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ANALYZING LAND COVER CHANGE AND IT'S DRIVERS BASED ON MULTI-SOURCE DATASETS: A CASE STUDY IN THE NORTHERN VIETNAMESE MOUNTAINS [1]

ANÁLISE DAS MUDANÇAS NA COBERTURA DA TERRA E SEUS FATORES DETERMINANTES COM BASE EM CONJUNTOS DE DADOS DE MÚLTIPLAS FONTES: UM ESTUDO DE CASO NAS MONTANHAS DO NORTE DO VIETNÃ

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Abstract
Land Use/Land Cover Change (LUCC) results from processes operating across multiple spatial scales and organizational levels. These changes are driven not only by exogenous factors, such as land-use policies, economic modernization, and globalization, but also by endogenous household-level livelihood decisions. This study compares land cover data from multiple sources to reconstruct historical land cover dynamics from the 1950s to the present across different spatial scales in the northern Vietnamese mountains. Analyses were conducted at the provincial level in Lao Cai Province and at district and village levels in Sa Pa district, using high- to very high-resolution remote sensing imagery. Results indicate a net loss of forest cover during the long-term period (1952–2012). In contrast, short-term analyses (2000–2014) reveal increasing forest cover at village, district, and provincial levels, with the largest gains observed at the provincial scale (8,630 ha yr^{-1}). Changes in Sa Pa district and selected communes were considerably smaller. Overall trends are consistent with national patterns. Multi-scale analysis identifies land-use policies, agricultural intensification, livelihood diversification, accessibility, and poverty as key drivers of land cover change in the northern Vietnamese mountains.

Keywords: Land Cover Change. Multi-Scale. Northern Vietnam. Remote Sensing.

Resumo
A mudança no uso e cobertura da terra (LUCC, na sigla em inglês) resulta de processos que operam em múltiplas escalas espaciais e níveis organizacionais. Essas mudanças são impulsionadas não apenas por fatores exógenos, como políticas de uso da terra, modernização econômica e globalização, mas também por decisões endógenas de subsistência em nível familiar. Este estudo compara dados de cobertura da terra de múltiplas fontes para reconstruir a dinâmica histórica da cobertura da terra desde a década de 1950 até o presente em diferentes escalas espaciais nas montanhas do norte do Vietnã. As análises foram conduzidas em nível provincial na província de Lao Cai e em níveis distrital e de aldeia no distrito de Sa Pa, utilizando imagens de sensoriamento remoto de alta a altíssima resolução. Os resultados indicam uma perda líquida de cobertura florestal durante o longo período (1952–2012). Em contraste, as análises de curto prazo (2000–2014) revelam um aumento da cobertura florestal em níveis de aldeia, distrito e província, com os maiores ganhos observados na escala provincial (8.630 ha ano $^{-1}$). As mudanças no distrito de Sa Pa e em comunas selecionadas foram consideravelmente menores. As tendências gerais são consistentes com os padrões nacionais. A análise multiescalar identifica as políticas de uso da terra, a intensificação agrícola, a diversificação dos meios de subsistência, a acessibilidade e a

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pobreza como fatores-chave da mudança na cobertura da terra nas montanhas do norte do Vietnã.

Palavras-chave: *Mudanças na Cobertura da Terra. Multiescala. Norte do Vietnã. Sensoriamento Remoto.*

1 INTRODUCTION

As many tropical countries, Vietnam was characterized by a net deforestation during the period 1950s-1990s (Lang, 2001). Since the 1990s, Vietnam has experienced a net increase in forest cover as a result of forest policies, economic growth, and market integration (Meyfroidt & Lambin, 2008a). However, forest cover dynamics vary locally, and national-scale inventories mask disparities that might exist at local scales (Clement & Amezaga, 2008; Clement et al., 2009; Meyfroidt & Lambin, 2008a; Sowerwine, 2004). Single-scale analyses of land cover change might not be enough to reflect the complexity of mountainous regions in e.g. northern Vietnam (Jean Christophe. Castella, Dang Dinh Quang, et al., 2002; Jadin et al., 2013b).

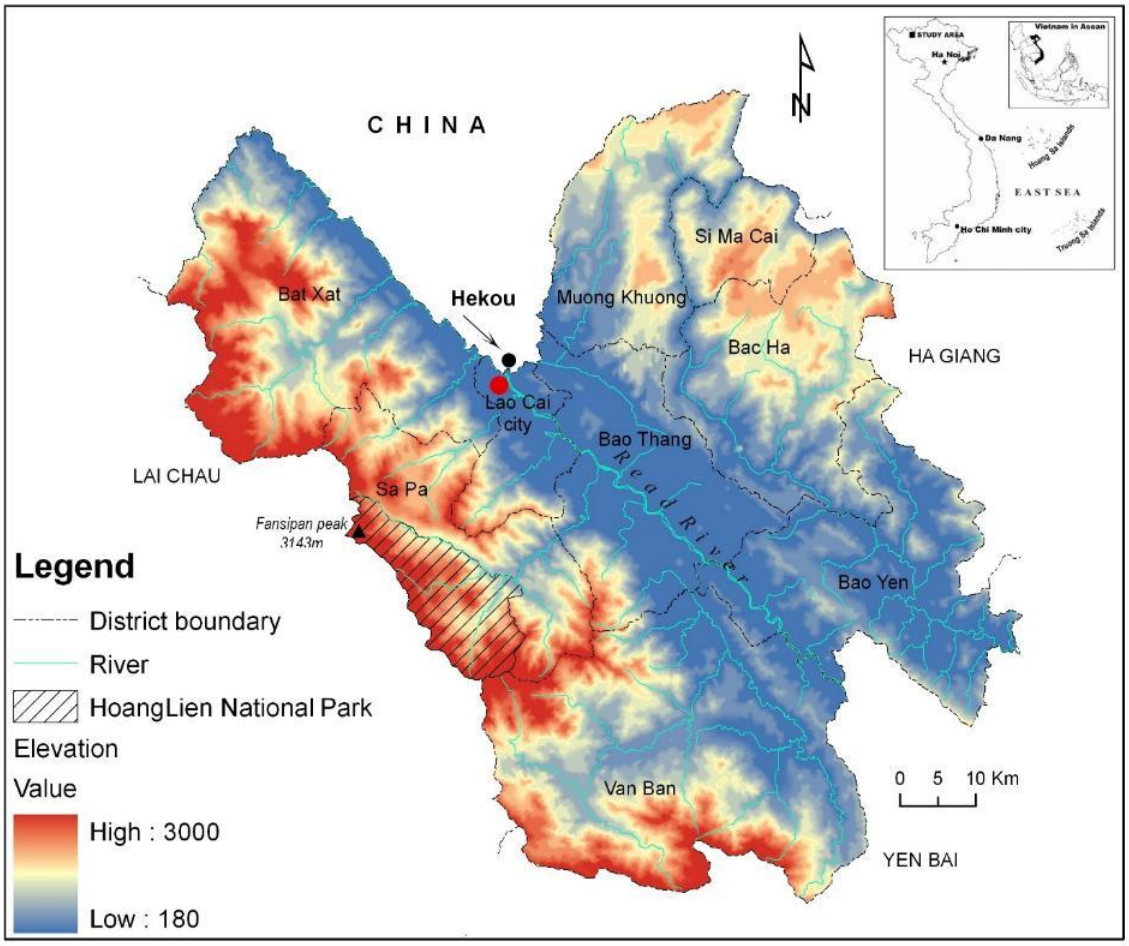
The integration of multi-source data is necessary to monitor land cover change at various spatial scales (Balthazar, 2014; Meyfroidt & Lambin, 2008b; C. Petit & E. F. Lambin, 2001; Vu, 2007; Zhao, 2007). Aerial photographs and Very High-Resolution SPOT images (VHR-SPOT) are known to be highly accurate for investigating historical land cover, but cover only limited area. Aerial photos are therefore often used to detect long-term land cover change (spanning 50 to 60 years) at local scale, covering individual villages or clusters of households. This approach has been successfully applied in previous studies by (Castella et al., 2005; Vanacker, 2002). Landsat images cover large areas (170 by 183 km), and offer up-to-date and costly-effective information on the earth surface (Balthazar, 2014). As the image availability is limited to the past 30 or 40 years (or even less for specific regions), Landsat images are suitable for investigating short-term land cover change at larger spatial scale such as provinces or districts (Dasgupta et al., 2005; Meyfroidt & Lambin, 2008a). In addition, in Vietnam, the land cover maps established by specialized agencies such as the Forest Inventory and Planning Institute of Vietnam (FIPI, belonging to Ministry of Agriculture and Rural Development) and the

General Department of Land Administration (belonging to Ministry of Natural Resources and Environment) are available at national and regional scale and cover the period from the early 1990s to 2010. These maps have been used to investigate forest cover change at national scale (Meyfroidt & Lambin, 2008b). To study land cover changes at different scales for long-term period, it is necessary to use different remote sensing data. This method has been applied in previous studies in the world and Vietnam (Chen et al., 2017; Dewan & Yamaguchi, 2009; Guo et al., 2022; Khanh Ni et al., 2020; Li et al., 2020; C. C. Petit & E. F. Lambin, 2001; Price & Nellis, 1996; Reis, 2008; Rembold et al., 2000; Symeonakis et al., 2004)

In this paper, land cover data from different sources were compared to resume the historical land cover dynamics (1950s-now) at multiple spatial scales. Lao Cai province in Northern Vietnam (ca.6000 km2) (Figure 1) was selected for the analysis at province level and Sa Pa district (ca.700 km2, located within Lao Cai province) was selected for the analysis at the district and village level. The study relies primarily on high to very high-resolution remote sensing images (Landsat, VHR-SPOT4, 5), aerial photographs and FIPI data. The following four research questions are addressed: (1) What are the major trends of land cover change over 60 years? (2) Can these changes robustly be detected using multi-source datasets? and (3) How do recent land cover changes (10-20years) fit with longer term trends (50 years)? (4) What are drivers of land cover change in the Northern Vietnamese Mountains?

Figure 1

Map of Lao Cai province



2 MATERIALS AND METHODS

2.1 Materials

Table 1 gives an overview of the data that were used for the land cover analysis. The data span a time period of 60 years, and data are available at relatively regular time intervals.

Table 1

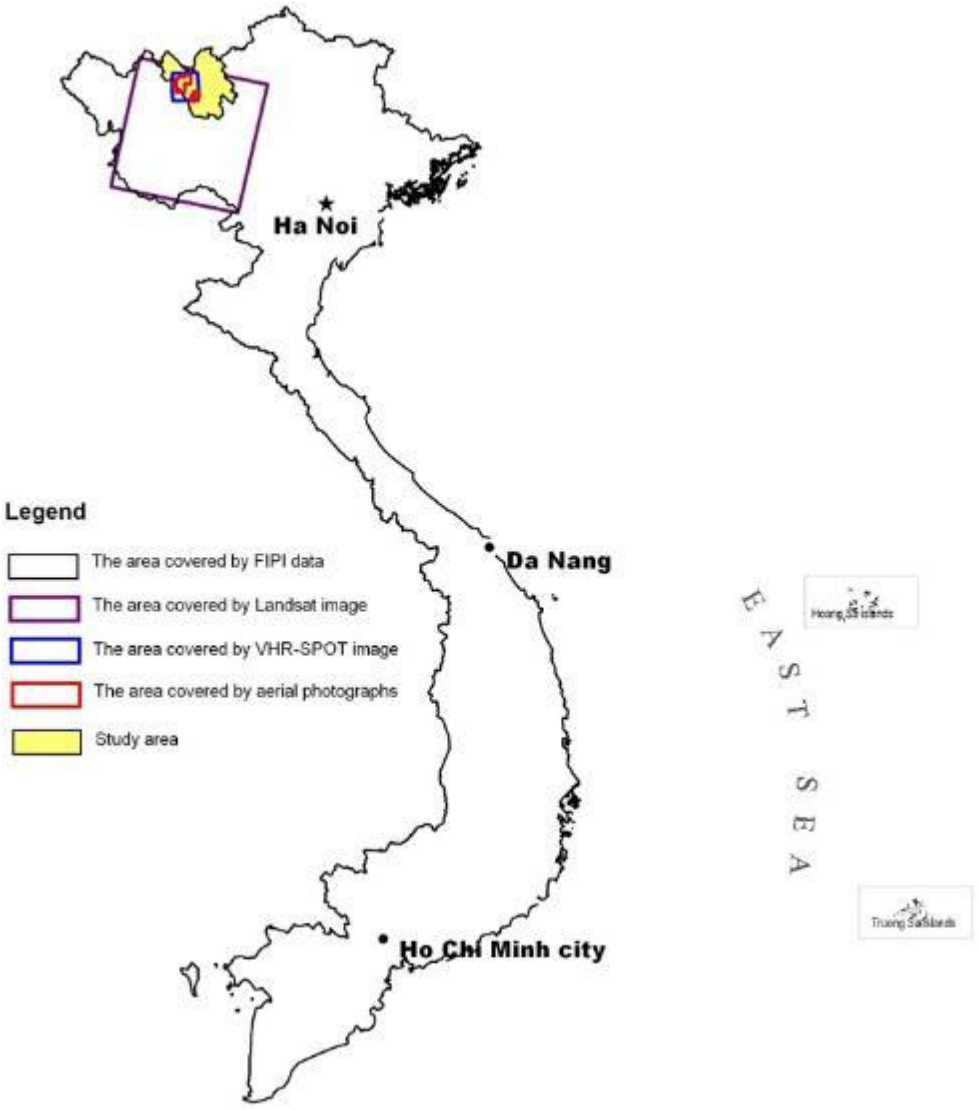
Characteristics of the data used for the land cover analysis (Aerial photographs, VHR-SPOT, Landsat images and FIPI data)

Characteristics	**Aerial photographs**	**VHR-SPOT**	**Landsat**	**FIPI**
Year	1952, 1993, 2002	2006, 2012	1993, 2006, 2014	1993, 2000, 2010
Type	Black and white	4 bands	7 bands	Digital maps
Size	60km^2	1569 km^2	31110 km^2	330,000 km^2
Scale (or resolution)	1/38,180; 1/47,500; 1/47,500	5m x 5m; 2.5m x 2.5m	30m x 30m	30m x 30m
Image quality	Good	Good	Good	Good
Covering	5 communes (Trung Chai, Ta Phin, San Sa Ho, Lao Chai and Nam Cang)	Sa Pa district	Sa Pa district	Lao Cai province
Land Cover categories	Closed canopy forest, Open canopy forest, Shrub, Paddy field, Upland field, Water body, Residential area, Road.	Closed canopy forest, Open canopy forest, Shrub, Paddy field, Upland field, Water body, Residential area, Road,	Closed canopy forest, Open canopy forest, Shrub, Paddy field, Upland field, Water body, Residential area.	Natural forest, Planted forest, Shrub, Arable land, Water body, Residential area,

Source: Hoang Thi Thu Huong et al., 2023

Figure 2

The delineation of the area covered by FIPI, Landsat, VHR-SPOT images and aerial photographs for this analysis



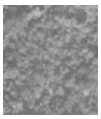
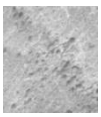
2.2 Land cover classification on very high-resolution images

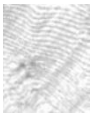
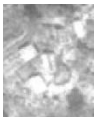
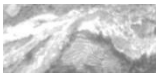
At small spatial scale, very high-resolution satellite images (VHR-SPOT) and aerial photographs were used. The time series spans the period from 1952 to 2012, and covers part of SaPa district (Table 1, Figure 2). The aerial photographs were obtained as scanned files from the Agency for Survey and Mapping, Ministry of Natural Resources and Environment, Vietnam (MONRE, 1952, 1993, 2002). The three sets of aerial

photographs were extracted for five communes within the SaPa district: (1) Trung Chai, (2) Ta Phin, (3) San Sa Ho, (4) Lao Chai and (5) Nam Cang (Figure 4). The first set of aerial photographs was taken between 1952 and 1954 and its printing scale is approximately 1/38,180. The second and third sets were taken in 1993 and 2002 respectively, and their printing scale is approximately 1/47,500. The photographic quality of the three series of photos is acceptable. The aerial photos were orthorectified and georeferenced using Photomod software (Racurs, 2009).

Table 2

Short description of the eight land cover types, as they were detected on aerial photographs and VHR-SPOT images

Land cover type	Terrestrial picture	VHR-SPOT image	Aerial photograph	Characteristics
Closed canopy forest				Closed canopy forests are distinguished on the aerial photos and VHR-SPOT by a dark tone, the 'cauliflower' texture, and most of the time by their specific location on steep slopes, at high altitudes and/or in gullies (Vu, 2007).
Open canopy forest				Open canopy forests have a more open cauliflower texture than closed canopy forests
Shrub				Shrub is distinguished by a lighter tone than forest. The texture still shows some patterns, but does not show the 'cauliflower' pattern typical of a continuous cover of trees (Vu, 2007).

Land cover type	Terrestrial picture	VHR-SPOT image	Aerial photograph	Characteristics
Paddy field				Paddy fields are recognized by their light (almost white) tone, by their steps and by their location in the valleys near rivers.
Upland field				Upland fields are recognized by the light, homogeneous tone and the texture. Upland fields often have angular forms.
Residential area				Residential areas were easily distinguished by the shape of the houses, by their location near infrastructure and by their non-uniform pattern (Vu, 2007).
Water body				Water body (rivers) and roads are easily recognized through their curved lines and light color. Roads are typically smoother and more uniform than rivers
Road				

The land cover maps of 2006 and 2012 were based on visual interpretation of VHR-SPOT satellite images of 2006 and 2012 with a resolution of 5 by 5m and 2.5 by 2.5m, respectively. All SPOT images were obtained in orthorectified and georeferenced format from the Ministry of Natural Resources and Environment, Vietnam (MONRE, 2006, 2012).

For all images (three sets of aerial photographs and two VHR-SPOT images), image segmentation was carried out with the eCognition Professional 6.0 software. As such, the digital image was segmented into a set of non-superimposable, discrete regions on the basis of their internal homogeneity criterion (Devereux et al., 2004; Ruelland et al., 2011). Land cover maps were produced by grouping manually the segments based on a visual interpretation. Eight categories were used (Table 2): (1) closed canopy forest, (2)

open canopy forest, (3) paddy field, (4) upland field, (5) shrub, (6) residential area, (7) water body, and (8) road.

2.3 Land cover classification on high resolution images

Three land cover maps were produced based on LANDSAT images that covers the SaPa district with a spatial resolution of 30m by 30m. The Landsat images were taken from Feb 1, 1993; Nov 4, 2006 and Jan 01, 2014 in the post-harvest period when the agricultural land is mostly bare. All Landsat images are orthorectified and corrected for atmospheric and topographic effects (Balthazar et al., 2012; Richter, 2011).

Then, a supervised maximum likelihood classification was applied to classify the Landsat images into 7 land cover categories: closed canopy forest, open canopy forest, shrubs, paddy field, upland field, water body and residential area (including paved roads). Interpreted patterns for the different land cover types were identified based on field work carried out in 2010.

2.4 Land cover maps based on Forest Inventory and Planning Institute of Vietnam (FIPI)

The land cover data used at province level were collected from the Forest Inventory and Planning Institute of Vietnam (FIPI) for the years 1993, 2000 and 2010. The FIPI maps were produced by supervised classification of Landsat satellite images that were validated by field inventories, and have a spatial resolution of 30m by30m. According to Meyfroidt and Lambin (2008b), FIPI maps can be considered as the most consistent maps at national level compared to other datasets, such as the IGBP (Loveland et al., 2000), AARS (Asian Association of Remote Sensing) (Wen & Tateishi, 2001), UNEP (United Nations Environment Programme) (Giri et al., 2003), or VCF (Vegetation Continuous Fields) (DeFries et al., 2000). The original land cover classification (13 classes) was generalized into 5 land cover categories to facilitate comparison with our land cover classification from Landsat images and aerial photographs: Natural Forest, planted forest, shrubs, arable land (including paddy and upland fields), water body, residential area (including paved roads) (Figure 6).

2.5 Accuracy assessment

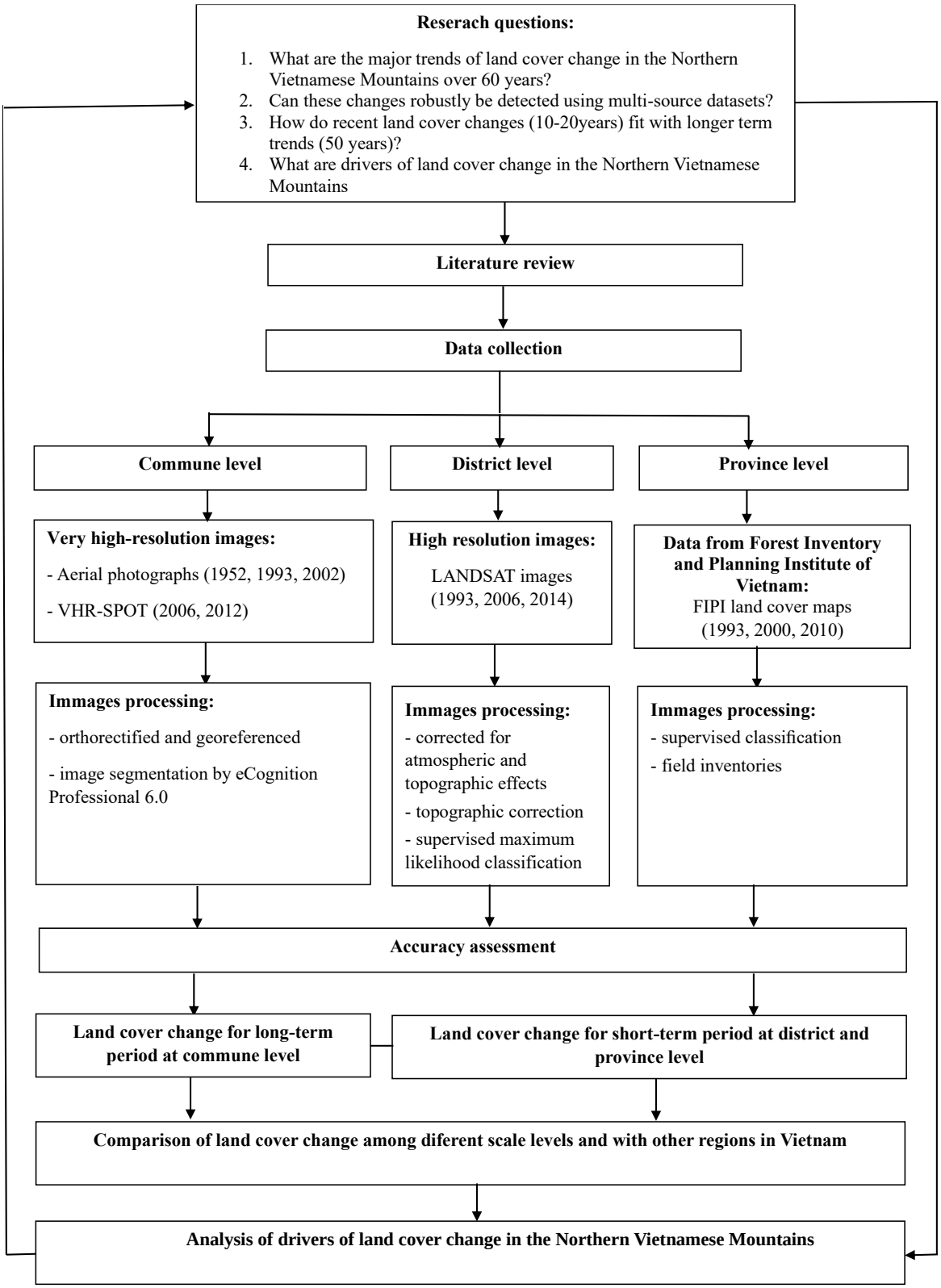
In this study, we assumed that the land cover maps derived from aerial photographs and VHR-SPOT image are more accurate (because of their smaller spatial resolution) than the land cover maps derived from a supervised classification of Landsat images and FIPI data. Therefore, we used these land cover maps (derived at very high spatial resolution) to evaluate the quality of the high-resolution land cover maps derived from Landsat and/or FIPI. For the land cover maps at high resolution of 1993 and 2000, the comparison was done with the information at very high resolution derived from aerial photographs of 1993 and 2002. For the HR information of 2006, 2010 and 2014, the comparison was done with a VHR-SPOT image of 2006 and 2012. A total 200 validation points were randomly selected with 10 to 78 sample points per land cover class, depending on the areal cover of the classes.

2.6 Land cover change analysis

The land cover maps derived from aerial photos (1952, 1993, 2002), VHR Spot images (2006, 2012), HR Landsat images (1993, 2006, 2014) and FIPI data (1993, 2000, 2010) were compared to calculate land cover changes. This was done by performing an overlay of two raster maps so that a cross-tabulation can be carried out by the raster calculator tool in ArcGIS 9.3. Flowchart of the study is shown in Figure 3.

Figure 3

Flowchart of the study



3 RESULTS

3.1 Accuracy assessment

The overall accuracy of the land cover classification from Landsat images was assessed at 71%, 83% and 82% (quantity disagreement of 5%, 4%, 5% and allocation disagreement of 24%, 13%, 13%) for the land cover maps of 1993, 2006 and 2014, respectively. The main errors result from confusion between (i) closed and open canopy forest, (ii) shrubs and open canopy forest, (iii) paddy fields and upland fields. Differentiation between closed and open canopy forests is difficult based on the pixel reflectance of Landsat images, and it is not straight forward to make the differentiation in the field neither. Besides, upland fields on steep slopes were hardly identified on the satellite images, as parcels as very small and have mixed spectral reflectance values. Therefore, we merged closed and open canopy forests into one 'forest class' and 'paddy field' and 'upland field' into one 'arable land' class.

The overall accuracy, quantity and allocation disagreement were computed for the two classifications (with/without regrouping) (Table 3). The overall accuracy increased substantially while quantity and allocation disagreement decreased after regrouping, as the overall accuracy was assessed at 80%, 86% and 85% (quantity disagreement of 5%, 3%, 4% and allocation disagreement of 15%, 11%, 11%) for the land cover maps of 1993, 2006 and 2014, respectively (Table 3). For this reason, we only analyzed 'forest' and 'arable land' in the later sections.

Table 3

Results of accuracy assessment of land cover classifications from Landsat images in Sa Pa district

Land cover	**Without regrouping**			**With regrouping**		
Year	*1993*	*2006*	*2014*	*1993*	*2006*	*2014*
Overall accuracy (%)	71.2	82.9	81.7	80.0	86.4	84.6
Quantity disagreement (%)	5.0	4.4	5.2	5.0	2.8	4.4
Allocation disagreement (%)	23.8	12.7	13.1	15	10.8	11

With the configuration of the initial seven classes, the accuracies may seem low but the spatial pattern of land cover types is consistent with field observations (Jadin et

al., 2013b). This suggests that the results of Landsat classification maybe useful to assess land cover changes for which no (complete) sets of aerial photographs are available.

For FIPI maps, the overall accuracy is much lower having values of 62%, 67% and 65% (quantity disagreement of 12%, 13%, 15% and allocation disagreement of 26%, 20%, 20%) for the land cover maps of 1993, 2000 and 2010, respectively. The low accuracy can be explained by classification system that was used for FIPI data. Aerial photo interpretation was based on the current status of the land surface to classify forests into closed and open canopy forests, while FIPI maps were based on the purposes of forest exploitation and divided forests into natural and planted forests. The difference in classification systems may be solved by grouping the two forest classes.

The overall accuracy, quantity and allocation disagreement were computed for the two classifications (with/without regrouping) (Table 4). The overall accuracy is increasing substantially, while quantity and allocation disagreement decrease after regrouping. The regrouped data have an overall accuracy of 69%, 73% and 71% (quantity disagreement of 10%, 8%, 14% and allocation disagreement of 21%, 19%, 15%) for the land cover maps of 1993, 2000 and 2010, respectively.

Table 4

Results of accuracy assessment of land cover maps from FIPI in Lao Cai province

Land cover	**Without regrouping**			**With regrouping**		
Year	*1993*	*2000*	*2010*	*1993*	*2000*	*2010*
Overall accuracy	62%	67%	65%	69%	73%	71%
Quantity disagreement	12%	13%	15%	10%	8%	14%
Allocation disagreement	26%	20%	20%	21%	19%	15%

3.2 Land cover change based on VHR data

The land cover maps obtained from aerial photographs and VHR-SPOT images for the years1952, 1993, 2002 and 2012 are shown in Figure 6A, B, C, D. Table 5 presents land cover changes between 1952 and 2012 in 5 selected communes. The area of forest has decreased by 9% between 1952 and 2012 while shrubs, arable land and residential area increased by 11%, 20% and 42%, respectively (Table 5).

Table 5

Land cover and land cover changes in the period 1952 –2012

Land cover	**Area (ha)**				**Change 1952-2002**		**Change 2002-2012**		**Change 1952-2012**	
	1952	1993	2002	2012	Differences	%	Differences	%	Differences	%
Forest	14602	12712	12583	13232	-2019	-14	649	5	-1370	-9
Arable land	2127	2657	2656	2367	529	25	-289	-11	240	11
Shrub	5264	6535	6719	6332	1455	28	-387	-6	1068	20
Residential area	149	181	184	211	35	23	27	15	62	42

Figure 4

Land cover maps of 5 selected communes in 1952, 1993, 2002 and 2012 (from aerial photographs and VHR-SPOT image)

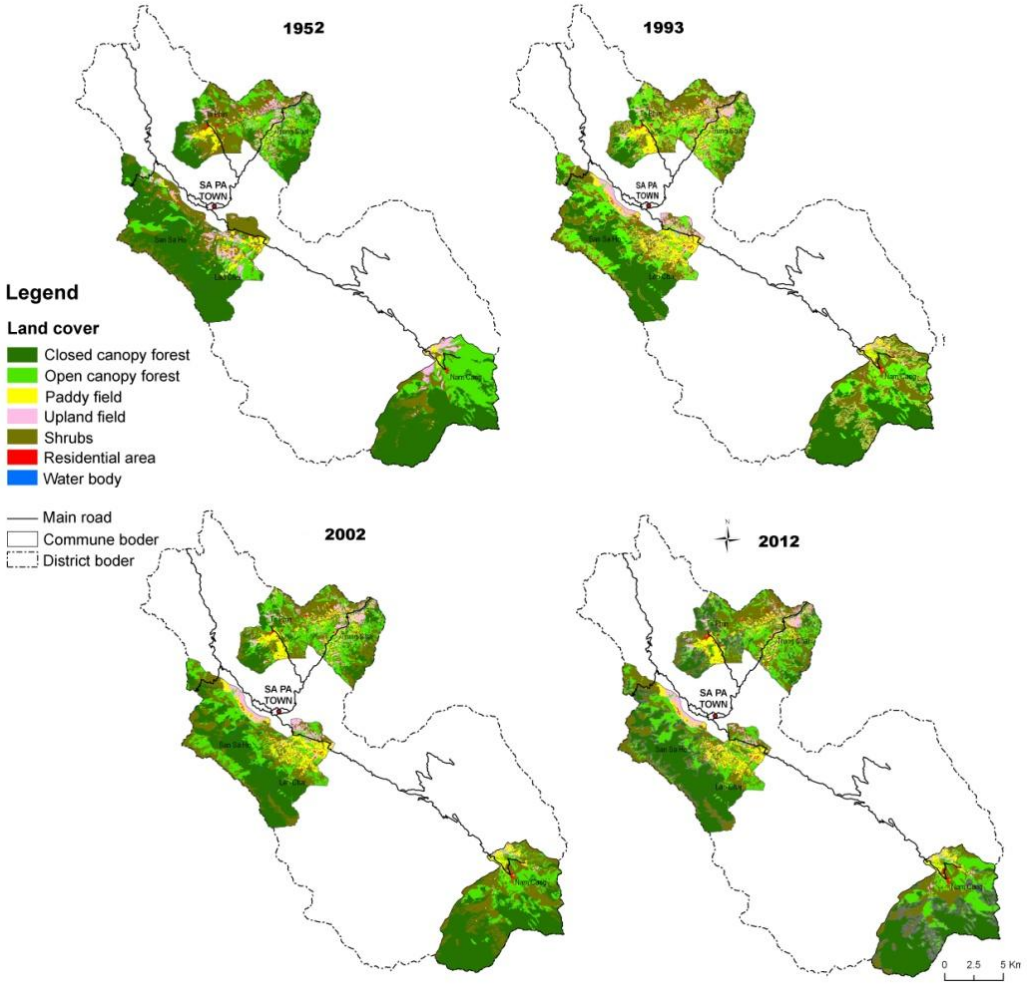


Table 6 shows the major land cover conversions in the selected communes for overall period 1952-2012. In this table, the grey cells are the unchanged areas, while the major changes are highlighted in bold. The major changes were the reduction of the forest area and the expansion of arable land. The conversion from shrub to forest and from arable land to shrubs is also remarkable. Over the last 60 years, 80% of the forest remained intact, while 18% has been transformed to shrubs and 2% to arable land. Similarly, only 59% of shrubs in 1952 remained: 25% was converted to forest and 15% to arable land (Figure 7).

Table 6

Absolute land cover changes between 1952 and 2012 for selected communes (ha)

2012-1952	Forest	Shrub	Arable land	Residential area
Forest	11719	**2563**	295	25
Shrub	**1347**	3100	**793**	24
Arable land	166	**665**	1278	18
Residential area	0	0	0	144

3.3 Land cover change based on HR satellite data

Figure 5 shows the land cover maps for the years 1993, 2006 and 2014 as derived from Landsat image classification. Table 7 presents land cover changes between 1993 and 2014 in SaPa district, which were calculated from the land cover classifications of 1993, 2006 and 2014. Between 1993 and 2014, the overall forest and arable land increased by respectively 7% and 17% while shrubs decreased by 32%. However, these trajectories mask substantial inter-interval differences. Between 1993 and 2006 forest decreased slightly by 1% while arable land increased by30%. But deforestation tendency seems to have reversed since 2006 in SaPa district. Forest increased by 8% while arable land decreased by 10% between 2006 and 2014. The shrubs decreased continuously between 1993 and 2014 (Table 7).

Figure 5

Land cover maps of Sa Pa district in 1993, 2006 and 2014 (from Landsat images)

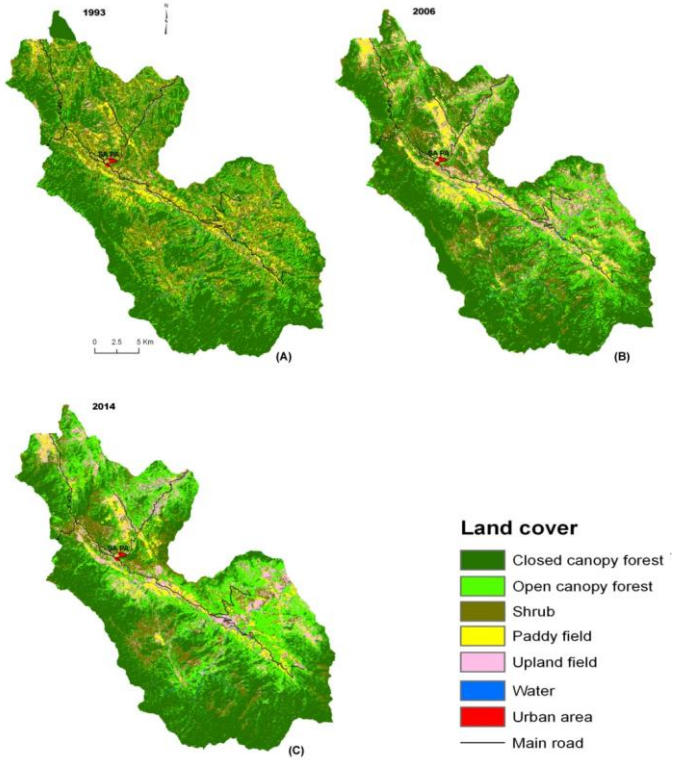


Table 7

Land cover and land cover changes in the period 1993 –2014 for SaPa district

Land cover	Area (ha)			Change 1993-2006		Change 2006-2014		Change 1993-2014	
	1993	2006	2014	Differences	%	Differences	%	Differences	%
Forest	45641	45209	48734	-432	-1	3525	8	3093	7
Arable land	8294	10751	9677	2457	30	-1074	-10	1383	17
Shrub	13696	11639	9277	-2057	-15	-2362	-20	-4419	-32

Table 7 show the major land cover conversions in SaPa district between 1993 and 2014. It can be seen that the major changes were conversion from shrubs to forest and from shrubs to arable land. Over the last 21 years, 85% of the forest remained intact, while 9% were transformed to shrub and 6% to arable land. Only 25% of shrubs remained, 50% were converted to forest and 25% to arable land.

3.4 Land cover change based on FIPI data

Figure 10 shows the land cover maps for the year 1993, 2000 and 2010 of Lao Cai province that were collected from FIPI data. Across all three dates, forest is dominant in the high mountains in the eastern and western parts of the province. Overall, for the period from 1993 to 2010, there is a clear trend of reforestation as forest cover increased from 31% in 1993 to 41% in 2000 and 54% in 2010. For the period 1993-2010, the forest increased by 75%. More specifically, the area covered by shrubs decreased in Lao Cai province over the last 17 years by 56%, while the residential area increased 160% between 1993 and 2010. Arable land increased by 26% between 1993 and 2000 and then decreased by 15% between 2000 and 2010. For overall period 1993-2010, the arable land increased only by 8% (Table 8).

Table 8

Land cover and land cover changes in the period 1993 –2010 of Lao Cai province

Land cover	**Area (ha)**			**Change 1993-2000**		**Change 2000-2010**		**Change 1993-20110**	
	1993	2000	2010	Differences	%	Differences	%	Differences	%
Forest	197799	258989	345292	61190	31	86303	33	147493	75
Arable land	127576	161353	137550	33777	26	-23803	-15	9974	8
Shrub	296161	198986	130390	-97175	-33	-68596	-34	-165771	-56
Residential area	7476	13583	19418	6107	82	5835	43	11942	160

Table 9 show the major land cover conversions in Lao Cai province between 1993 and 2010. The major changes were conversion from shrub to forest and arable land. Over the last 17 years, only 24% of the shrubs remained unchanged, while 48% were transformed to forest, and 25% to arable land. Similarly, 76% of forest in 1993 remained intact: 16% was converted to shrub and 8% to arable land. Only 33% of arable land remained, 41% has been converted to forest, 22% to shrub and 4% to residential area.

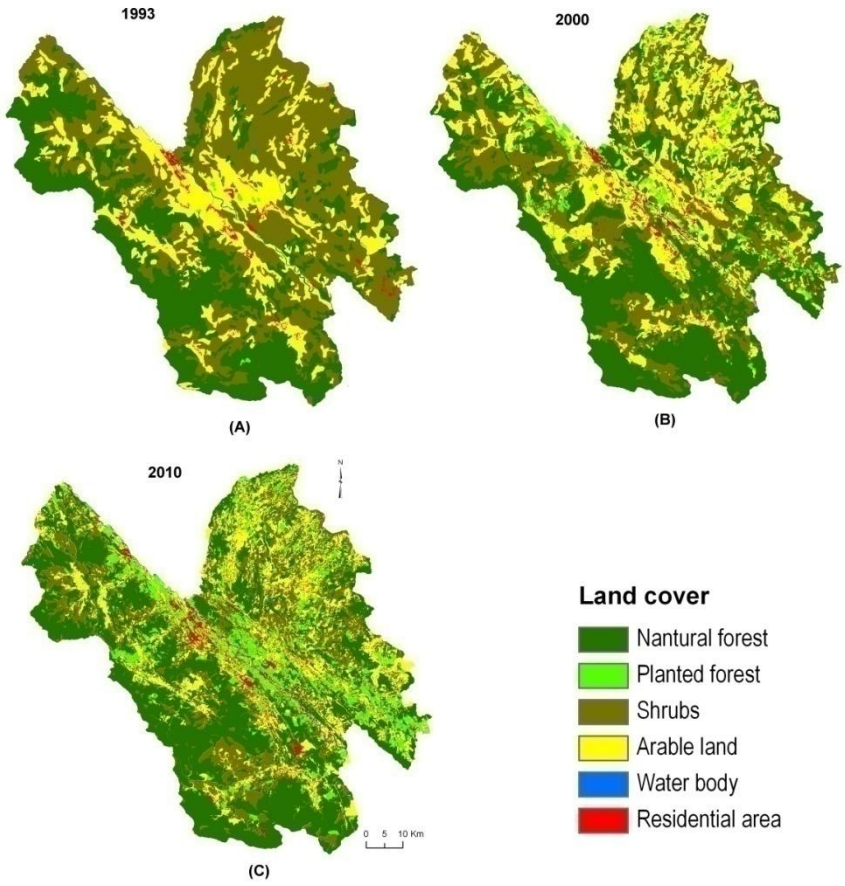
Table 9

Absolute land cover changes between 1993 and 2010 in Lao Cai province (ha)

2010-1993	Forest	Shrub	Arable land	Residential area
Forest	148501	31180	16980	0
Shrub	**142239**	71465	**74564**	7816
Arable land	**50765**	26954	41393	4602
Residential area	0	200	276	7000

Figure 6

Land cover maps of Lao Cai province collected from FIPI for 1993, 2000 and 2010



4 DISCUSSIONS

4.1 Land cover change over last 60 years (1952-2012)

Figure 7 presents the trends of land cover change over the past 60 years for 5 selected communes. The trends are based on the best available land cover data, i.e. the

very high-resolution aerial photographs and VHR SPOT images. For overall period (1952-2012), the major trends are the expansion of arable land and shrubs; and reduction of forest. The overall area covered by forest decreased by 9% while area covered by shrubs and arable land increased by 11% and 20%, respectively during last 60 years. However, these trajectories mask substantial inter-interval differences. The tendency of forest cover change seems to have reversed since 2002, some years after the implementation of forest policies and the introduction of tourism in SaPa district. The area covered by forest increased slightly after 2002 by 5% while shrubs and arable land decreased by 6% and 11%, respectively during the period 2002-2012 (Table 5). A forest transition occurred in the study area at the beginning of the 2000s.

Figure 7

The trends of main land cover categories over the past 60 years in the case study: (A) Forest, (B) shrubs and (C) arable land

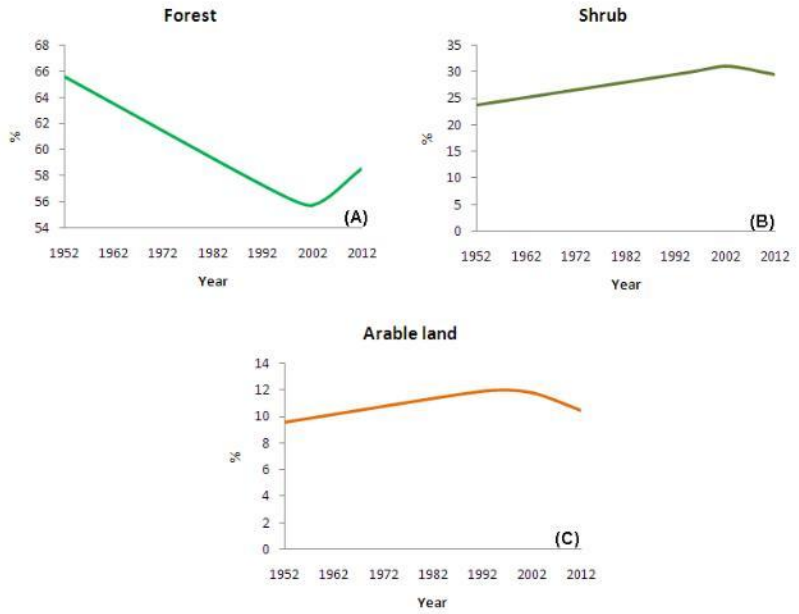


Table 10 presents the conversion rate calculated for the different time periods. The conversion from forest to shrubs peaked during 1952-1993 with the rate of 70ha/year while the conversion from shrub to forest peaked recently during 2002-2012 with the rate of 132ha/year. This reveals a trend of deforestation before 2000s and a recent phase of reforestation. The conversion from shrub to arable land peaked during first period (1952-

1993) while the conversion from arable land to shrub reached highest rate during 2002-2012. This result shows a trend of land expansion during the first period and recent trend of land abandonment. The first period (1952-1993) was remarkable with the highest rate of conversion from forest to shrub and shrub to arable land while the third period (2002-2012) was characterized with the highest rate of conversion from shrub to forest and from arable land to shrub. The mid-period (1993-2002) is characterized by lower land cover change rates.

Table 10

Overall land cover change rate at different periods (ha/yr)

Major land cover changes	**1952-1993**	**1993-2002**	**2002-2012**
Forest to shrub	70	14	65
Forest to arable land	6	2	5
Shrub to forest	27	2	132
Shrub to arable land	21	6	11
Arable land to forest	4	0	4
Arable land to shrub	11	8	41

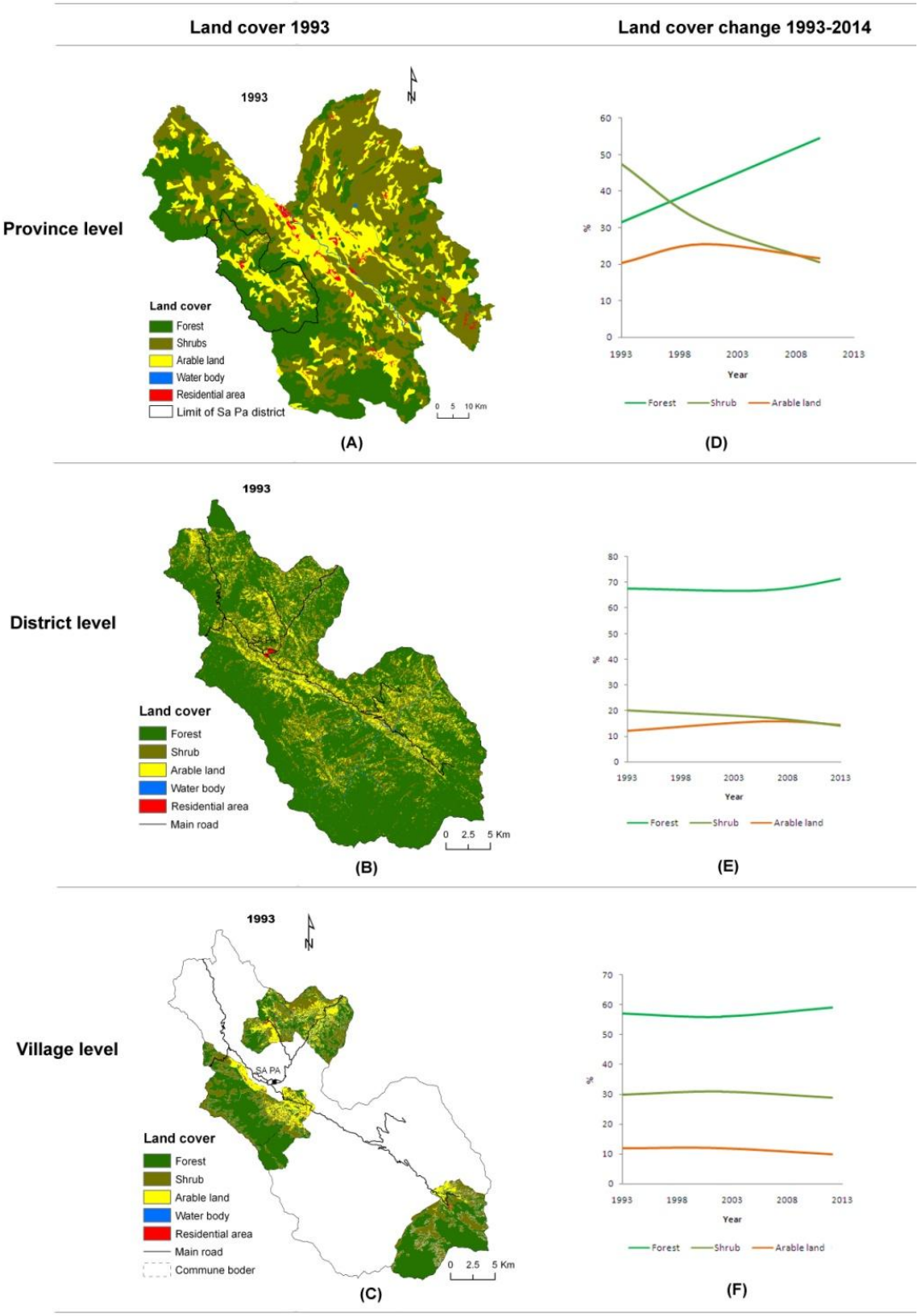
4.2 Land cover change at province, district and village level

Figure 8 shows the land cover maps for different administrative levels (province, district, village) for the year 1993. The land cover data at the provincial level are derived from FIPI, at district level from Landsat classification, and at village level from aerial photographs or VHR SPOT images.

The comparison of the trajectories of land cover change at different administrative levels is shown in Figure 8D, E and F. Although the trends in land cover change are somehow similar at the different administrative levels, it is clear that the largest forest cover dynamics were observed at the provincial level (Figure 8D). These data suggest that land cover dynamics within the mountainous SaPa district are slower than the ones observed in the central part of the Lao Cai province.

Figure 8

Comparison of land covers (A, B, C) and land cover change (D, E, F) from different administrative levelsin the study area

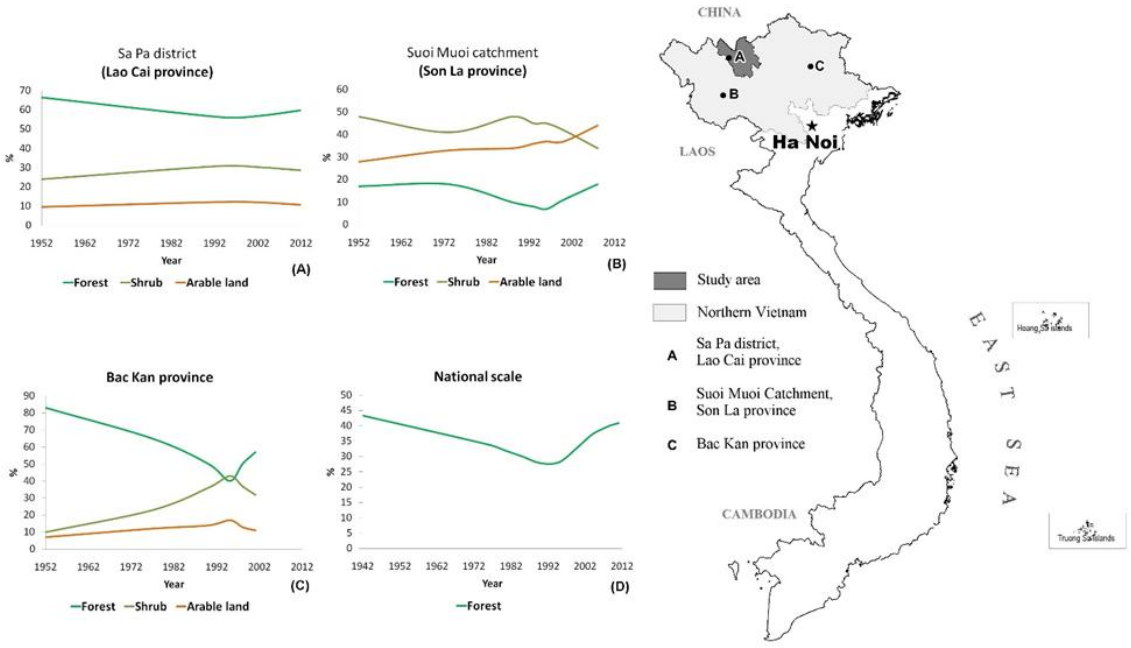


4.3 Comparison with national-scale land cover dynamics

In Figure 9, the land cover dynamics in SaPa district are compared with those of other northern provinces and with national-scale land cover dynamics. The overall trends of forest cover change are similar at regional and national scale. All figures show a decrease of forest cover between 1952 and 1990s and a recent phase of forest cover increase. However, in Sa Pa district (Lao Cai province), the forest increase started in the early 2000s (Figure 9A), some years later than what has been observed at national scale and in other regions. This might be due to the fact that the impact of land use policies and socio-economic transformation is spatially variable (Jean Christophe. Castella, Nathalie Rachel. Tronche, et al., 2002). Lao Cai and Bac Kan province have abundant forest resources, and they were covered for 54% and 58% resp.by forests in 2010 (GSO, 2011). Their forest cover is high compared to 40% forest cover at the national level (GSO, 2011), and 40% in the Son La province (GSO, 2011).

Figure 9

Comparison land cover change trajectories among national scale and different regions in Northern Vietnam: (A) Sa Pa district, Lao Cai province; (B) Suoi Muoi catchment, Son La province (Vu, 2007); (C) Bac Kan province (Castella et al., 2005; Fatoux et al., 2002), and (D) Trajectory of forest cover change at national scale (De Jong et al., 2006; GSO, 2012c).



The changes in arable land are different between the three regions (Figure 9A, B, C). In Lao Cai and Bac Kan province (northeast Vietnam), shrubs and arable land increased between 1950s and 1990s and decreased in recent years. While in Suoi Muoi catchment (Son La province, northwest Vietnam), arable land increased continuously from the 1950sto recent years. The recent decrease of arable land and shrubs in the northeastern provinces is probably associated with a reduction in shifting cultivation (Castella et al., 2005). Most swidden rice fields with low yields have been left fallow to regenerate into shrubs and/or forest (Sowerwine, 2004). In contrast, in Suoi Muoi catchment, shifting cultivation is still observed in some ethnic minority communities such as Thai, Khang, Hmong and Khomu (Vu et al., 2013). In this region, the conversion of shrubs to arable land (and vice versa) occurred, something which is typical for shifting cultivation practices. In a shifting cultivation system, farmers create temporary upland

fields by cutting and burning off the vegetative cover. After a few years of intensive cultivation, the soil is depleted and the upland fields are taken out of production in order to allow a natural recover of shrubs and forests (Vu, 2007).

In comparison with the study of Vu (2007) for Son La province and Castella et al (2005) for Bac Kan province, the land cover dynamics in SaPa district are small (Figure 9A, B, C). In SaPa district, the forest cover between 1952 and 2012 changed of only -9% in favor of shrubs and arable land that changed of +20% and +11% (percentage of category). These rates were much higher in Bac Kan province, where forest cover changed of -31% while shrubs and arable land changed of +220% and +57% resp. between 1952 and 2001. Similarly, in Suoi Muoi catchment, where the forest and arable land changed of+6% and +57% resp. while shrubs changed of -29% between 1952 and 2008 (Figure 9B). Furthermore, the percentage of forest that remained intact between 1952 and 2012 in SaPa district is about 80-85%, in contrast to only 35% in Suoi Muoi catchment (Vu, 2007).

4.4 Driver of land cover change in the northern Vietnamese Mountains

Previous studies have indicated that land use/cover changes in the northern Vietnamese mountains are the result of a combination of factors such as land use policies (Clement & Amezaga, 2008, 2009; Clement et al., 2007; Clement et al., 2009; Vu, 2007), livelihood diversification (Hoang et al., 2014; Hoang et al., 2020), poverty alleviation (Hoang et al., 2024) , agricultural intensification (Castella et al., 2005), accessibility (Castella et al., 2005; Hoang et al., 2024), scarcity of forest products (Meyfroidt & Lambin, 2008a) and population growth (Hoang et al., 2024; Jadin et al., 2013a).

4.4.1 Impact of policies on land cover change

The strong increase in forest plantations that is observed for the Lao Cai province is likely the result of forest policies. The allocation of land to individual households in 1993, the Program 327 in the mid-1990s, and the Five Million Hectare Reforestation Project (5MHRP) (from 1998-2010) were probably very effective in this province, as a

large part of the natural forest growth and increase in plantation forest was observed in the period 1993-2010. After the allocation of forest land to individual households, shifting cultivation was legally not possible because all land was allocated to individual households and forest land was protected. This policy inevitably forces rural households to develop new production systems to compensate for the ban on swidden cultivation and it has stimulated people to cultivate their fields more intensively (Castella et al., 2006; Vu et al., 2013). The program 327 and 5MHRP were intended to stimulate the forestry sector, and to encourage local people to plant trees under the subsidy of the government for reforestation (Clement & Amezaga, 2008). Following the forest rehabilitation programs, the Vietnamese Government also planned the location of supply regions for timber and wood processing centers. The forestry sector in Lao Cai province is linked to the Viet Tri and Bai Bang paper factories. There is a high demand for forestry products in Vietnam, as 80% of raw materials for furniture manufacturing in Vietnam are from imports(De Jong et al., 2006; Meyfroidt & Lambin, 2009). H.T.T. Hoang (2014) shows that plantation forests were more likely to be planted in areas with a low forest cover. This might be due to the scarcity of wood around timber and wood processing centers, which might have led to an increase in forest plantations to meet the market demand.

4.4.2 Poverty and land cover change

Although forest cover has increased rapidly in the Lao Cai province, the overall forest cover change masks substantial inter-communal differences (Hoang et al., 2024). By using a principal component analysis, Hoang et al. (2024) unravel the association between forest cover change and various socio-economic, demographic and land use variables. Rich and accessible communes are characterised by a strong increase in plantation forests, while poor and more isolated areas are characterised by an increase in forests after natural regeneration. This statementsupport earlier research of Meyfroidt and Lambin (2008a) that reported that the occurrence of plantation forests islimited in remote areas. This could partly be due to a lack of infrastructure and market opportunities for timber compared to more acessible areas, as commercial forest plantations are not an economically feasible option for remote areas (Clement et al., 2007).

4.4.3 Agricultural intensification and land cover change

Several local studies in Northern Vietnam revealed that reforestation was not only a response toforest policies but also agricultural intensification (Castella et al., 2006; Clement & Amezaga, 2008; Clement et al., 2007; Clement et al., 2009; Meyfroidt & Lambin, 2008a; Sikor, 2001). From the 1990s onwards, the Vietnamese government has encouraged the use of hybrid rice seeds in combination with chemical fertilizers and pesticides to increase crop yields on paddy fields and to improve local food security (Bonnin & Turner, 2012; Turner, 2012). On average, the yield of rice crops in Lao Cai province went up from 2.3 ton/ha in 1990 to 3.3 ton/ha in 2000 and 4.3 ton/ha in 2010 (GSO, 1990, 2000, 2010b). Although the population of Lao Cai province increased 1.2 times during last 10 years (from 526,824 in 2000 to 626,220 people in 2010), the production of cereals per capita still increased from 241kg in 2000 to 368kg in 2010 (GSO, 2000, 2010a)as a result of the increase of cereal yield. Slash-and-burn cultivation in the uplands declined rapidly as food security was guaranteed. The area of swidden rice dropped from 5,245 ha in 2000 to 1,433ha in 2010 (GSO, 2000, 2010a). Forest regeneration often took place in the fallow fields. The increase in paddy rice yields has also positive impacts on forest plantations (Meyfroidt & Lambin, 2008a). In areas with high accessibility and growing markets, households were profitable to convert abandoned fields to forest plantations or perennial crops such as multi-year industrial crops and fruit crops. Together with an increase in plantation forest, the area of perennial crops in Lao Cai province increased from 7,587ha in 2000 to 11,392ha in 2010 (GSO, 2000, 2010a).This is a specific type of forest increase that occurs when smallholders develop orchards, woodlots, agroforestry systems, home gardens, and hedgerows (Meyfroidt & Lambin, 2011).

In addition, the increase in cropping frequency in mountain paddies was another factor contributing to natural forest regeneration (Meyfroidt & Lambin, 2008a). The development of rice multi-cropping allowed many households to become food self-sufficient without having to rely on upland rice cultivation anymore (Castella & Erout, 2002). As the cultivation on the paddy fields is highly labor-intensive, few labor force was left for slash-and-burn agriculture. Upland plots were thus either abandoned or planted with trees, depending on resource endowments and opportunities.

4.4.4 Population growth, agricultural pressure and land cover change

Although Lao Cai province has experienced a net reforestation in the period 1993-2010, deforestation is still observed in some remote communes. Land pressure and unclear ownership rights of forest land may lead to the expansion of cultivated land and deforestation, as observed elsewhere in the hilly region of Vietnam (Tachibana et al., 2001; Vu, 2007). High land pressure and growing land scarcity or landlessness may push farmers to the forest frontier (Geist & Lambin, 2001). Although the policy of forest land allocation has been implemented in Northern Vietnam in1993, some communes applied this policy later or less effectively, possibly leading to little impact on forest protection (J C Castella et al., 2002; Clement & Amezaga, 2009).

In Lao Cai province, the relationship between population and land cover change may be blurred because of the effects of migration (Hoang Thi Thu Huong et al., 2023). There is in-migration before 2005 and out-migration after that (Table 11).

Table 11

Population growth of Lao Cai province in the period 1992-2010

	Unit	1992*	1993*	2005**	2007**	2008**	2009**	2010**
Natural growth	%/year	3.6	3.5	1.8	1.5	1.7	1.8	1.8
Net migration rate	%/year	0.5	1.1	-0.12	-0.49	-0.09	-0.06	-0.01

* *Data collected from (People Committee of Lao Cai province, 1995)*
** *Data collected from (GSO, 2012a, 2012b)*

The high in-migration rate that was measured in 1993 is likely caused by two important decisions in 1993: (1) Lao Cai was separated from Hoang Lien Son province (which included Lao Cai and Yen Bai province) and (2) Hekou Border Economic Cooperation Zone was instituted to promote trade between China and Vietnam (Roche & Michaud, 2000). These policies led to a large flow of people from neighboring provinces to Lao Cai searching for jobs or business opportunities. Moreover, in-migrations to Lao Cai were encouraged by the government to decrease population pressure on the densely populated river deltas (Lundberg, 2004). These led to rapid population growth in the urban areas of this province with high in-migration. As most of this population was involved in off-farm activities, the population increase seems to have had less impact on forest cover.

But after 2005, the in-migration to Lao Cai province slowed down and an out-migration from rural areas of Lao Cai to the Central Highlands of Vietnam appeared (Hardy, 2000), which led to negative migration rates after 2005 (Table 11). As the population growth is significant in the urban areas that are less dependent on agriculture and forest resources and as the growth is recently slowing down in rural areas, the impact of population growth on forest cover change is not clear.

5 CONCLUSIONS

This study used multi-temporal remote sensing data to evaluate land cover changes in Lao Cai province at different scale levels. This method proves effective to resume the history of land cover in the study area over the past 60 years in the context that remote sensing data in Vietnam is not continuous in time and does not cover all the space. This method can be applied in studying land cover changes in mountainous areas like Lao Cai province. When comparing different data sources, clear differences were obtained in the land cover change rates. This is mostly associated with the different classification system that was used for aerial photographs, Landsat images and FIPI data. The accuracy of the land cover maps improves after regrouping land cover classes. The major trends inland cover change obtained from the different datasets are roughly similar. As we are not much interested in the exact classification of individual pixel, but rather in the broad patterns and trends of land cover, we can consider that the three datasets are complementary.

The research results show that when considering the entire time period 1952 to 2012, the land cover data at very high-resolution shows that a net loss of forest area occurred in the five selected communes in SaPa district. Between 1952 and 2012, the overall forest cover decreased by 9% in favor of shrubs and arable land that increased by 20% and 11%. When considering only the last 15 years (2000-2014), the land cover data all show an increase of forest cover by about 3 to13% at village, district and provincial level. The largest increase in forest cover is observed at the province level, with an increase of 8630ha/year. The forest cover dynamics in SaPa district and the five selected communes was much lower with rates of 440ha/year and 65ha/year, respectively. The trends of land cover change that are observed in the study area are roughly similar to what

is reported at the national scale and for other regions in Northern Vietnam. However, the land cover conversions are smaller in SaPa district, compared to the other regions in Northern Vietnam.

At national-scale, it is documented that deforestation happened between 1952 and 1990, and that this was followed by a recent phase of forest increase. In the study area, forest cover increased was observed only from the early 2000s, some years later than that was reported for the national level and other regions in Northern Vietnam. The trends of arable land and shrubs in the study area were characterized by an increase of shrubs and arable land during the period 1952 to 2002, and a reversal of these trends since the 2000s. These trajectories are consistent with the trends that are observed at the national scale. However, the trajectories mask substantial inter-communal differences. This difference reflects that forest increase in the northern Vietnamese mountains is not only due to land use policy, but also to other factors such as agricultural intensification, market integration, and economic growth. Forest plantations were most attractive in relatively accessible and well-developed regions, as there is a growing market for timber products so that planting trees was an economically feasible option. In the poor, remote areas, increases in rice yields due to agricultural intensification led to a reduction of swidden cultivation. Forest regeneration therefore took place in fallow fields. Although population growth is often cited to be a major factor for explaining land cover dynamics, it was not associated with forest cover change in the study area.

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AUTHORS' PARTICIPATION

Both authors participated in the research, discussions, and writing of this article.

REFERENCES

Balthazar, V. (2014). *Remote sensing of forest cover change and ecosystem dynamics in mountain areas* Université Catholique de Louvain]. Louvain-La-Neuve, Belgium.

Balthazar, V., Vanacker, V., & Lambin, E. (2012). Evaluation and parametrization of ATCOR3 topographic correction method for forest cover mapping in mountain areas. *International Journal of Applied Earth Observation and Geoinformation*, *18*, 436-450.

Bonnin, C., & Turner, S. (2012). At what price rice? Food security, livelihood vulnerability, and state interventions in upland northern Vietnam. *Geoforum*, *43*, 95–105.

Castella, J.-C., Boissau, S., Nguyen, H. T., & Novosad, P. (2006). Impact of forestland allocation on land use in a mountainous province of Vietnam. *Land Use Policy*, *23*(2), 147-160. https://doi.org/10.1016/j.landusepol.2004.07.004

Castella, J. C., Boissau, S., Thanh, N. H., & Novosad, P. (2002). Impact of forestland allocation on agriculture and natural resources management in Bac Kan Province, Viet Nam. In J. C. Castella & D. D. Quang (Eds.), *Doi Moi in the Mountains. Land use changes and farmers's livelihood stratergies in Bac Kan province Vietnam* (pp. 175-195). The Agricultural Publishing House.

Castella, J. C., & Erout, A. (2002). Montaine paddy rice: the cornerstone of agricultural production systems in Bac Kan province Vietnam. In J. C. Castella & D. D. Quang (Eds.), *Doi Moi in the Mountains. Land use changes and farmers's livelihood stratergies in Bac Kan province Vietnam* (pp. 175-195). The Agricultural Publishing House.

Castella, J. C., Pham, H. M., Kam, S. P., Villano, L., & Tronche, N. R. (2005). Analysis of village accessibility and its impact on land use dynamics in a mountainous province of northern Vietnam. *Applied Geography 25*, 308-326. http://www.sciencedirect.com/science/article/pii/S0143622805000287

Castella, J. C., Quang, D. D., Long, T. D., & Doanh, L. Q. (2002). Scaling up local diagnostic studies to understand development issues in a heterogeneous mountain environment: An introduction to the SAM Program. In J. C. Castella & D. Q. Dang (Eds.), *Doi Moi in the mountains* (pp. 149-173). The Agricultural Publishing House.

Castella, J. C., Tronche, N. R., & Nguyen, V. (2002). Landscape changes in Cho Don District during the doi moi era (1990-2000) and their implications for sustainable natural resource management in Vietnam's mountainous provinces In J. C. Castella & D. Q. Dang (Eds.), *Doi Moi in the mountains* (pp. 149-173). The Agricultural Publishing House.

Clement, F., & Amezaga, J. M. (2008). Linking reforestation policies with land use change in northern Vietnam: Why local factors matter. *Geoforum*, *39*, 265-277.

Clement, F., & Amezaga, J. M. (2009). Afforestation and forestry land allocation in northern Vietnam: Analysing the gap between policy intentions and outcomes. *Land Use Policy*, *26*, 458-470.

Clement, F., Amezaga, J. M., Orange, D., & Toan, T. D. (2007). *The impact of goverment policies on land use in northern Vietnam: an institutional approach for understanding farmer decisions* (IWMI Research Report, Technical Report, Issue.

Clement, F., Orange, D., Williams, M., Mulley, C., & Epprecht, M. (2009). Drivers of afforestation in Northern Vietnam: Assessing local variations using geographically weighted regression. *Applied Geography*, *29*(4), 561-576. http://www.sciencedirect.com/science/article/pii/S0143622809000101

Chen, B., Huang, B., & Xu, B. (2017). Multi-source remotely sensed data fusion for improving land cover classification. *ISPRS Journal of Photogrammetry and Remote Sensing*, *124*, 27-39. https://doi.org/https://doi.org/10.1016/j.isprsjprs.2016.12.008

Dasgupta, S., Deichmann, U., & Wheeler, D. (2005). Where is the Poverty–Environment Nexus? Evidence from Cambodia, Lao PDR, and Vietnam. *World Development*, *33*(4), 617–638. http://www.sciencedirect.com/science/article/pii/S0305750X05000069

De Jong, W., Sam, D. D., & Hung, T. V. (2006). *Forest rehabilitation in Vietnam: histories, realities and future*. Center for International Forestry Research (CIFOR).

DeFries, R. S., Hansen, M. C., Townshend, J. R. G., Janetos, A. C., & Loveland, T. R. (2000). A new global 1-km dataset of percentage tree cover derived from remote sensing. *Global Change Biology*, *6*, 247-254.

Devereux, B. J., Amable, G. S., & Posada, C. C. (2004). An efficient image segmentation algorithm for landscape analysis. *International Journal of Applied Earth Observation and Geoinformation*, *6*, 47-61.

Dewan, A. M., & Yamaguchi, Y. (2009). Land use and land cover change in Greater Dhaka, Bangladesh: Using remote sensing to promote sustainable urbanization. *Applied geography*, *29*(3), 390-401.

Fatoux, C., Castella, J. C., Zeiss, M., & Manh, P. H. (2002). From rice cultivator to agroforester within a decade: the impact of Doi Moi on agricultural diversification in a mountainous commune of Cho Moi District, Bac Kan Province, Vietnam. In J. C. Castella & D. D. Quang (Eds.), *Doi Moi in the Mountains. Land use changes and farmers's livelihood stratergies in Bac Kan province Vietnam* (pp. 73–98). The Agricultural Publishing House.

Geist, H. J., & Lambin, E. F. (2001). *What Drives Tropical Deforestation? A meta-analysis of proximate and underlying causes of deforestation based on subnational case study evidence*. LUCC Report Series No. 4. CIACO

GSO. (1990). *Lao Cai statistical yearbook 1990*. Statistical Publishing House.

GSO. (2000). *Lao Cai statistical yearbook 2000*. Statistical Publishing House.

GSO. (2010a). *Lao Cai statistical yearbook 2010*. Statistical publishing house.

GSO. (2010b). *National Vietnamese Census, Year book*. The people committee of Sa Pa district. Lao Cai, Vietnam

GSO. (2011). *Vietnam statistical year book 2010*. Hanoi, Vietnam: Statistical publishing house

GSO. (2012a). *In-migration rate by province* http://www.gso.gov.vn/default_en.aspx?tabid=467&idmid=3&ItemID=14426

GSO. (2012b). *Out-migration rate by province* http://www.gso.gov.vn/default_en.aspx?tabid=467&idmid=3&ItemID=14425

GSO. (2012c). *Vietnam statistical year book 2011*. Hanoi, Vietnam: Statistical publishing house

Guo, X., Ye, J., & Hu, Y. (2022). Analysis of Land Use Change and Driving Mechanisms in Vietnam during the Period 2000–2020. *Remote Sensing*, *14*(7), 1600. https://www.mdpi.com/2072-4292/14/7/1600

Giri, C., Defourny, P., & Shrestha, S. (2003). Land cover characterization and mapping of continental Southeast Asia using multi-resolution satellite sensor data. *International Journal of Remote Sensing*, *24*, 4181-4196.

H.T.T. Hoang. (2014). *Multi-Scale Analysis of Human-Environment Interactions. A case-study in the Northern Vietnamese Mountains* Katholieke Universiteit Leuven]. Belgium.

Hardy, A. (2000). Strategies of migration to upland areas in contemporary Vietnam. *Asia Pacific Viewpoint*, *41*(1), 23-34.

Hoang, H. T. T., Rompaey, A. V., & Vu, K. C. (2024). Spatial patterns of poverty and forest cover dynamics in the Vietnamese Highlands. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-024-05023-4

Hoang, H. T. T., Vanacker, V., Van Rompaey, A., Vu, K. C., & Nguyen, A. T. (2014). Changing human–landscape interactions after development of tourism in the northern Vietnamese Highlands. *Anthropocene*, *5*, 42-51. https://doi.org/https://doi.org/10.1016/j.ancene.2014.08.003

Hoang, T. T. H., Van Rompaey, A., Meyfroidt, P., Govers, G., Vu, K. C., Nguyen, A. T., Hens, L., & Vanacker, V. (2020). Impact of tourism development on the local livelihoods and land cover change in the Northern Vietnamese highlands. *Environment, Development and Sustainability*, *22*(2), 1371-1395. https://doi.org/10.1007/s10668-018-0253-5

Hoang Thi Thu Huong, Vu Kim Chi, & Anton Van Rompaey. (2023). Monitoring land cover change based on multi-scale analysis: A case study in Lao Cai province, Vietnam. International Conference on Earth and Environmental Sciences, Mining for Digital Transformation, Green Development and Response to Global Change, Ho Chi Minh city.

Jadin, I., Vanacker, V., & Hoang, H. T. T. (2013a). Drivers of Forest Cover Dynamics in Smallholder Farming Systems: The Case of Northwestern Vietnam. *AMBIO*, *42*(3), 344-356. https://doi.org/10.1007/s13280-012-0348-4

Jadin, I., Vanacker, V., & Hoang, T. T. H. (2013b). Drivers of Forest Cover Dynamics in Smallholder Farming Systems: The Case of Northwestern Vietnam. *AMBIO*, *42*(3), 344-356. http://link.springer.com/article/10.1007/s13280-012-0348-4

Khanh Ni, T. N., Tin, H. C., Thach, V. T., Jamet, C., & Saizen, I. (2020). Mapping Submerged Aquatic Vegetation along the Central Vietnamese Coast Using Multi-Source Remote Sensing. *ISPRS International Journal of Geo-Information*, *9*(6), 395. https://www.mdpi.com/2220-9964/9/6/395

Lang, C. (2001). Deforestation in Vietnam, Laos and Cambodia. In V. DK (Ed.), *Deforestation, Environment, and Sustainable Development: A comparative analysis* (pp. 111-137).

Li, Q., Qiu, C., Ma, L., Schmitt, M., & Zhu, X. X. (2020). Mapping the Land Cover of Africa at 10 m Resolution from Multi-Source Remote Sensing Data with Google Earth Engine. *Remote Sensing*, *12*(4), 602. https://www.mdpi.com/2072-4292/12/4/602

Loveland, T. R., Reed, B. C., Brown, J. F., Ohlen, D. O., Zhu, Z., Yang, L., & Merchant, J. W. (2000). Development of a global land cover character istics database and IGBP DISCover from 1km AVHRR data. *Inter national Jour nal of Remote Sensing 21*(6-7), 1303-1330.

Lundberg, M. (2004). *Kinh settlers in Vietnam's northern highlands: natural resources management in a cultural context* Linko¨ping University]. Linko¨ping.

Meyfroidt, P., & Lambin, E. (2009). Forest transition in Vietnam and displacement of deforestation abroad. *PNAS*, *106*(38). https://doi.org/16139–44. doi:10.1073/pnas.0904942106

Meyfroidt, P., & Lambin, E. F. (2008a). The causes of the reforestation in Vietnam. *Land Use Policy 25*(2), 182-197. http://www.sciencedirect.com/science/article/pii/S0264837707000609

Meyfroidt, P., & Lambin, E. F. (2008b). Forest transition in Vietnam and its environmental impacts. *Global Change Biology 14*(6), 1319–1336. http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2486.2008.01575.x/pdf

Meyfroidt, P., & Lambin, E. F. (2011). Global Forest Transition: Prospects for an End to Deforestation. *Annual Review of Environment and Resources*. https://doi.org/10.1146/annurev-environ-090710-143732

MONRE. (1952). *Aerial photos*.

MONRE. (1993). *Aerial photos*.

MONRE. (2002). *Aerial photos*.

MONRE. (2006). *VHR-SPOT image 2006*.

MONRE. (2012). *VHR-SPOT image 2012*.

People Committee of Lao Cai province. (1995). *Dân số, lao động, việc làm và mức sống dân cư tỉnh Lào Cai thời kỳ 1995-2010 (Population, labour, employment and living standars of Lao Cai province in the period 1990-2010)*.

Petit, C., & Lambin, E. F. (2001). Integation of multi-source remote sensing data for land cover change detection. *International Journal of Geographical Information Science*, *15*, 785-803.

Petit, C. C., & Lambin, E. F. (2001). Integration of multi-source remote sensing data for land cover change detection. *International Journal of Geographical Information Science*, *15*(8), 785-803. https://doi.org/10.1080/13658810110074483

Price, K. P., & Nellis, M. D. (1996). *Development of a Land Use Mapping and Monitoring Protocol for the High Plains Region: A Multitemporal Remote Sensing*

Application.

Racurs. (2009). *Photomod 4.4 Overview. User manual*.

Reis, S. (2008). Analyzing land use/land cover changes using remote sensing and GIS in Rize, North-East Turkey. *Sensors*, *8*(10), 6188-6202.

Rembold, F., Carnicelli, S., Nori, M., & Ferrari, G. A. (2000). Use of aerial photographs, Landsat TM imagery and multidisciplinary field survey for land-cover change analysis in the lakes region (Ethiopia). *International Journal of Applied Earth Observation and Geoinformation*, *2*(3), 181-189. https://doi.org/https://doi.org/10.1016/S0303-2434(00)85012-6

Richter, R. (2011). *Atmospheric/Topographic Correction for Satellite Imagery—ATCOR-2/3 User Guide, Version 8.0*. ReSe Applications Schla¨pfer.

Roche, Y., & Michaud, J. (2000). Mapping ethnic group in Lao Cai province, Vietnam. *Asia Pacific Viewpoint*, *41*(1), 101-110.

Ruelland, D., Tribotte, A., Puech, C., & Dieulin, C. (2011). Comparison of methods for LUCC monitoring over 50 years from aerial photographs and satellite images in a Sahelian catchment. *International Journal of Remote Sensing*, *32*(6), 1747-1777.

Sikor, T. (2001). The allocation of forestry land in Vietnam: did it cause the expansion of forests in the northwest? *Forest Policy and Economics*, *2*, 1-11.

Sowerwine, J. (2004). Territorialisation and the Politics of Highland landscapes in Vietnam: Negotiating property relations in policy, meaning and practice. *Conservation and Society*, *2*(1), 98-117.

Symeonakis, E., Koukoulas, S., Calvo-Cases, A., Arnau-Rosalen, E., & Makris, I. (2004). A landuse change and land degradation study in Spain and Greece using remote sensing and GIS. Proceedings of XXth ISPRS Congress, Istanbul, Turkey, http://www. isprs. org/istanbul2004/comm7/papers/110. pdf,(15 January, 2006),

Tachibana, T., Trung, M. N., & Keijiro Otsuka. (2001). Agricultural Intensification versus extensification: A case study of Deforestation in the Northern Hill region of Vietnam. *Journal of Environmental Economics and Management*, *41*, 44 - 69.

Turner, S. (2012). "Forever Hmong": Ethnic Minority Livelihoods and Agrarian Transition in Upland Northern Vietnam. *The Professional Geographer*, *64*(4), 540-553. http://dx.doi.org/10.1080/00330124.2011.611438

Vanacker, V. (2002). *Geomorphic Response to Human Induced Environmental Change in Tropical Mountain Areas. The Austro Ecuatoriano as a Case-study* Katholieke University Leuven].

Vu, K. C. (2007). *Land use change in the Suoi Muoi catchment* KULeuven]. Leuven, Belgium.

Vu, K. C., Van Rompaey, A., Govers, G., Vanacker, V., Schmook, B., & Nguyen, H. (2013). Land Transitions in Northwest Vietnam: An Integrated Analysis of Biophysical and Socio-Cultural Factors. *Human Ecology*, *41*(1), 37– 50. http://link.springer.com/article/10.1007%2Fs10745-013-9569-9

Wen, C. G., & Tateishi, R. (2001). 30-second degree grid land cover classification of Asia. *International Journal of Remote Sensing*, *22*, 3845-3854.

Zhao, X. (2007). *Integation of multi-source data for the detection and analysis of long term land cover change* Enschede, The Netherlands.

Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

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