introduction of land ownership titles, farmers increased their investment in plots (including chemical fertilization), and fallow periods were abandoned from crop rotations completely. Remaining cropping systems were monoculture hybrid maize or hybrid cassava intercropped with hybrid maize. Occasionally, maize was intercropped with timber trees such as *Tectona grandis* or *Chukrasia tabularis*. From 1999 to 2007, hybrid maize became the dominant crop except in areas with very poor soil conditions (Figure 6).

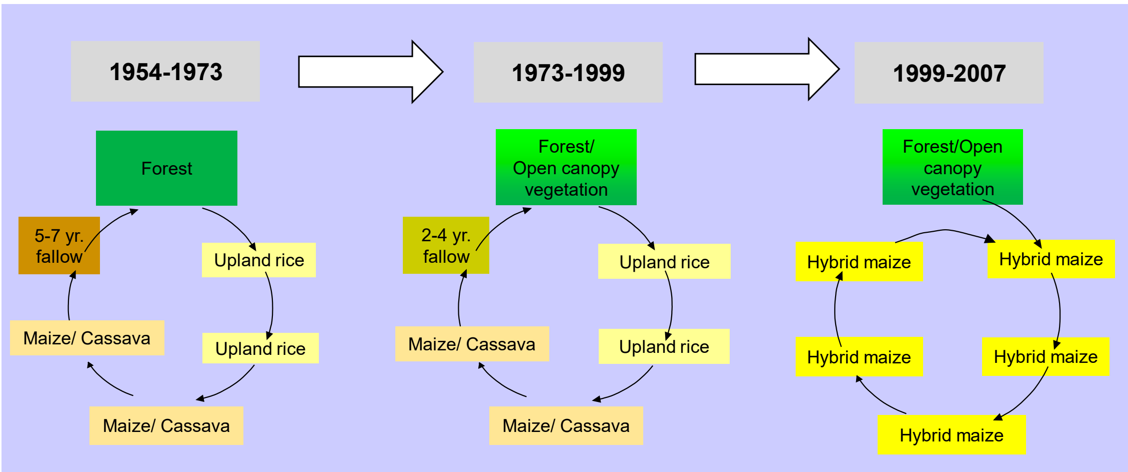

Figure 6. Identified major crop rotation patterns in upland areas of Chieng Khoi commune from 1954 to 2007.

3.2. Land Use Mapping Using Outcomes of Participatory Procedures

Post-classification of the aerial photographs of 1954 derived five land use classes: residential area, water body, forest, paddy rice, and upland cultivation area. A total of 80% of older farmers agreed with the final classified map during the validation discussion. The land use class "water body" was visible in the image and differed from the paddy rice, whereas, upland fields and young fallow areas were not distinguishable with available black and white aerial photos. 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.

Land use classes for the periods of 1993, 1999, and 2007 were classified in six groups: forest, open canopy vegetation, residential, water body, upland, and paddy rice with an overall accuracy values each year of 81.1%, 98.5%, and 82.5%, while Kappa coefficients were 0.68, 0.98, and 0.74 for these years, respectively (Figures S3 and S4). The land use class "water body" represented the artificial lake in the Chieng Khoi commune (40 ha).

Change detection was conducted using cross tabulation analysis to determine the quantity of conversions between different land cover classes with Table 4 showing the area of land types from 1954 to 2007. Water body and paddy rice areas increased and decreased in area during the assessment period of 53 years. Residential area increased from 4 ha to 44 ha from 1954 to 2007. Forest area dropped from 83.4% in 1954 to 29.7% in 2007, which was mainly associated with the increase in upland cultivation area from 10.1% in 1954 to 22.7% in 2007, and open canopy vegetation from 1.6% to 42.1%, respectively. Upland cultivation area almost doubled from 1954 to 2007. The overall trends of increasing upland cultivation and decreasing forest area were consistent during the assessment period of 1954 to 2007 (Figure 7).

Table 4. Statistic LU type areas derived from remote sensing classification in the Chieng Khoi commune from 1954 to 2007.

No	Land Use Types	Area (ha)			
		1954	**1993**	**1999**	**2007**
1	Forest	2595	1146	1303	929
2	Residential	4	20	44	44
3	Open canopy vegetation	51	1552	1239	1317
4	Paddy rice	140	83	92	110
5	Water body	4	18	26	17
6	Upland cultivation	315	308	423	708
	Total *	3109	3127	3127	3125

* Difference in total areas relates to resolutions of the original remote sensing sources; 1954 (5 m), 1993 and 1999 (30 m), and 2007 (5.8 m).

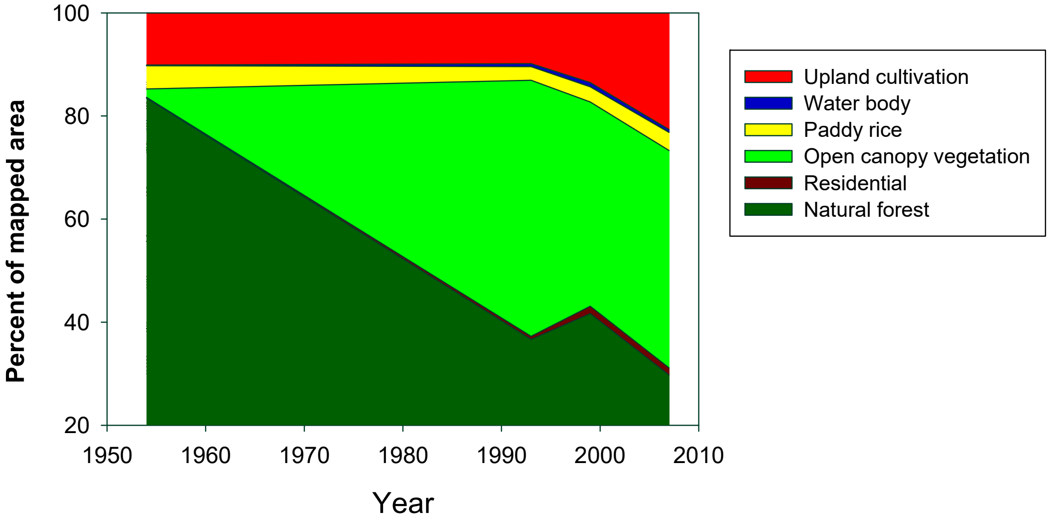

Figure 7. Area covered by different land use types from 1954 to 2007 in the Chieng Khoi commune.

3.3. Crop-Level Classification in 1954 and 2007

3.3.1. 1954

Building on the first land use classification outcomes described above, the resulting output was used for a more detailed crop-level classification. For this purpose, findings of the participatory procedures such as crop rotation patterns (Figure 6), farmer decision rules (Figure 5), and crop choices (Table 3) were used for the corresponding spatial allocation process. During 1954–1973, the local average cropping period was four years, while fallow periods covered six years. Thus, after ten years, abandoned cropping areas would have developed into a secondary forest type (Figure 6). Subsequently, for classifying each crop, the total upland cultivated area of Chieng Khoi was divided into 10 proportions (or "defined areas" of 31.5 ha), with each proportion representing an average area covered by one cultivation cycle (2× upland rice, 2× maize and cassava, 6× fallow). Spatial locations of each proportion were adjusted in ArcGIS and PCRaster based on farmer decision rules (Figure 4). The location of first and second proportions were assigned for upland rice areas, third and fourth proportions were assigned for maize and cassava intercropping, and from fifth to tenth proportions were assigned for fallow areas. Table 5 presents the outcomes of the spatial adjustment process (Figure 4), the resulting maximum distance to residential areas, and additional criteria referring to local soil types and topographic features. Figure 8 illustrates the produced crop-level land use map of 1954 and depicts that large areas of upland cultivation were left fallow during this time period.

Table 5. Maximum distances of upland crops to homesteads in the Chieng Khoi commune in 1954, used during the adjustment processes using farmer decision rules on upland crop distribution.

Crops	Maximum Distance to Homestead (m)	Additional 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 with upland rice, maize, and cassava.	188
Total			315

3.3.2. 2007

A detailed crop-level land use map for the year 2007 was produced applying a similar approach as described above using the initially classified land use map plus information building on the farmer decision rules described in Section 3.1. In this case, a detailed classification was conducted to obtain land use types at crop-level, mainly maize, cassava, and intercropped (maize and cassava), which was not distinguishable based on using the remote sensing data only. During this time, the maize hybrid variety was the dominant monocropping type that was planted without fallow periods in Chieng Khoi (see Section 3.1.2), although cassava and intercropped fields were still detected on poor soil areas based on farmer decision rules. Maize, cassava, and intercropping were distinguished with high overall accuracy values (84.4%) and an acceptable Kappa coefficient (0.74). The detailed land use map for 2007 finally resulted in the separation of eight land use classes including the additional three classes of maize (282 ha), cassava (283 ha), and intercropped maize and cassava (163 ha) (Figure 8), respectively.

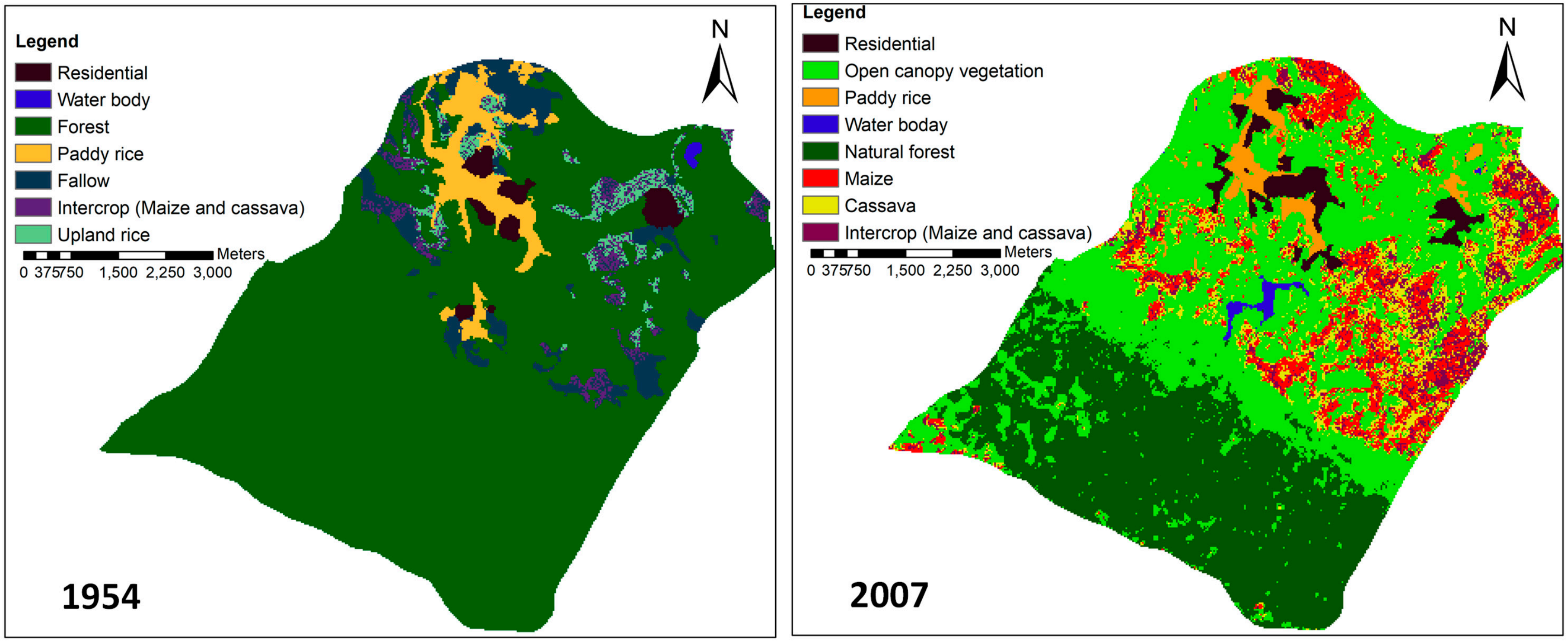

Figure 8. Detailed land use maps for 1954 and 2007 of Chieng Khoi commune, Yen Chau district, Son La, Vietnam. The detailed maps were classified from aerial photograph and LISSS III integrated with local knowledge.

3.4. Crop Transitions and Expansion

Figure 9 shows large areas that were transformed into cultivated areas (591 ha), while 117 ha remained as cultivation areas during the assessment period of 53 years. In 2007, the distance to residential areas was no longer an important criterion of farmers' crop choice due to infrastructure improvements (transportation by motorbikes) and attractive high cash crop prices. As a result, upland cultivation areas occurred in the entire watershed area in 2007. Upland rice was used as the main upland crop in 1954, however, was abandoned by 2007 in the Chieng Khoi commune as depicted by the comparison of the detailed crop type maps of 1954 and 2007. Furthermore, maize cultivated in a monocropping arrangement appeared only in 2007, while maize and cassava intercropping were reported for both periods. Although, the choice of intercropped maize and cassava in the assessment years differed. While in 1954, farmers decided for intercropped maize and cassava in areas far from the residential areas, characterized by fertile soils without stones, farmers intercropped cassava in those areas previously only cropped by maize after yields started to decline in 2007.

Figure 9 further reveals that about 34% of natural forest remained in the southwest part of the commune, while some areas of paddy rice and settlement locations remained at the same location over the 53 years. Other land use classes occupied about 66% of the communal area, mainly attributed to upland crops and large areas of natural forest that were replaced by different land use classes, especially when focusing on the analysis from the center and towards the northern parts of the commune.

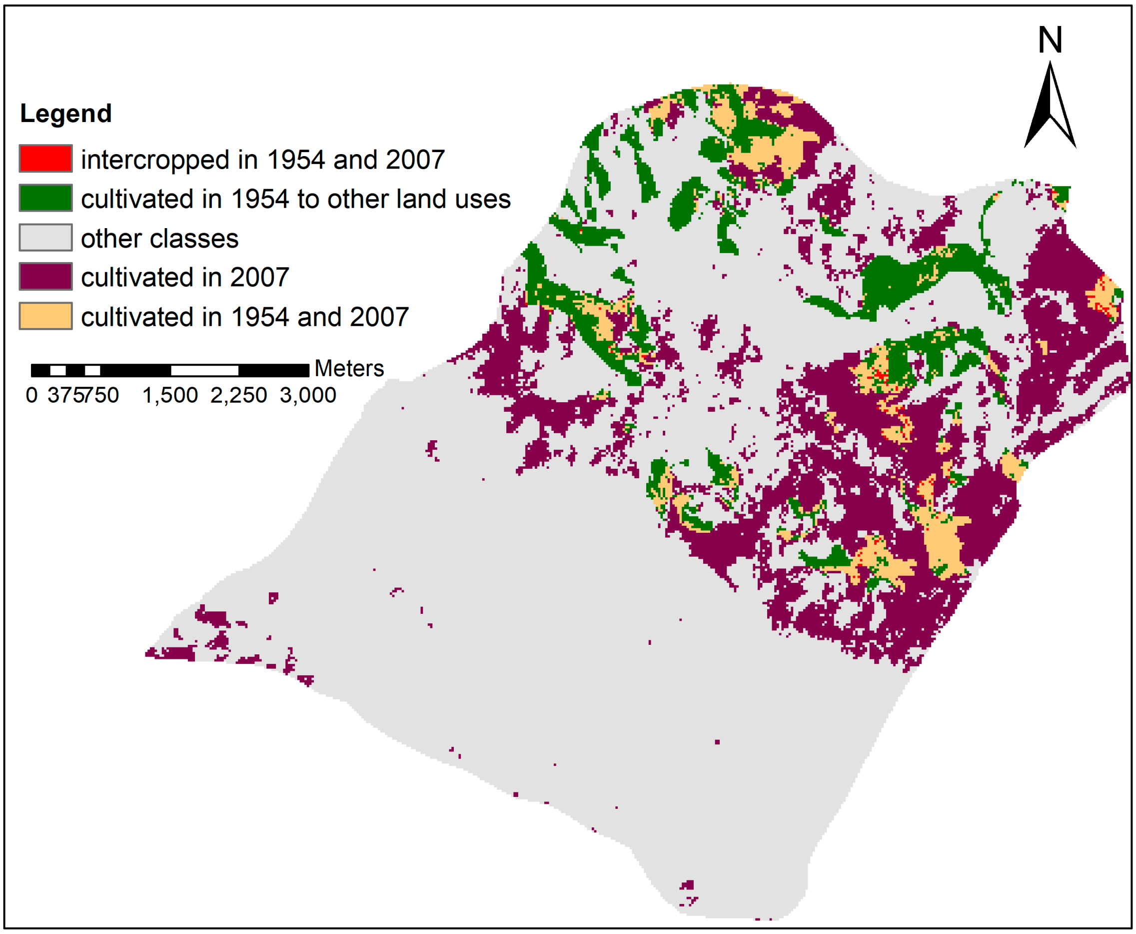

Figure 9. Change detection upland cultivation areas in the Chieng Khoi commune from 1954 to 2007.

4. Discussion

4.1. Innovative Crop Mapping Approach

The presented approach combined farmer knowledge from various forms of participatory elicitations and remote sensing data for the mapping of historical land use patterns. The identification of detailed crop type systems in 1954 and 2007 could be achieved based on the division into a two-stage approach building on the elucidated farmer decisions on cropping preferences. The conducted map adjustment processes further enabled the allocation of individual crop types to a specific upland area. These processes were done for each crop area by the distance to residential areas and were one of the most time-consuming parts of our participatory analysis. Compared to a study by Vittek et al. [40], our approach allowed us to map out more detailed locations of the main crops while using historical remote sensing data. The developed approach is especially interesting when focusing on detailed crop rotation patterns, which can be relevant for identifying hotspots of current and potentially future land degradation. On the contrary, building solely on farmer decision rules can be also considered a weakness of the presented approach as it was influenced by memory recalls and potentially uncertain information as elucidated by the participatory focus group discussions. However, given the nature of historical land use mapping exercises, the obtained information was the only information source that allowed for a retrospective assessment of past land use and crop type patterns [1]. Our study revealed how historical land use change dynamics transformed upland cropping patterns of the Chieng Khoi commune, and how the expansion of cropping areas evolved during the assessment period of 53 years. In this context, validating the detailed crop type map of 1954 was another challenge of this study. Many of the participating elder farmers could not remember precisely the location of individual crop fields, and thus validation of historical crop locations followed focus group agreements. Additionally, many agricultural policies were influenced by government actions and cross-sectoral policy frameworks [41], which could not be acknowledged in the conducted participatory mapping processes, although the spatial expansion of upland crop areas was considered accurate by local stakeholders. Our approach showed the results of interactions between farmers' needs, their action, and their resulting livelihood patterns as well as government policies.

The employed approach of multi-criteria farmer decision by scoring was useful in providing information on crop rotation cycles and the most important crops cultivated in the Chieng Khoi commune during the assessment period. Scoring and ranking exercises also helped focus group participants to prioritize on the most relevant crops for avoiding a form of false precisions, thereby supporting the research team in understanding the use of other minor crops such as herbs and vegetables, or the cultivation of fruit trees such as mango in a home garden setting. Such information cannot be considered in all facets during the mapping process. Our approach included the level of accessible data that is usually common in many rural regions, where data limitation often pose challenges to government authorities and local stakeholders [14,21]. Hence, the developed approach could be used as a role model for such regions. For example, the participatory decision rules elucidated during focus group discussions can be combined with other types of open source remote sensing data or archives. Moreover, decision rules on farming practice can be beneficial in a developing country context as compared to only producing historical land use and crop type maps from a classical remote sensing analysis. Our study illustrates that participatory rural appraisals can enhance and support historical data analysis for land use change research, eventually compensating data limitations often existing in rural environments. As such, it can provide important information for decision support or landscape management at the communal or watershed level for many rural regions of the Global South.

4.2. Importance of Local Stakeholders in Classifying Historical Land Use Maps

Local knowledge of farmers and villagers supported the land use classification process. Without their contribution of historical ground truthing points and farmer decision rules, the employed remote sensing classification approach, whether supervised or unsupervised, would not be sufficient in depicting historical land use patterns nor investigating upland crop distribution patterns. Kibret et al. [12] used a multitemporal approach to improve land use classification of agricultural crops over a 41 year period (1972 to 2013) in South Central Ethiopia using MODIS and LANDSAT satellite image. Although in the case of Kibret et al. remote sensing data were available for the assessment period, local knowledge was still a useful input for the employed supervised classification approach and reduced misclassified pixels by 18%. In our study, local knowledge was not only used for the land use classification at crop level, but was also implemented to validate the historical land use maps. This information provided a significant value for the classification exercises as farmers played an important role in determining historical land use change patterns [13–15]. Our study falls in line with studies such as [13,42] relying on a combination of remote sensing classification and local knowledge sources for land use mapping, but by comparison covering a much longer time horizon of more than five decades allowing long-term analysis of human–environment interactions. Moreover, Mundia et al. [42] concluded that participatory mapping is a good tool to involve local communities in a research process and to promote awareness and empowerment of local stakeholders. Participatory approaches, as part of a wider rural appraisal concept, are becoming more and more accepted as a means for documenting and incorporation long-term social-ecological knowledge into the research process. Building on local stakeholder's knowledge fosters public support for sustainable land management practices and knowledge exchange, and for understanding the spatial patterns of ecosystems and landscape interactions.

4.3. Lessons Learned and Implications for Regional Landscape Management

The study findings revealed that stakeholder's cognitive, spatial knowledge can be converted into maps that can inform policy making. Local spatial knowledge, as elucidated by the participatory mapping exercises, can be used to understand driving factors of land use change, and improve land tenure and land management decision-making processes at the local level [43]. The methodological approach developed for this study can be beneficial for local government authorities because it essentially builds on two focus group discussions, a series of key informant interviews, and open source remote sensing data. For example, staff of land management bureaus holding basic GIS knowledge could build on a similar concept to reveal historical cropping patterns of a particular landscape area to support local government decision processes. A study by Basupi et al. [10] showed the value of integrating local spatial knowledge into policy making and how this supported sustainable landscape management. The combination of freely available remote sensing data and participatory rural appraisals is receiving wider recognition as a form of low-cost landscape assessments, in particular for data-limited areas such as northwestern Vietnam [28,42]. Open access remote sensing data, as provided by Google Earth, is becoming increasingly used for understanding land and surface cover dynamics in a landscape setting [11,42]. The successfulness of such endeavors, however, only plays out by the combination of remote sensing and ground truthing information. Hence, participatory appraisals as employed in this study can be also considered a cost-effective method for ground truthing campaigns. Engaging farmers and building on their decision rules proved to be not only useful for land classification and map validation processes, but also lead to an improved awareness of local stakeholders involved in the research process by understanding how unsustainable farming practices can lead to land degradation [44,45]. The produced detailed crop type maps can also be used as a baseline for landscape planning and natural resource management. For example, cultivation areas that were cropped continuously for a longer period of time, as depicted for example in Figure 9, may also be used to identify hotspots of soil nutrient imbalances. Such areas can then receive greater attention for landscape restoration or reforestation efforts [46].

5. Conclusions

This study revealed how participatory rural appraisals and remote sensing data can be integrated for documenting long-term socioecological knowledge of local farmers and to analyze land use change patterns during more than five decades. The developed methodological approach can be especially beneficial for data-limited environments which is a prevalent phenomenon in many developing regions. The generated long-term historical land use and crop type dataset was used for understanding how anthropogenic activities altered the study area and what potential impact this can have on the natural resource base and future farming activities. 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 map adjustment processes enabled a detailed crop type change detection process which highlights the urgent need of implementing sustainable land management practices in the case of the Chieng Khoi commune and northwestern Vietnam in general.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-445X/8/9/130/s1, Figure S1: Local soil map of the Chieng Khoi commune for reference year 1954, modified from Clemens et al. [36]. 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, Figure S2: Slope map and distance maps of the Chieng Khoi commune, Figure S3: Remote sensing data (aerial photograph 1954, Landsat 1993, 1999 and LISS III 2007), Figure S4: Land use map of 1954, 1993, 1999, and 2007 classified from remote sensing data in Appendix 5a using the supervised classification method. Table S1: Crop choice matrixes developed during focus group discussions; abbreviations refer to the choice-crop as a result of the pairwise ranking exercises; crops with a higher score refer higher farmers' choice; crop choice matrixes refer to different years and stages representing participants agreements during focus group discussions, Table S2: Comparison of identifying areas after the adjustment process with defined areas, as cropping areas to produce the required food intake according to farmers; positive values indicating that estimated cropping areas were higher than the defined target area*, while negative values indicate estimated cropping areas lower than the defined targeted values. The calculation of the sixth year fallow area received the largest deviation from the "defined value", in this case −0.78 ha, the smallest different areas were the calculation for the second year of fallow, fifth year fallow (+0.02 ha), and second year maize and cassava (−0.02 ha). While increasing the distance to reach the defined areas, upland rice crop (in first and second year) had the closest distance to residential areas (1.1 km) while fallow (at all stages) revealed the longest distance to residential areas (2.14 km). The area resulting from all calculations slightly differed with defined areas. For validating the map, four out of six participants agreed with the resulting crop-level maps, while one participant disagreed, and one participant only partly agreed (this farmer mentioned that he gave the grade 5/10 for the result).

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