ICIMOD Working Paper 2015/5

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Assessment of Change in Forest Cover and Biomass Using Geospatial Techniques to Support REDD+ Activities in Nepal

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International Centre for Integrated Mountain Development, Kathmandu, Nepal, August 2015

Published by
International Centre for Integrated Mountain Development
GPO Box 3226, Kathmandu, Nepal

ISBN 978 92 9115 344 2 (printed)
978 92 9115 346 6 (electronic)

Production team
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Photos: Hammad Gilani, Nabin Baral

Printed and bound in Nepal by
Hill Side Press Pvt Ltd, Kathmandu, Nepal

Citation: Gilani, H; Murthy, MSR; Bajracharya, B; Karky, BS; Koju, UA; Joshi, G; Karki, S; Sohail, M (2015) *Assessment of change in forest cover and biomass using geospatial techniques to support REDD+ activities in Nepal.* ICIMOD Working Paper 2015/5. Kathmandu: ICIMOD

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Foreword

The forests of the Hindu Kush Himalayan region play a major role in maintaining the mountain ecosystem and supporting people's livelihoods. They provide a wide range of goods from timber and fuelwood to food products and fodder, and provide many economic and social benefits. They help conserve water and maintain water quality, prevent or reduce the severity of floods and avalanches, hinder erosion, and help regulate the climate. On a global scale, the important role of forests as sinks and sources of carbon is gaining increasing recognition as a major issue for climate change. However, notwithstanding their crucial role, forests across the region remain under threat from overexploitation and conversion of land to other uses.

Forests need to be protected and managed sustainably both to mitigate climate change and to ensure people's wellbeing. The Reducing Emissions from Deforestation and Degradation (REDD) mechanism, and its expanded successor REDD+, offers a very promising approach for protecting and enhancing forest. The incentive-based mechanism defines a new paradigm for forest management. It is a smart strategy that can reduce deforestation and land degradation as well as enhance ecosystem-based adaptation strategies in forest dependent communities. The co-benefits of REDD+ activities can include poverty reduction and biodiversity conservation. But implementing REDD+ will only be possible if appropriate cost-effective ways can be developed to measure forests, and assess changes in forest area and biomass.

ICIMOD has been studying the status of forests in the Himalayan region for more than 30 years with the aim of improving understanding of the important role that forests play, gathering and disseminating information on improved management approaches, identifying governance issues and improved governance approaches, and developing baseline information on forest area and status and changes over time. The study presented here is a further important step in this work. It describes the development and testing of a method for delineating forest area using a participatory GIS approach with high resolution satellite images. The information provides baseline data for comparison in future studies as well as a way of delineating permanent representative sample plots. The study showed that biomass and carbon stocks can be assessed from satellite images with integration of only a small amount of data from the sample plots. Comparison with results from field-based measurements showed that optical remote sensing can provide usable values for forest biomass over a large area and in a timely and cost-effective manner.

The study was made possible through the support of the Norwegian Agency for Development Cooperation (Norad), which financed the main REDD pilot project, and the National Aeronautics and Space Administration (NASA) and United States Agency for International Development (USAID) through the SERVIR-HIMALAYA Initiative, as well as the commitment of the implementing partners, Asia Network for Sustainable Agriculture and Bio-resources (ANSAB) and Federation of Community Forestry Users Nepal (FECOFUN), and the many researchers, field staff, and community forestry users involved in different stages of the activities. The approach offers a promising possibility for measuring carbon stocks for REDD+ monitoring and we hope that the results will be useful for all those concerned with finding practical and effective approaches to fulfil the conditions for implementing the REDD+ mechanism.

David Molden, PhD
Director General, ICIMOD

Foreword

The rate of the deforestation and forest degradation trend in Nepal has been decreasing in recent years and the overall state of forests is improving. This achievement is attributed in a large part to the success of Nepal's community based forest management programme, which is widely recognized as a successful model for conserving forests, raising awareness among local people, and decentralizing forest governance. Nepal has become a world leader in community-based forest management. Nevertheless, deforestation and degradation continue to pose a problem in some areas, and there is still need for improvement.

REDD+ offers a potential mechanism for supporting and strengthening the community forestry approach, and providing compensation to local communities for maintaining and improving their forests. The Government of Nepal has expressed a keen interest to participate in the REDD+ mechanism and has been receiving assistance from the Forest Carbon Partnership Facility of the World Bank to support the REDD+ readiness process. One of the key elements of REDD+ readiness is to develop a National Forest Monitoring system to provide data and information suitable for monitoring, reporting, and verification (MRV) of changes in forest carbon. The MRV system must be scientifically robust and consistent to forest reference emission level so that changes in forest carbon stock during the accounting period is accurately detected and measured. Thus, a reliable and plausible MRV system is essential for participating in the REDD readiness process.

A good MRV system should be simple, adjustable, and replicable so that negative impacts can be mitigated and positive impacts scaled up. However, designing a simple, reliable, and robust MRV system is difficult, not least because of the lack of reliable information on forest resources and land use change over time, and the high cost of detailed field measurements. Thus we very much welcome this report, which describes a cost-effective approach for delineating forest area and monitoring forest carbon stocks using participatory GIS with high resolution satellite images. The present results are limited to monitoring and measuring, but have the potential to be extended for use in reporting and verification. The satellite images offer the possibility of achieving results on a wide scale, more rapidly and at much lower cost than is possible with field measurements alone. The remote sensing project also focused on capacity building of staff in national and regional forestry institutes and mobilization and awareness campaigns for field staff and communities. This will be very important in improving local ownership of the REDD+ process in Nepal. We are very pleased to have played a significant role in the development of these results, and look forward to extending and testing the approach on a wider scale in the future.

Resham Bahadur Dangi
Joint Secretary
REDD Implementation Center
Government of Nepal

22 December 2014

Acronyms and Abbreviations

ANSAB	Asia Network for Sustainable Agriculture and Bioresources
AGB	above ground biomass
CF	community forest
CFUGs	community forest user groups
CPA	crown projection area
DBH	diameter at breast height
DEM	digital elevation model
DFO	district forest office
DGPS	differential global positioning system
FECOFUN	Federation of Community Forestry Users Nepal
GIS	geographic information system
GPS	Global Positioning System
ICIMOD	International Centre for Integrated Mountain Development
ITC	International Institute for Geo-Information Science and Earth Observation (Netherlands)
LHF	leasehold forest
Lidar	light detection and ranging
MRV	monitoring, reporting and verification
NASA	National Aeronautics and Space Administration
OBIA	object based image analysis
PF	private forest
REDD	Reducing Emissions from Deforestation and forest Degradation
RS	remote sensing

Acknowledgements

This report is based on five years (2009–2014) of continuous work by a large number of scientists, researchers, field staff, and ICIMOD colleagues and we would like to thank them all. We would also like to express our sincere thanks to the donor agencies – the Norwegian Agency for Development Cooperation (Norad), and the National Aeronautics and Space Administration (NASA) and United States Agency for International Development (USAID) through the SERVIR-Himalaya initiative – and the implementing agencies – Asia Network for Sustainable Agriculture and Bioresources (ANSAB), Federation of Community Forestry Users Nepal (FECOFUN), and ITC-Netherlands. We express our gratitude to the district forest officers in the three districts and forest department staff for their support during the fieldwork. This work would not have been possible without the active participation of the community forest user groups in the three districts, and we are very grateful to them all. We sincerely thank our former colleagues Salman Asif Siddique and Eak Bhadur Rana for support during the initial phase of the project, Yousif Ali Hussin, and Louise van Leeuwen from ITC-Netherlands for her contribution in the capacity building and outreach sessions. Last but not least, we thank ICIMOD's management for their encouragement and providing the facilities to complete this work.

Executive Summary

The Reducing Emissions from Deforestation and Forest Degradation (REDD) mechanism offers a promising approach for protecting and enhancing the world's forests. The Cancun Agreement on REDD+, which incorporates the role of conservation, sustainable management of forests and enhancement of forest carbon stocks, at the sixteenth Conference of the Parties to the United Nations Framework Convention on Climate Change, included measurement, reporting, and verification (MRV) as one of the most critical elements necessary for the successful implementation of REDD+.

Key Messages

- High resolution satellite imagery is a cost-effective tool that can support REDD+ monitoring
- Local institutions play an important role in monitoring forest carbon changes
- Annual measurements of sample plots taken by community forest user groups can be verified using geospatial techniques
- The use of high resolution satellite images provides a framework for monitoring, reporting, and verification of local forest carbon change that can be scaled up to the national level

Approximately 40% of Nepal's land area is forested. The rate of deforestation and forest degradation has been reduced in recent years and the overall state of forests is improving. The success in improving the state of forests is attributed in large part to the success of the community forestry programme, which is widely recognized as a successful model for conserving forests, raising awareness among local people, and decentralizing forest governance. Nepal is considered a world leader in community-based forest management. Notwithstanding these advances, deforestation and forest degradation continue to pose a problem in some areas, and there is still need for improvement. REDD+ offers a potential mechanism for supporting and strengthening the community forest approach, and providing compensation to community forest users for maintaining and improving their forests.

This report has been prepared under the project 'Design and setting up of a governance and payment system for Nepal's community forest management under REDD' executed jointly by the Asia Network for Sustainable Agriculture and Bioresources (ANSAB), Federation of Community Forestry Users Nepal (FECOFUN), and the International Centre for Integrated Mountain Development (ICIMOD), and financed by the Norwegian Agency for Development Cooperation (Norad) under the Climate and Forest Initiative. Scientific methodologies for quantification and monitoring of spatial changes were developed under the SERVIR-Himalaya initiative of the National Aeronautics and Space Administration (NASA) and United States Agency for International Development (USAID). The geospatial component of the project was implemented in three watersheds, Kayar Khola in Chitwan District, Ludi Khola in Gorkha District, and Charnawati in Dolakha District, representing the three regions of plains, hills, and mountains. It included 112 community forests, 89 leasehold forests, and 4 private forests.

A participatory GIS (geographic information system) approach was used with high resolution satellite images from GeoEye-1 and IKONOS-2 to delineate the boundaries of different forest regimes. Permanent sample plots were positioned using land/forest cover strata and are being measured each year by communities. Forest cover change was assessed to support understanding of deforestation and forest degradation. Forest tree crown cover, biomass, and carbon change were quantified for different time periods and the change over time was analysed. The results of field-based and remote-sensing based measurements of carbon stocks were compared. The use of satellite imagery to highlight forest changes, and to identify other events such as forest fires, was also demonstrated.

National and regional training events and workshops were conducted with support from the International Institute for Geo-Information Science and Earth Observation (ITC) for capacity building. Scientific articles describing the project and results are being published in close collaboration with international researchers and scientists.

Introduction

The role of forests

Forests provide a wide range of goods – including timber, fuelwood, food products, and fodder – and many important services. They play a vital role in conserving ecosystems, maintaining water quality, and preventing or reducing the severity of floods, avalanches, erosion and siltation, and drought and can regulate climate on a regional scale. Forests also provide a wide range of economic and social benefits, such as employment, forest products, and sites of cultural value (FAO 2006).

Recently, the important role of forests as sinks and sources of carbon has been gaining increasing recognition as a major issue for climate change (World Bank 2010). At present, forests cover around 31% of the total global land area; they store a vast amount of carbon in their biomass (289 Gt), and more in their soil and dead wood and litter (FAO 2010a). At the same time, deforestation and forest degradation are responsible for about 20% of global greenhouse gas (GHG) emissions (FAO 2010a). Tropical forests are an important pool of both sinks and sources of carbon; estimation of carbon stock in these forests is crucial for understanding the global carbon cycle and as a basis for reducing global warming (Sierra et al. 2007).

Land and forest cover change

Change in land and forest cover has been identified as one of the most important drivers of change in ecosystems and their services (Koschke et al. 2012) and is thus one of the most critical factors to monitor. Loss of forest services is usually due to deforestation or forest degradation. Deforestation is the non-temporary change of land use from forest to other (e.g., forest to settlement) and is defined as reduction of forest crown cover to less than 10%. Forest degradation refers to changes within a forest class that negatively affect the stand or site, including a reduction in species composition and/or biological diversity, a reduction in tree productivity, and a reduction in tree density (i.e., a reduction in crown cover to not less than 10%). Forest degradation is often reflected in a change from closed to open forest (GOFC-GOLD 2009).

Forest degradation is a major source of carbon emissions. Degradation is indicated by a reduction in canopy cover and/or reduction in forest quality and is most commonly the result of logging, grazing, collection of fuelwood, forest fire, or disease. It is often a complex process (Lambin 1999) and is of great concern to the people in developing countries where REDD+ programmes are being implemented (Nandy et al. 2011). In many cases it can be addressed through community participation (Lambin and Strahlers 1994; le Polain de Waroux and Lambin 2012). The forest structure can be interpreted as an implicit reference to the growing stock, which may be used as a proxy for several purposes. A broader approach is likely to be necessary, however, Lund (2009) describes three commonly used parameters and/or proxy indicators for forest degradation:

- Reduction in biomass for volume of growing stock or carbon stored, often reflected by a decrease in canopy cover and/or the number of trees per unit area
- Reduction in biological diversity – numbers of different species (dominant and non-dominant), numbers of specific species, and number of habitats
- Reduction in soil, as indicated by soil cover, depth, or fertility

Nepal and the REDD mechanism

The REDD mechanism is a very promising approach for protecting and enhancing the world's forests by reducing deforestation and forest degradation. The expanded form known as REDD+ includes the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks. In developing countries, REDD+ could finally create financial incentives for keeping forests standing instead of cutting them down for timber, pulp and paper, cattle, palm oil, and rubber (Phelps et al. 2010). The Cancun Agreement on REDD+ sought to safeguard the multiple uses and benefits of forests, and discussed the challenges of integrating forests and REDD+

into broader low-carbon development strategies. The 194 parties to the UNFCCC also agreed to establish a Green Climate Fund (GCF) with the potential to channel hundreds of billions of dollars in aid from rich economies to poor, vulnerable nations (Cerbu et al. 2011).

In Nepal, 5.83 million hectares (40%) of the total 14.7 million hectares of land is forested (DOF 2012). The rate of deforestation and forest degradation has been reduced in recent years and overall the state of forests is improving. The success in improving the state of forests is attributed in a large part to the success of the community forestry programme, which is widely recognized as a successful model for conserving forests, raising awareness among local people, and decentralizing forest governance. Nepal is considered a world leader in community-based forest management. Notwithstanding these advances, deforestation and forest degradation continue to pose a problem in some areas. According to the FAO (2010b), Nepal is one of the countries where deforestation is now relatively low at <50,000 ha/year, but still with a need for improvement. The annual rate of deforestation is highest in the lowland Terai (1.6%), followed by the High Himalayas (0.97%), and the Siwalik Hills (0.87%) (Niraula et al. 2013). REDD+ offers a potential mechanism for supporting and strengthening the community forest approach, and providing compensation to community forest users for maintaining and improving their forests.

Nepal is one of 14 countries in the first batch selected by the Forest Carbon Partnership Facility (FCPF) of the World Bank (WB) to address global climate issues according to the REDD+ principles. The REDD Implementation Centre under the Ministry of Forests and Soil Conservation (MOFSC) is implementing REDD+ readiness activities in Nepal. The government has established a three-tiered institutional mechanism for implementing REDD+, with the REDD+ Multi-sectoral, Multi-stakeholder Coordinating and Monitoring Committee as the apex body, the REDD+ Working Group (RWG) at the operational level, and the REDD Implementation Centre, Ministry of Forests and Soil Conservation as the coordinating entity. The three bodies have been working together to prepare a REDD National Strategy and implementation plan.

To support Nepal's REDD+ activities, ICIMOD in collaboration with the Federation of Community Forestry Users Nepal (FECOFUN) and the Asia Network for Sustainable Agriculture and Bioresources (ANSAB) is implementing a project on 'Design and setting up of a governance and payment system for Nepal's Community Forest Management (CFM) under REDD+' financed by the Norwegian Agency for Development Cooperation (Norad) under the Climate and Forest Initiative. The project covers more than 10,000 ha of community-managed forests and has an outreach to over 16,000 households with more than 89,000 forest-dependent people. The Nepal project is one of the world's first carbon offset projects involving local communities in monitoring the carbon in their forests and providing the necessary training for them to do so. The project is being implemented in three community forest areas in Chitwan, Gorkha, and Dolakha districts to demonstrate the feasibility of applying a results-based REDD+ payment mechanism involving local communities, including marginalized groups, to support community forest management and reduce deforestation and forest degradation by linking sustainable forest management practices with an economic incentive.

Monitoring, reporting, and verification

Monitoring, reporting, and verification (MRV) is included in the Cancun Agreement as one of the critical elements necessary for the successful implementation of any REDD+ mechanism. The agreement calls for a robust and transparent national system for forest monitoring and reporting, although reference levels can be developed at the subnational level as an interim measure, and mentions the need for methodologies for developing national forest reference emission levels and/or forest reference levels.

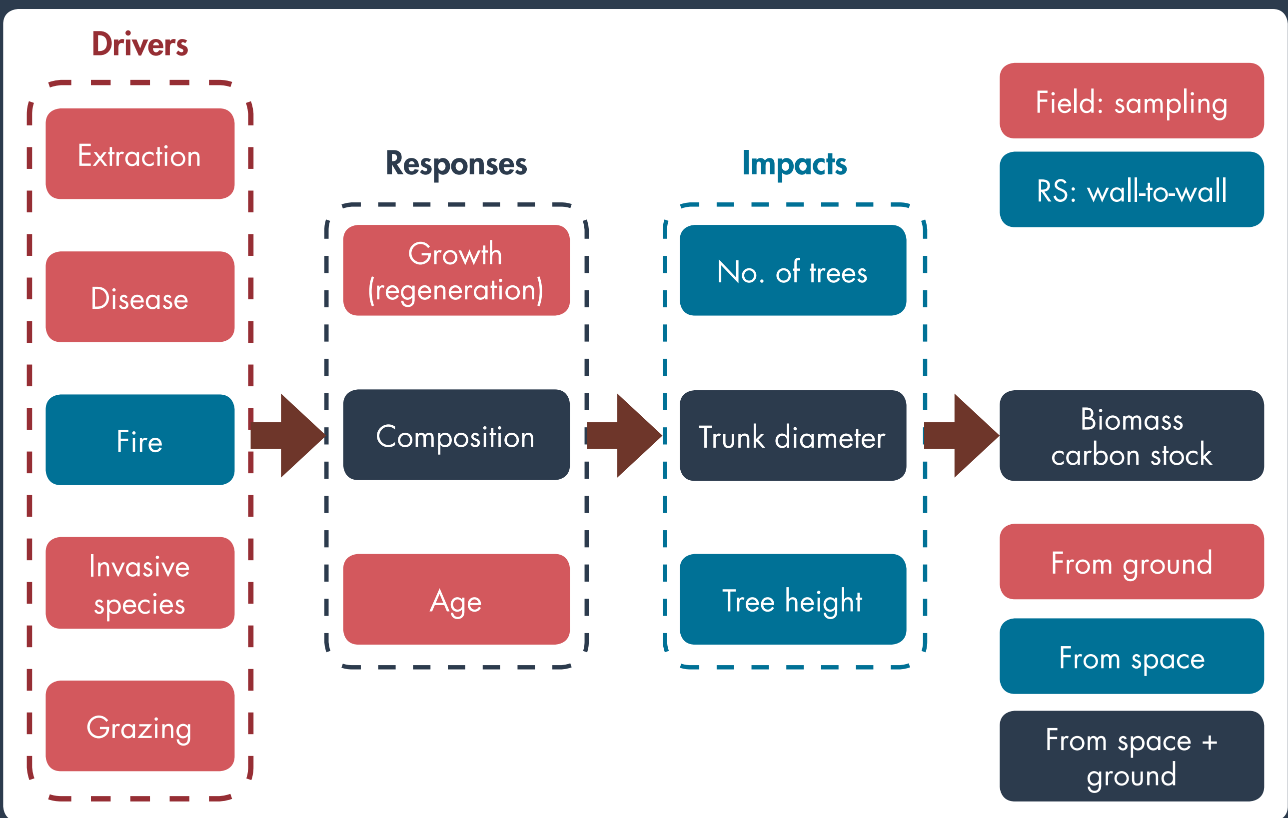
MRV involves both collection of baseline information and measurements over time to identify changes in forest carbon stocks, both locally and nationally. The amount of carbon stored in a forest depends on a number of factors including the total area and the biomass per hectare. In general, forest biomass consists of above-ground and below-ground living mass, including trees, shrubs, vines, roots, and the dead mass of fine and coarse litter associated with the soil. Most research on biomass estimation focuses on above ground biomass (AGB), which contains almost 80% of total biomass.

A range of different methods are available for developing land cover maps and estimating AGB and forest carbon stocks. Lu (2006) has reviewed and summarized approaches based on field measurements, remote sensing (RS), and geographic information systems (GIS). Geospatial technology has an immense potential to address certain critical components of the MRV process such as baseline forest biomass (carbon) assessment and monitoring, additionality, leakage, and persistence. Remote sensing images provide a useful resource for developing land and forest cover maps and analysing change across wide areas that are otherwise poorly accessible, with ground measurements for verification (GOFC-GOLD 2009). Remote sensing technologies offer a number of advantages in assessing and monitoring both land cover and deforestation and forest degradation:

- Remote sensing can be used for analysis at multiple scales ranging from a few metres to several kilometres, and thus from detailed study at local level to forest resources assessment at global level.
- Remotely sensed data can be acquired at repeated time intervals (e.g., daily, monthly) and can thus be used for regular monitoring of forest resources over time.
- Measurements can be made on a near real time basis, which is particularly useful for monitoring events such as forest fire.
- Remote sensing data has synoptic coverage and information can be acquired from places where accessibility is an issue.
- Wavelengths can be used that are not visible to the human eye.

Remote sensing instruments and techniques (space-borne/air-borne) are now widely used for forest cover change assessments and deforestation monitoring at local, national, and regional scales (Baccini et al. 2004; DeFries et al. 2007), with limited ground measurements available for verification. Monitoring and mapping forest degradation and carbon stocks are more challenging as they tend to rely more on ground measurements. Forest degradation and carbon stock monitoring can take place at different levels using a combination of different technologies (remote sensing and ground based) as shown in Figure 1.

Figure 1: **Levels and tools for forest degradation and carbon stock monitoring**



Most developing countries don't have sufficient forest inventory data of the type needed to get accurate biomass figures, and remote sensing methods are becoming increasingly attractive to scientists for biomass estimation, mapping, and accuracy assessments (Nelson et al. 1988; Franklin and Hiernaux 1991; Steininger 2000; Foody et al. 2003; Zheng et al. 2008; Lu 2006; Ahmed et al. 2013). A number of attempts have been made to estimate forest biomass and carbon stock using different platforms (air-borne and space-borne) and sensors (optical, radar, and LiDAR [light detection and ranging]) (Gibbs et al. 2007). Furthermore, several methods have been proposed for estimating forest biomass using remote sensing techniques that make use of a combination of regression models, vegetation indices, and canopy reflectance models (Gonzalez et al. 2010; Huang et al. 2013). The remote sensing based measurements are used in combination with forest inventory measurements in permanent field plots. Inventory measurements are required in the initial stages for training image interpretation, for developing the specific factors to be used in estimating carbon stocks in different forest types, and for groundtruthing and verification of accuracy. However, increasingly sophisticated and varied remote sensing approaches are reducing the requirement for field plots. Remote sensing approaches using multi-resolution data provide an alternative to the traditional plot-based methods and enable repeat monitoring even in remote locations in a cost-effective way (Patenaude et al. 2005). Remote sensing can provide spatial, temporal, and spectral information and can thus be used as a tool for accurate estimation of carbon to meet the requirements of the Kyoto Protocol and United Nations Collaborative Programme on REDD+ (Rosenqvist et al. 2003; Andersson et al. 2009).

The Geospatial Component of the ICIMOD REDD+ Pilot Project

ICIMOD has been working for many years to develop and promote the application of geo-information and Earth observation tools and technologies to mountain development issues. Between 2009 and 2014, a methodology was developed for continuous monitoring of forests with systematic assessment of biomass and carbon stocks through remote sensing and field data for operational MRV in REDD+ under the ICIMOD led REDD+ pilot project. The aim was to assess the performance of the REDD+ pilot projects using remote sensing data and GIS methodologies. The scientific methodology for quantification and monitoring of spatial changes was developed under the SERVIR-Himalaya initiative of the National Aeronautics and Space Administration (NASA) and United States Agency for International Development (USAID). This report describes the approach and major results of the activities under this geospatial component of the REDD+ pilot project.

The geospatial project had three main objectives:

- Provision of baseline information
  - Delineation of project and social forest boundaries
  - Land and forest cover mapping and change analysis
- Biomass and carbon stock estimation
  - Tree canopy morphology – crown projection area (CPA) change analysis
  - Stratification of permanent sample plots
  - Modelling of biomass and carbon stocks and change assessment
  - Comparison of AGB estimates obtained through remote sensing and field inventories
- Engagement of partners and stakeholders
  - Capacity building of national and regional forestry institutes
  - Mobilization and awareness campaigns for field staff and communities
  - Scientific research to investigate different methods and tools

High resolution satellite images and various modelling techniques were used to provide the baseline data on land and forest cover required as a basis for the REDD+ payment mechanism and to quantify biomass and carbon stock. The status of forest fire was also analysed. Regional, national, and sub-national level capacity building was carried out for different institutions and community users involved in the project. Research and capacity building of national stakeholders were performed in close collaboration with ITC-Netherlands.

Project Methodology

The project used a participatory GIS approach with high resolution satellite images from GeoEye-1 and IKONOS-2 to delineate the boundaries of different forest regimes. Permanent sample plots were positioned using land/forest cover strata and are being measured each year by communities. Forest cover change was assessed to support understanding of deforestation and forest degradation, and forest crown, biomass, and carbon change were quantified for different time periods and change over time analysed. The results of field-based and remote-sensing based measurements of carbon stocks were compared. The detailed methods are summarized below.

Project sites

The REDD+ pilot project was implemented in three watersheds, one in each of the different geographic regions in Nepal: Kayar Khola in Chitwan District in the plains, Ludi Khola in Gorkha District in the hills, and Charnawati in Dolakha District in the mountains (Figure 2). It covered 112 community forests (CFs), 89 leasehold forests (LHFs), and 4 private forests (PFs). The major characteristics of the pilot watersheds are summarized in Table 1. Details of the area of individual CFs, LFs, and PFs in each watershed are provided in Annex 1.

The Kayar Khola watershed covers an area of 8,002 ha at an elevation of 245 to 1,944 m in Chitwan District in the Central Development Region of Nepal. The 16 CFs and 74 LHFs cover an area of 2,670 ha. The watershed is inhabited by socially and ethnically diverse groups including forest-dependent indigenous communities such as Chepang and Tamang, as well as Brahmin and Chhetri communities.

The Ludi Khola watershed covers an area of 5,750 ha at an elevation of 318 to 1,714 m in Gorkha District in the Western Development Region of Nepal. The 31 CFs and 4 PFs cover an area of 1,892 ha. The watershed is characterized by social diversity with Brahmin, Chhetri, Dalit, Gurung, Magar, and Tamang, among the major ethnic groups.

Figure 2: **Location of project sites**

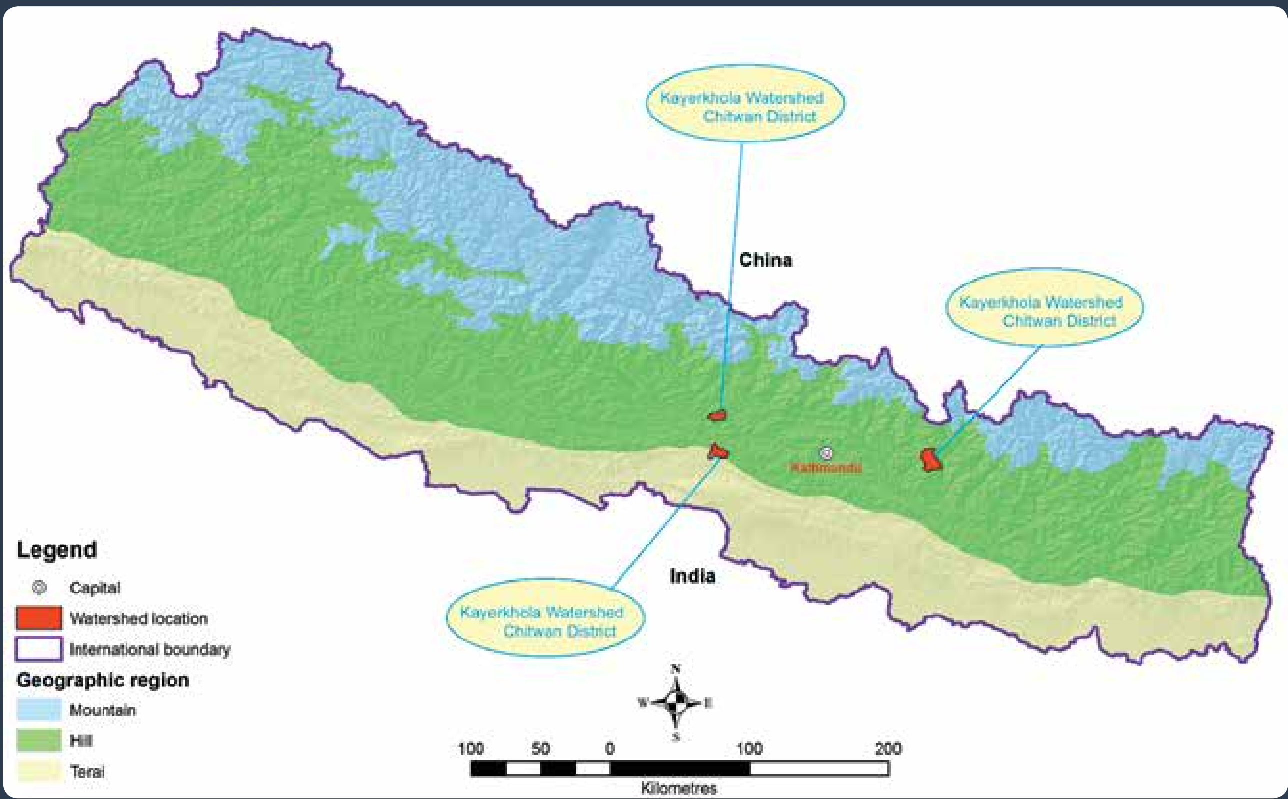


Table 1: **Main features of the project sites**

Watershed	District	Area (ha)	Elevation (masl)	Community forests (CF)		Leasehold forests (LHF)		Private forests (PF)	
				No.	Area (ha)	No.	Area (ha)	No.	Area (ha)
Kayar Khola	Chitwan	8,002	245–1,944	16	2,385	74	285	0	0
Ludi Khola	Gorkha	5,750	318–1,714	31	1,888	0	0	4	3.7
Charnawati	Dolakha	14,037	835–3,549	65	6,094	15	57	0	0
Total		**27,789**		**112**	**10,367**	**89**	**342**	**4**	**3.7**

The Charnawati watershed covers an area of 14,037 ha at an elevation of 835 to 3,549 m in Dolakha District in the Central Development Region of Nepal. The 65 CFs and 15 LHFs cover an area of 6,151 ha. The population is socially diverse with Brahmin, Chhetri, Dalit, Newar, Tamang, and Thami among the major ethnic groups.

Data, software, and field equipment

The study used high resolution satellite images from GeoEye-1 and IKONOS-2 for delineation of the boundaries of watersheds, CFs, LHFs, and PFs at the three selected sites. The images used are listed in Table 2. The satellite images were also used as a basis for assessing land/forest cover change, tree canopy monitoring, and carbon sequestration and biomass change. A digital elevation model (DEM) derived from topographic sheets was used to understand the topography of the area as well as for ortho-rectification of the satellite images.

Table 2: **Characteristics of the satellite images**

Watershed	Satellite	Sensor	Acquisition date	Spatial resolution	Spectral bands (nm)
Kayar Khola	GeoEye	GeoEye-1	2 Nov 2009 15 Dec 2012	2 m (XS) 0.5 m (Pan)	Blue (450–510) Green (510–580) Red (655–690) Near infrared (780–920) Pan (450–800)
	IKONOS	IKONOS-2	3 Aug 2002	4 m (XS) 1 m (Pan)	
Ludi Khola	GeoEye	GeoEye-1	2 Nov 2009 29 Dec 2012	2 m (XS) 0.5 m (Pan)	
Charnawati	GeoEye	GeoEye-1	11 Feb 2009 29 Dec 2012		

For the preparation of base data layers, digital layers of the relevant topographic sheets were acquired from the National Geographic Information Infrastructure Project (NGIIP), Department of Survey, Government of Nepal. The data layers correspond to topographic sheets of scale 1:25,000/50,000 based on 1992 aerial photographs for eastern Nepal and 1996 aerial photographs for western Nepal and published from 1995 onwards. The datasheets were merged to generate layers of contours, settlements, roads, trails, and streams for each watershed.

The main software used in the research is summarized in Table 3. Object based image analysis (OBIA) was performed using Earth Resources Data Analysis System (ERDAS) Imagine and eCognition Developer software. ArcGIS was used to carry out GIS operations. Microsoft Office and statistical software packages were also used in the study.

The main equipment used in the field work is shown in Table 4. A global positioning system (GPS) and iPAQ were used for finding the position of the sample plots and recording the centre. Tree diameter (DBH) was measured using diameter tape and tree height was measured with a Haga altimeter. Field data collection forms were used to record field information.

Table 3: **Software used in the research**

Software	Purpose
ArcMap	GIS processing, analysis, and map formation
eCognition Developer	Object-based image analysis
ERDAS Imagine	Image processing and remote sensing applications
SPSS and R	Statistical analysis
Microsoft Excel	Statistical analysis
Microsoft PowerPoint	Presentation of research
Microsoft Visio	Diagrammatic representations
Microsoft Word	Writing

Table 4: **Field equipment used for field data collection**

Equipment	Purpose
Garmin GPS and iPAQ	Location
Diameter tape (5 m)	Measuring tree diameter
Measuring tape (30 m)	Measuring the plot radius
Haga altimeter	Height measurement
Fieldwork datasheet	Field data collection

Pre-processing of satellite images

Satellite images are often affected by factors which decrease image quality. Especially if high accuracy is required, image pre-processing has to be performed in advance whether using satellite images for single or time series analyses. Various algorithms and filters can be used in pre-processing. The steps used in this study are summarized in the following paragraphs.

The GeoEye-1 high resolution satellite images from November 2009 were orthorectified band by band using rational polynomial coefficients along a horizontal 20 m topographic digital elevation model (DEM) by applying a cubic convolution method in zone 45 of the Universal Transverse Mercator coordinate system, with datum and spheroid from the World Geodetic System (WGS) 84. A differential global positioning system (DGPS) receiver made by Leica Geosystems (SR20) was used to assess the accuracy of the orthorectified satellite dataset. Permanent reference points were acquired from the Nepal Department of Survey to fix the reference DGPS set; 25 random points were collected across each watershed using the rover DGPS, the overall root mean square (RMS) error was 3 cm. Layer stacking was performed to make the multispectral image.

The GeoEye-1 images captured in December 2012 were already orthorectified by the sensor but slight positional disturbance was observed so geo-rectification was performed based on the GeoEye-1 (2009) satellite images. A similar procedure was adopted for the IKONOS-2 images from 2002.

GeoEye-1 spectral bands at lower resolution (2 m) were merged with the high spatial resolution information (0.5 m) from the panchromatic image using the intensity hue and saturation fusion method, chosen because it can effectively separate RGB (red, green, blue) images into spatial (I) and spectral (H, S) information. Low pass median filters were applied prior to segmentation to prevent oversegmentation (Platt and Schoennagel 2009); 3 x 3 and 5 x 5 low pass filters were used to minimize spatial variation, typically noise, through a smoothing process. Median filters were used as they produce more homogeneous image segments and may reduce the amount of convolution in the final segmented polygons resulting from the high resolution satellite images (Mora et al. 2010). Researchers have used median filters with different window sizes for individual tree crown delineation depending on the homogeneity of the images, but window sizes of 3 x 3, 5 x 5, and 7 x 7 are the most common (Mora et al. 2010; Gougeon and Leckie 2006; Erikson and Olofsson 2005; Platt and Schoennagel 2009). The IKONOS-2 multispectral images of 4 m resolution and panchromatic images of 1 m resolution were fused in a similar way to generate a pan-sharpened image with 1 m spatial resolution.

Image enhancement is used to improve low contrast satellite images to facilitate interpretation. A 'standard deviation stretch' algorithm was applied to improve the image contrast so that crowns could be clearly identified (Hashimoto et al. 2011). Application of the algorithm enhances the spectral behaviour of the satellite images; the magnitude of the enhancement depends on the standard deviation value defined by the analyst. This study used a standard deviation interval value of -2.5 to +2.5 standard deviations from the mean of the existing pixel values. This stretched the values to the complete range of output screen values. The brightness contrast utility of ERDAS Imagine was also used to further enhance the visual details of the satellite images.

Baseline Information for REDD+ Monitoring

Baseline information is essential for MRV in REDD+ to understand the current scenario of project sites. In this study, high resolution satellite images were used to delineate the boundaries of the community, leasehold, and private forests, and provide baseline information on area. Land cover was mapped using the same images, and served as a baseline for stratification of the permanent sample plots as well as for subsequent analysis of change.

Delineation of community, leasehold, and private forests

Field maps were prepared for the delineation of community, leasehold, and private forests in the three watersheds by printing out the high resolution GeoEye-1 satellite images in A0 size. Additional information were included from topographic maps for better identification of locations. Fieldwork was carried out using a participatory GIS approach in which members of community forest user groups (CFUGs) worked together with staff from local organizations and partners ANSAB and FECOFUN to identify and map the boundaries of the individual community forests (Figure 3). Key community concerns related to boundaries were discussed and resolved in groups. Ancillary information such as the existing maps and descriptions prepared by the CFUGs were used as the basis for demarcation. Features like streams, ridges, and trails were used to identify the exact locations. In the areas where community and other forests (national or leasehold) were adjacent to each other, a GPS survey was carried out together with the local participants. The demarcated areas were then plotted on the field maps; the maps were digitized at a later stage. A total of 112 CFs, 89 LHFs, and 4 PFs were delineated (Annex 1).

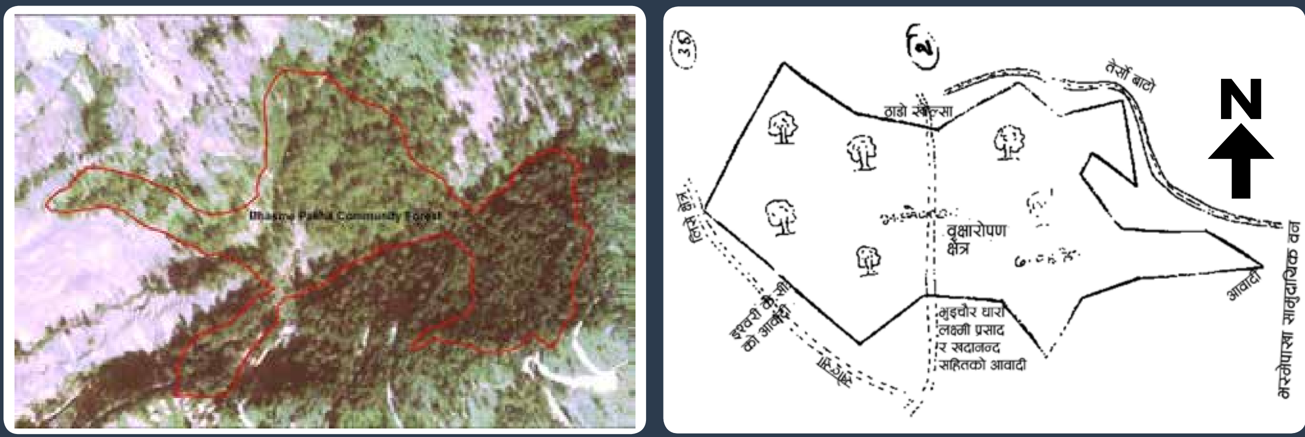
In some cases, comparison of the delineated community forests with the existing records showed considerable differences in both shape and size (see, for example, Figure 4). A workshop with CFUG members and the district forest office (DFO) is recommended for endorsement of the maps.

Land and forest cover mapping

Image segmentation is used to locate objects and boundaries electronically within digital images to facilitate analysis. The techniques were developed in the 1980s but used to a lesser extent in geospatial applications (Blaschke 2010). Essentially, image segmentation means identifying adjacent pixels that are similar with respect to some characteristic, such as colour, intensity, or texture, and dividing the image into distinct regions ('segments') each containing pixels with similar attributes. The algorithms used for image segmentation can be broadly divided into pixel-based and object-based. Whereas pixel-based classification of remotely sensed images mainly uses

Figure 3: **CFUG members delineating the community forest (left); differential global positioning system survey equipment (right)**

Figure 4: **Delineated boundary (left) and sketch map (right) of Bhasmepakha Community Forest in Charnawati watershed**



spectral patterns, the object-based technique uses both spectral and spatial patterns and takes the geometry of objects into account (Baatz et al. 2001). In recent times, object based image analysis (OBIA) has become the method of choice in geospatial applications as it provides much faster and more accurate results than conventional pixel-based image classification algorithms (Blaschke 2010; Quintano and Cuesta 2010; Knorn et al. 2009; Stathakis and Vasilakos 2006; Thessler et al. 2008). Segmentation is followed by image classification, which essentially means adding labels that refer to meaningful real world objects (e.g., 'water', 'forest') to the pixels in the digital image (Benz et al. 2004). The classification is used to prepare thematic maps from the remotely sensed images.

Satellite image segmentation and classification

In this study, a recently introduced object based image analysis (OBIA) technique was used for segmentation and classification. The major steps are shown diagrammatically in Figure 5 and typical images in Figure 6. A multi-resolution algorithm was used for segmentation of the satellite image, which locally minimized the average heterogeneity of image objects for a given resolution (Blaschke 2010). Image segmentation was performed and analysed using various combinations of parameters (scale, shape, and compactness). First, a suitable scale parameter for the segmentation was identified using a trial method in which object primitives were considered to be internally homogeneous, i.e., all pixels within an object primitive belong to one cover class. A rule-based technique ('if and then' condition) was used to enable

Figure 5: **Flow chart for object based image classification**

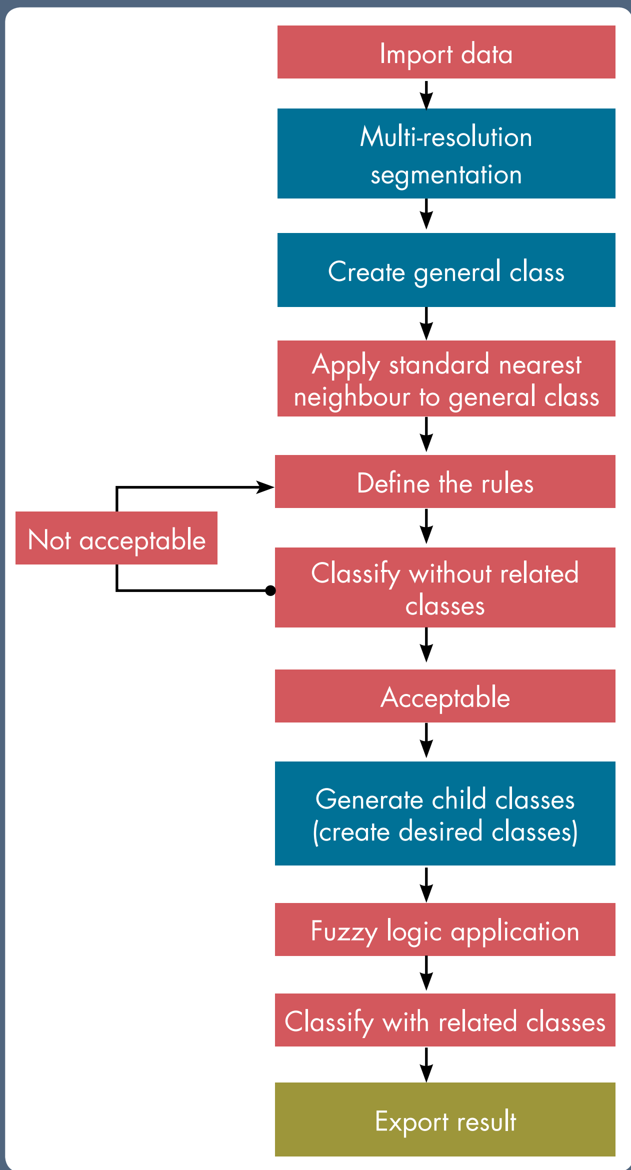
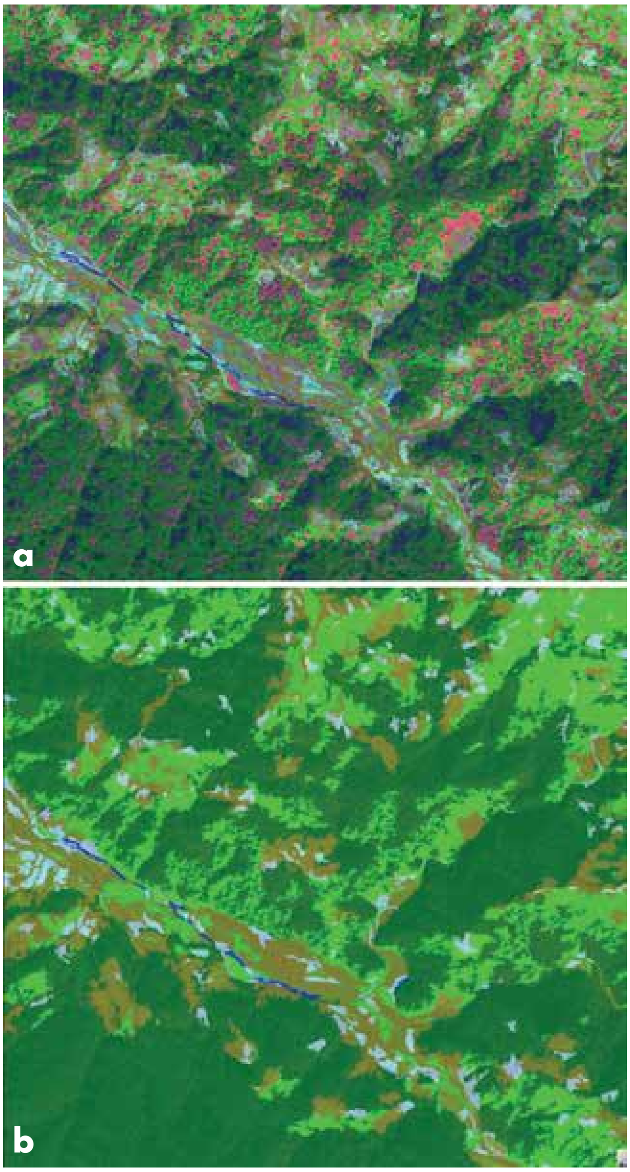


Figure 6: **Segmentation (a) and classification (b) images**



accurate and more rapid land cover mapping. Various conditions were applied to identify and map each class. Classification was supported by the use of a synthetic image layer called 'image index' created from the existing bands of the multispectral image. This new layer can provide unique and valuable information which is not found in any of the individual bands (Tucker and Seller 1986). Key satellite image indices such as Normalized Difference Vegetation Index (NDVI), Soil Adjusted Vegetation Index (SAVI), Water Mask, and others were calculated for easy identification of the land cover classes. The aspect and slope from the DEM and unsupervised classification results were also incorporated as ancillary data for classification. The final output was a set of land cover maps for the individual watersheds.

Land and forest cover accuracy assessment

Accuracy assessment of the land cover maps derived from the 2009 GeoEye-1 satellite images was performed through generation of stratified random sample plots. A specified number of sample plots was generated for each land cover class proportional to the percentage area contribution of that class to total land cover area. The land cover class of these field plots was determined from field observation. A confusion error matrix technique was used to ascertain the overall accuracy (producer's and user's accuracies) and kappa values. Land cover from 2009 was used as a reference to classify the satellite images from 2002 and 2012. The results are shown in Table 5. The land cover maps were then further validated and refined using the results of visual image interpretation over the entire watershed with a 1 x 1 ha spatial grid.

Land and Forest Cover Change

Land cover change

Table 5: **Accuracy assessment of land cover**

Watershed	Reference samples	Accurate samples	Overall accuracy (%)	Average producer's accuracy (%)	Average user's accuracy (%)
Kayar Khola	150	141	94	73	96
Ludi Khola	120	115	96	75	97
Charnawati	200	179	90	85	98

The change in land cover from 2002 to 2009 and 2012 (Kayar Khola watershed) and from 2009 to 2012 (Ludi Khola and Charnawati watersheds) was assessed at the watershed level and within CF, LHF, and PF areas separately. The land cover maps for the different years are shown in Figures 7–9. The maps were evaluated and compared in terms of area; the results are shown in Tables 6–8. All watersheds and forest types showed an overall increase in forest area. Some areas showed a decrease in the open forest class, but this was always associated with an increase in the relevant closed forest class and thus indicated an improvement in forest quality. The satellite images were evaluated visually to identify examples of change in forest cover, especially deforestation in Annex 2.

Figure 7: **Land cover in Kayar Khola watershed in 2002, 2009, and 2012**

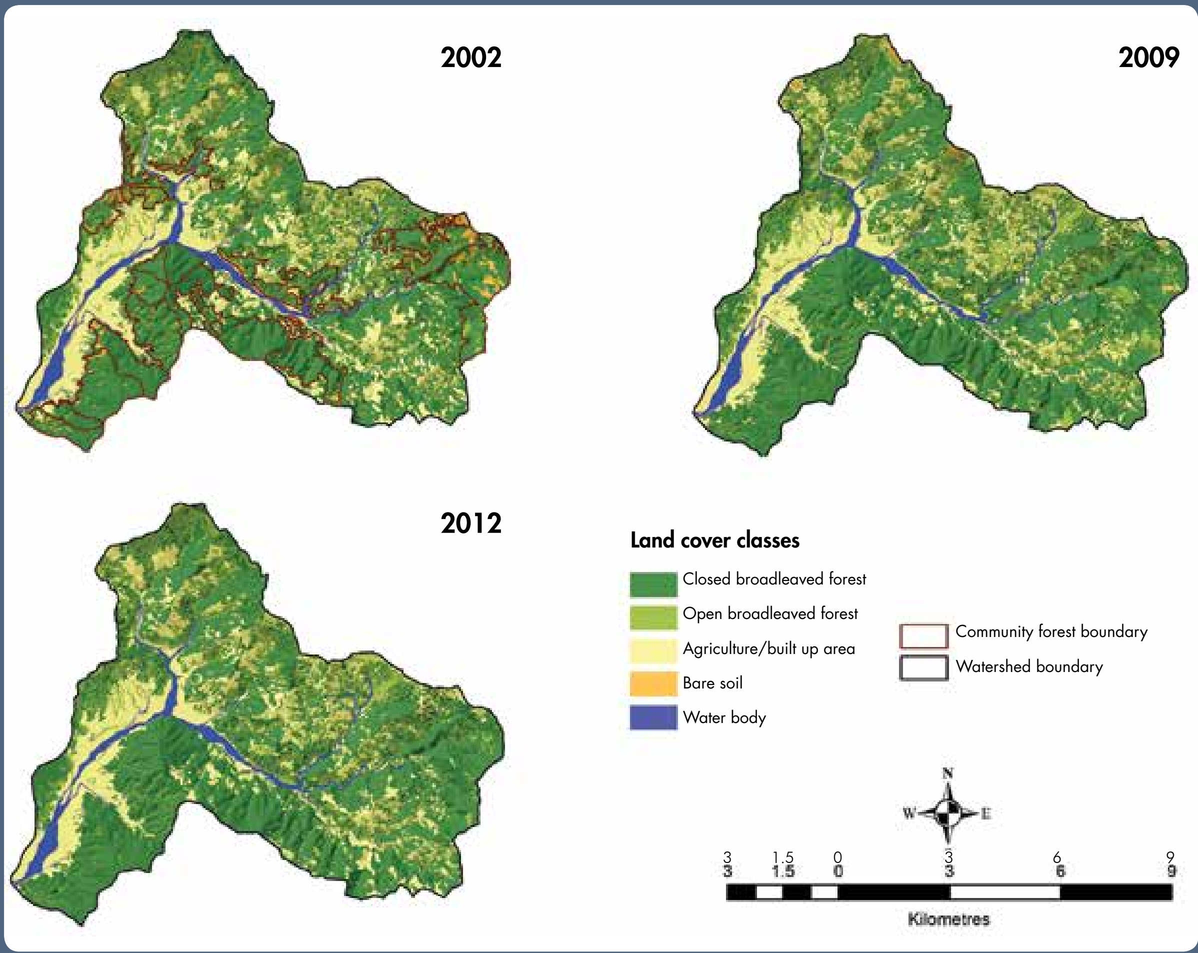


Figure 8: **Land cover in Ludi Khola watershed in 2009 and 2012**

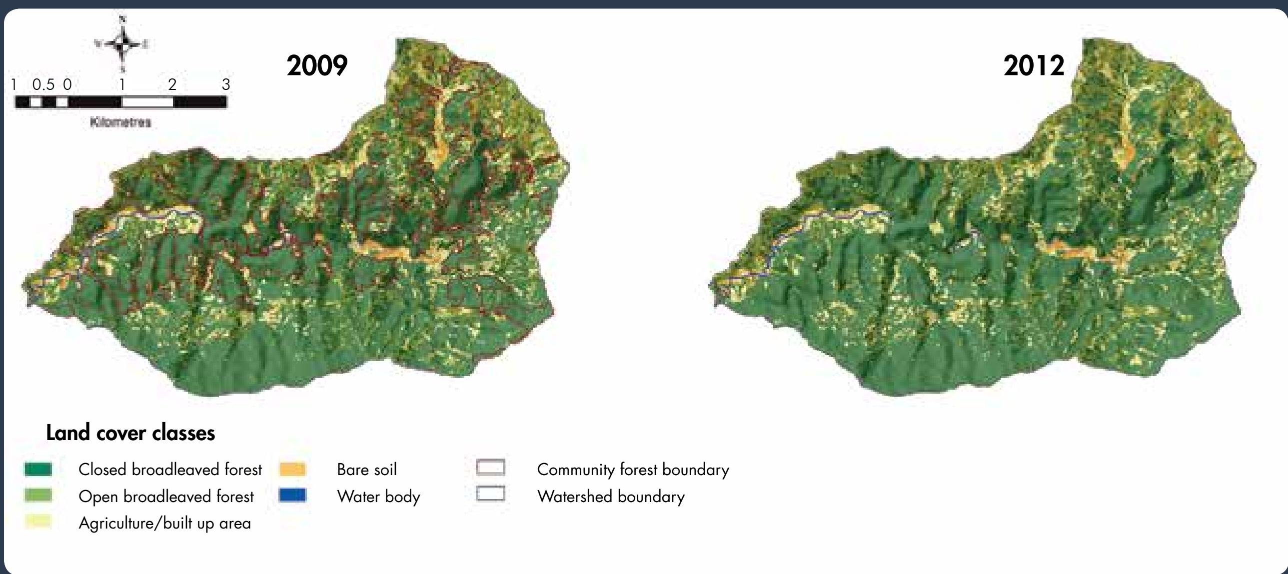


Figure 9: **Land cover in Charnawati watershed in 2009 and 2012**

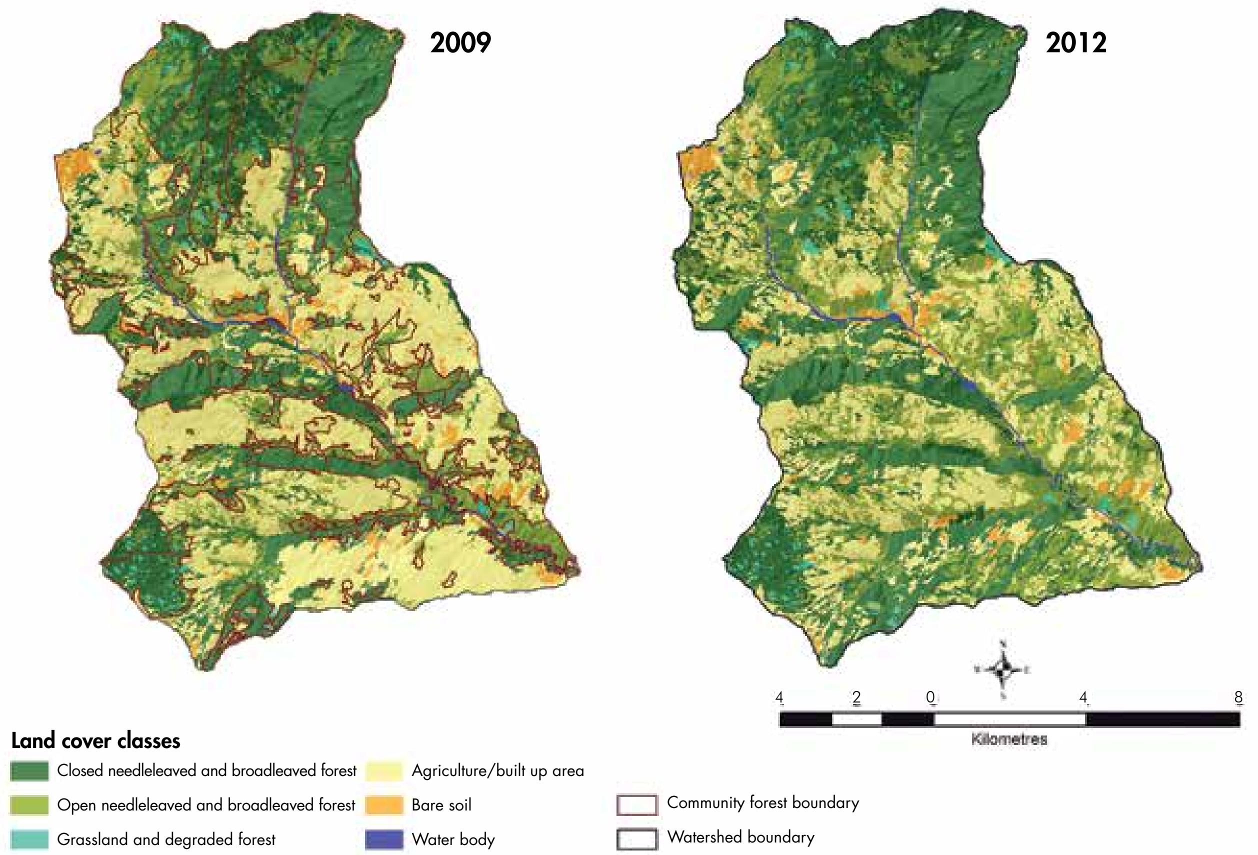


Table 6: **Land cover change in Kayar Khola watershed**

	Land cover class	Area (ha) 2002	2009	2012
Watershed	Closed broadleaved forest	3,860	4,008	4,110
	Open broadleaved forest	1,724	1,856	1,782
	Agriculture and built-up area	2,110	2,021	2,021
	Barren area	272	83	56
	Water body	36	34	33
	Total watershed			**8,002**
CFs	Closed broadleaved forest	1,821	1,888	1,936
	Open broadleaved forest	346	434	418
	Agriculture and built-up area	49	32	26
	Barren area	165	26	0.4
	Water body	0.7	2	1.7
	Total CFs			**2,382**
LHFs	Closed broadleaved forest	141	147	158
	Open broadleaved forest	80	87	84
	Agriculture and built-up area	62	51	42
	Barren area	1.6	0.2	0.1
	Water body	0.2	0.6	0.2
	Total LHFs			**285**

Table 7: **Land cover change in Ludi Khola watershed**

	Land cover class	Area (ha) 2009	2012
Watershed	Closed broadleaved forest	3,873	3,913
	Open broadleaved forest	996	1,000
	Agriculture and built-up area	632	594
	Barren area	241	234
	Water body	9.5	9.5
	Total watershed	**5,751**	**5,751**
CFs	Closed broadleaved forest	1,635	1,641
	Open broadleaved forest	219	224
	Agriculture and built-up area	15	5.7
	Barren area	19	16
	Water body	0.04	0.03
	Total CFs	**1,888**	**1,888**
PFs	Closed broadleaved forest	3.1	3.2
	Open broadleaved forest	0.5	0.5
	Agriculture and built-up area	0.1	0.04
	Barren area	0	0
	Water body	0	0
	Total PFs	**3.7**	**3.7**

Table 8: **Land cover change in Charnawati watershed**

	Land cover class	Area (ha) 2009	2012
Watershed	Close needleleaved and broadleaved forest	4,991	5,678
	Open needleleaved and broadleaved forest	2,501	3,540
	Grassland and degraded forest	204	201
	Agriculture and built-up area	5,710	4,004
	Barren area	629	612
	Water body	1.0	1.1
	Total watershed	**14,037**	**14,037**
CFs	Close needleleaved and broadleaved forest	3,755	3,951
	Open needleleaved and broadleaved forest	1,593	1,675
	Grassland and degraded forest	156	152
	Agriculture and built-up area	552	273
	Barren area	38	44
	Water body	0	0
	Total CFs	**6,094**	**6,094**
LHFs	Close needleleaved and broadleaved forest	2.7	7.6
	Open needleleaved and broadleaved forest	28	25
	Grass land and degraded forest	0	0
	Agriculture and built-up area	26	24
	Barren area	0.8	0.5
	Water body	0	0
	Total LHFs	**57**	**57**

Forest cover change

Analysis of the basis of forest cover change addressed two questions using a change matrix technique:

- How much area has changed from forest to non-forest and from non-forest to forest within different time intervals in each constituted unit?
- How much area has changed between forest classes, e.g., closed broadleaved to open broadleaved and open broadleaved to close broadleaved?

The results are given for each watershed in Tables 9–14 and shown in the form of forest cover change maps in Figures 10–12.

Table 9: **Forest cover change in Kayar Khola watershed**

	Land cover class	Area (ha) 2002–2009	2009–2012
Watershed	Forest to non-forest	250	140
	Non-forest to forest	531	168
CFs	Forest to non-forest	25	1.1
	Non-forest to forest	180	33
LHFs	Forest to non-forest	3.6	0.3
	Non-forest to forest	14	9.5

Table 10: **Change among forest classes in Kayar Khola watershed**

	Forest class	Area (ha) 2002–2009	2009–2012
Watershed	Closed broadleaved to open broadleaved forest	149	10
	Open broadleaved to closed broadleaved forest	15	126
CFs	Closed broadleaved to open broadleaved forest	29	4.4
	Open broadleaved to closed broadleaved forest	4.4	32
LHFs	Closed broadleaved to open broadleaved forest	4.1	0
	Open broadleaved to closed broadleaved forest	2.2	5.4

Table 11: **Forest cover change in Ludi Khola watershed**

	Land cover class	Area (ha) 2009–2012
Watershed	Forest to non-forest	27
	Non-forest to forest	73
CFs	Forest to non-forest	0.6
	Non-forest to forest	13

Table 12: **Change among forest classes in Ludi Khola watershed**

	Forest class	Area (ha) 2009–2012
Watershed	Closed broadleaved to open broadleaved forest	3
	Open broadleaved to closed broadleaved forest	16
CFs	Closed broadleaved to open broadleaved forest	3
	Open broadleaved to closed broadleaved forest	10

Table 13: **Forest cover change in Charnawati watershed**

		Area (ha)
	Land cover class	2009–2012
Watershed	Forest to non-forest	166
	Non-forest to forest	1,892
CFs	Forest to non-forest	62
	Non-forest to forest	340
LHFs	Forest to non-forest	1.4
	Non-forest to forest	3.5

Table 14: **Change among forest classes in Charnawati watershed**

		Area (ha)
	Forest class	2009–2012
Watershed	Closed needleleaved and broadleaved to open needleleaved and broadleaved forest	67
	Open needleleaved and broadleaved to closed needleleaved and broadleaved forest	256
CFs	Closed needleleaved and broadleaved to open needleleaved and broadleaved forest	45
	Open needleleaved and broadleaved to closed needleleaved and broadleaved forest	180
LHFs	Closed needleleaved and broadleaved to open needleleaved and broadleaved forest	0
	Open needleleaved and broadleaved to closed needleleaved and broadleaved forest	4.6

Figure 10: **Forest cover change in Kayar Khola watershed (2002–2012)**

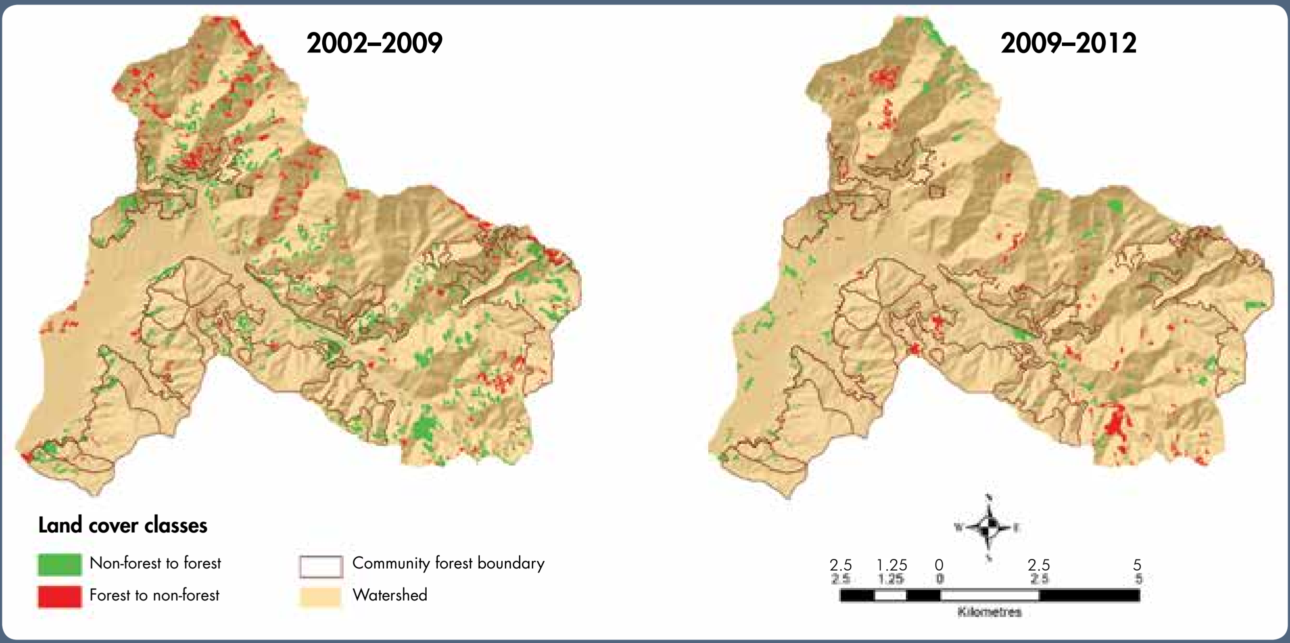
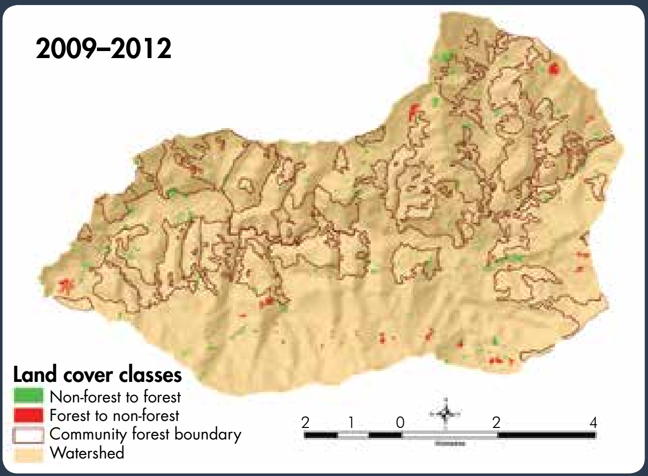


Figure 11: **Forest cover change in Ludi Khola watershed (2009–2012)**



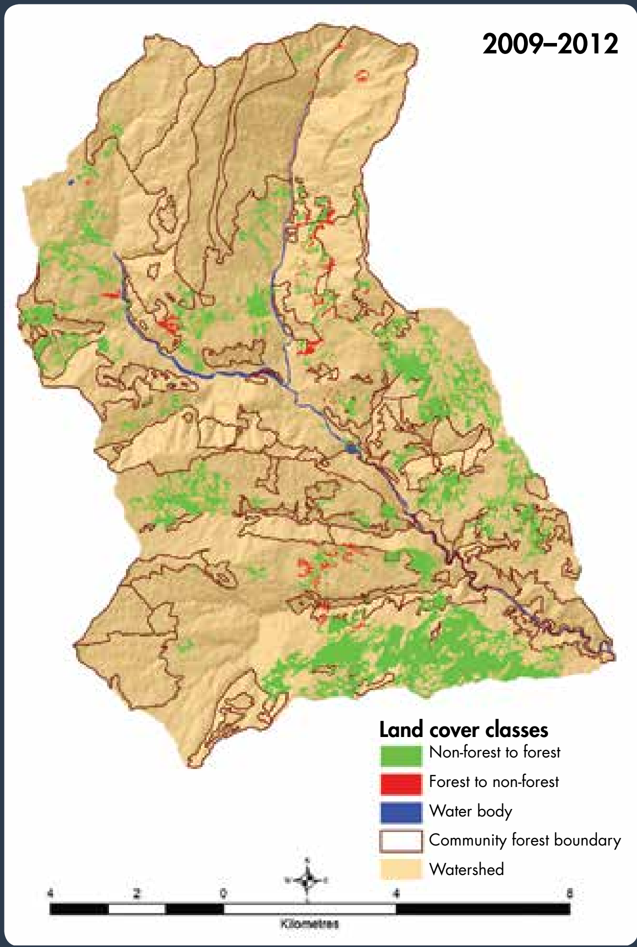
Stratification of permanent field plots

The 2009 land cover of each watershed was used as a basis for identifying the number and location of permanent sample plots for field measurements using a random sampling technique. The forest classes were treated as strata for the distribution of the plots. Sample plots were established by the local communities and measured annually (2010–2013) with technical support from the project implementing agencies. The distribution of sample plots is given in Annex 3. Detailed documentation is available at www.communityredd.net/assets/files/Technical%20Carbon%20Report_2012.pdf.

Estimation of Above Ground Biomass and Carbon Stocks

MRV in REDD+ requires estimation of forest biomass and total carbon stocks. The main factor influencing change in carbon stocks is change in AGB, and most research focuses on AGB measurement. Many methods have been developed to estimate forest AGB (Franklin and Hiernaux 1991; Hashimoto et al. 2011). The most accurate is to cut down all the trees in an area, dry them in their component parts, and then measure the weight of all the leaves, branches, and trunks and convert the values to the carbon equivalent. However, this is impractical to do for more than a few trees because it is both extremely time consuming and destructive. Instead, researchers have used this destructive approach to create relationships between forest tree metrics such as diameter at breast height (DBH) and tree height and their biomass content. These relationships are used to create allometric equations that can be used to estimate biomass either based on one or more specific tree characteristics that are easy to measure in the field (e.g., DBH and tree height), or by using remote sensing derived metrics such as tree crown diameter and tree height. Gibbs et al. (2007) reported that estimations based on data from very high resolution optical remote sensors had a low to medium uncertainty overall, with one of the major limitations being that there were no allometric relations available based on crown area. This limitation has been overcome with the advance of geospatial methods (Song and Dickinson 2008; Mbaabu et al. 2014).

Figure 12: **Forest cover change in Charnawati watershed (2009–2012)**

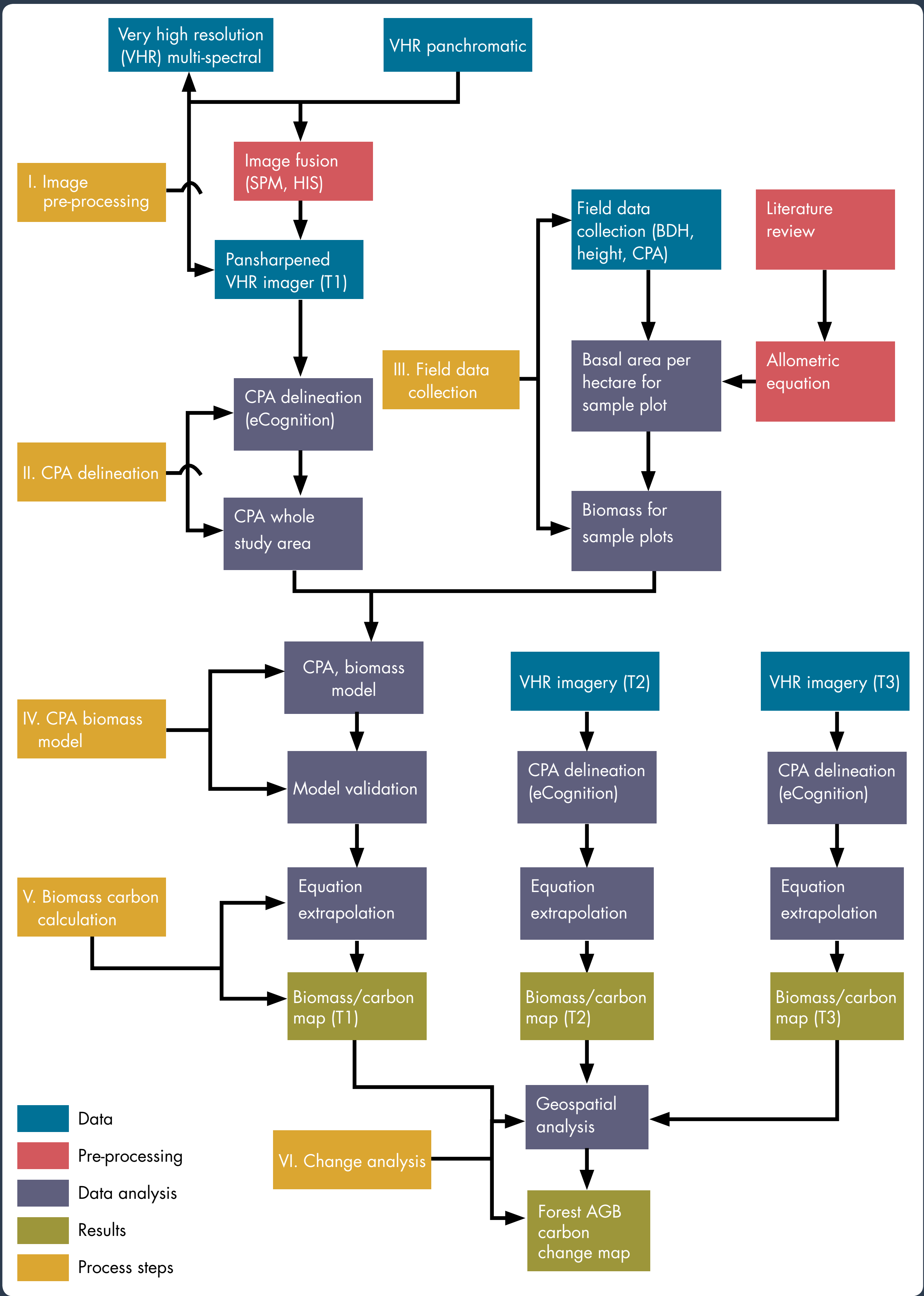


In the present study, the status and spatial change of biomass and carbon stock in the Kayar Khola and Ludi Khola watersheds were assessed from analysis of satellite images with integration of ground information. The overall methodology is shown in Figure 13. The individual steps and selected results are described in the following sections. Briefly, AGB was estimated using the values for tree crown cover. The crown projection area (CPA) in the watersheds and different forest areas was evaluated in the satellite images using automated object-based image analysis (OBIA). A model relating CPA to AGB in the study area was developed using a combination of OBIA data with field data from the permanent sample plots. Carbon stocks were calculated from the AGB values and biomass/carbon maps developed for the watersheds. The results for different years were analysed and used to calculate change in carbon stocks over time and to prepare carbon change maps. The change values derived from the automated analysis were compared with the values obtained from the field measurements carried out by communities in the field plots.

Detection and delineation of tree crowns

Detection and delineation of tree crowns, and estimation of total crown projection area (CPA), can be used to model tree structural variables such as stem diameter, height, and biomass that are useful in forest inventory and evaluation of growth performance (Culvenor 2002). The relationship between forest crown cover and biomass is well established and has been widely used at different scales, thus identification of tree crown area and number can be used as a basis for biomass estimation.

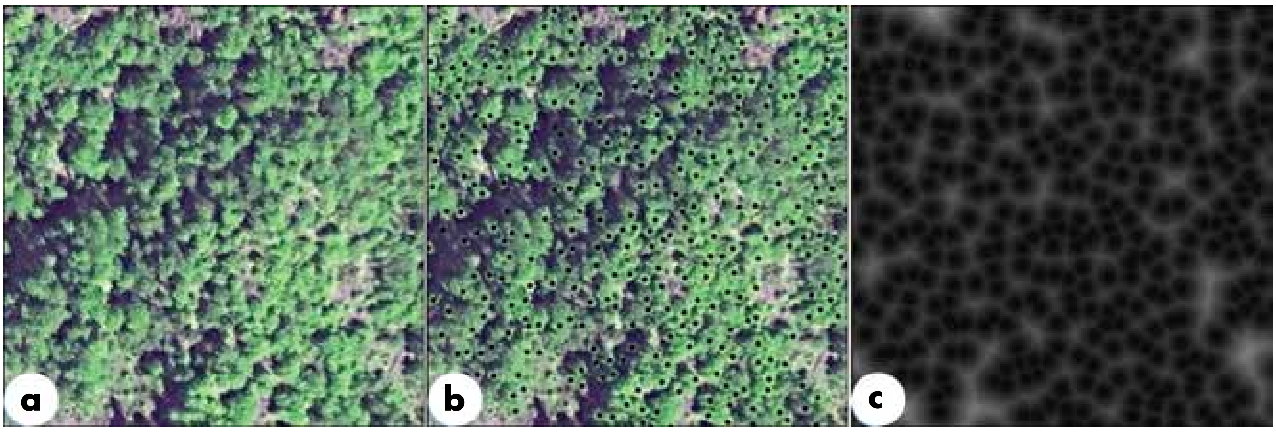
Figure 13: **Flow chart of process for AGB and carbon stock mapping and change analysis**



Different OBIA techniques have been used for tree crown detection and delineation including the valley following approach (Ke and Quackenbush 2011), region growing (Ke and Quackenbush 2008; Culvenor 2002), watershed transformation (Wang et al. 2004), multi-resolution segmentation (Kim et al. 2009), wavelet segmentation (Coillie et al. 2008), and multi-scale object specific segmentation (Hay et al. 2005). Most recently, researchers have started to integrate active (LiDAR) and passive (multi-spectral) optical remote sensing datasets in segmentation techniques to generate more accurate and precise results in forested areas (Kim et al. 2010; Erdody and Moskal 2010).

In the present study, tree crown number and total CPA were analysed in high resolution satellite imagery, assigned to different tree crown size classes, and analysed statistically and graphically. Object based image analysis (OBIA) with a region growing technique was used for CPA detection and delineation at the watershed level. In this method, tree tops are identified as maxima and the shadows between trees as minima. The segments are 'grown' from these maxima and the valleys act as boundaries (see Figure 14). The first step in region growing was to create minimum size homogeneous objects through 'chessboard segmentation'; the brightest pixels were then identified as seed pixels (tree tops). Regions were 'grown' from the seed pixels up to the local minima, resulting in homogeneous objects based on predefined homogeneity criteria (Cui et al. 2008; Erikson 2003; Shih and Cheng 2005).

Figure 14: **Delineation of crown projection area (CPA): a) satellite image, b) image with local maxima/tree tops, c) distance from tree tops**



CPA accuracy assessment

Ke and Quackenbush (2011) identified three main ways to assess the accuracy of detected and delineated tree crowns in satellite images: (1) how well the delineated crowns represent the position of reference crowns; (2) how well the delineated crown size represents the size of reference crowns; and (3) how well the results represent the forest stand properties. There is no single well-established standard method for accuracy assessment but the most commonly used method is to compare the total number of detected trees against reference tree counts at plot level (Culvenor 2002; Ke and Quackenbush 2011). Change in tree crowns is assessed from overall change in number and/or area; one to one (canopy to canopy) assessment would be very challenging due to the systematic and non-systematic errors encountered during the acquisition of satellite images for different time periods (Potere 2008).

In this study, the accuracy of the CPA delineated through OBIA was assessed by comparing with the CPA derived from the images manually. Sixteen windows or grids (100 x 100 m) were selected in each watershed, and tree crowns were manually delineated and counted through image interpretation. The number of trees automatically delineated in the same grids using the region growing technique were also recorded (Tiede et al. 2006, 2007). A linear regression line was plotted between the automatically delineated and manually counted numbers and the coefficient of determination was calculated. The coefficient of determination was 0.83 for Kayar Khola watershed (Figure 15) and 0.88 for Ludi Khola watershed (Figure 16).

Figure 15: **Validation of segmented image, Kayar Khola watershed**

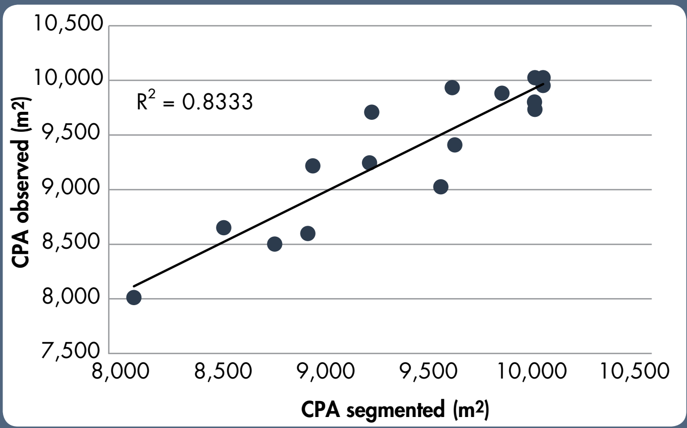
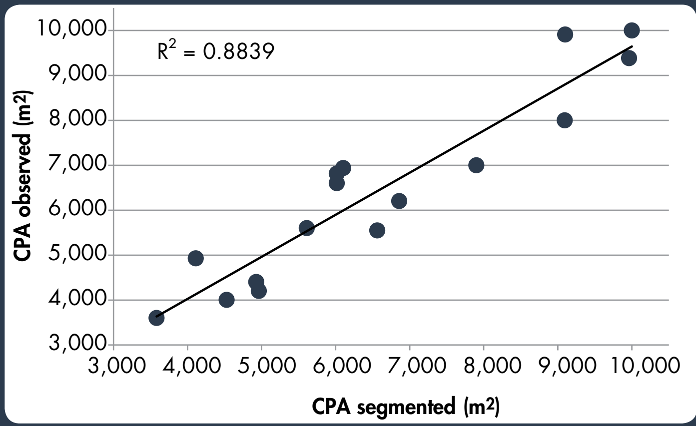


Figure 16: **Validation of segmented image, Ludi Khola watershed**



CPA change assessment

The total number of delineated tree crowns, and the number in each of six different size classes, were recorded for the whole of each watershed and within the different types of forest in each of the years investigated. Figures 17–20 show the change in the total number in different size classes within the whole watershed and in the CF area for Kayar Khola and Ludi Khola. Tables 15 and 16 show the CPA in the whole watershed, individual CFs, and all LHFs or PFs in Kayar Khola and Ludi Khola for the individual years, together with the change over time.

A total of 2,854,925 tree crowns were found in the Kayar Khola watershed in 2002; the number increased by 137,746 to 2,992,671 in 2009, and by a further 1,541 to 2,994,212 in 2012. A total of 4,176,796 tree crowns were found in the Ludi Khola watershed in 2009; the number increased by 234,856 to 4,411,652 in 2012.

Figure 17: **Change in tree crown size and number in Kayar Khola watershed**

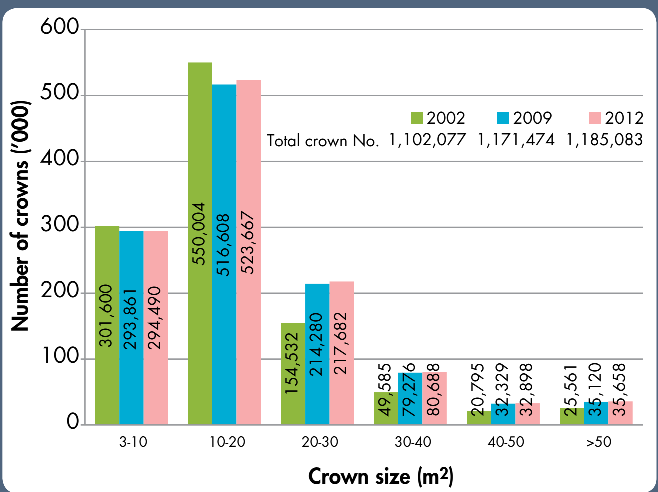


Figure 18: **Change in tree crown size and number in CFs in Kayar Khola watershed**

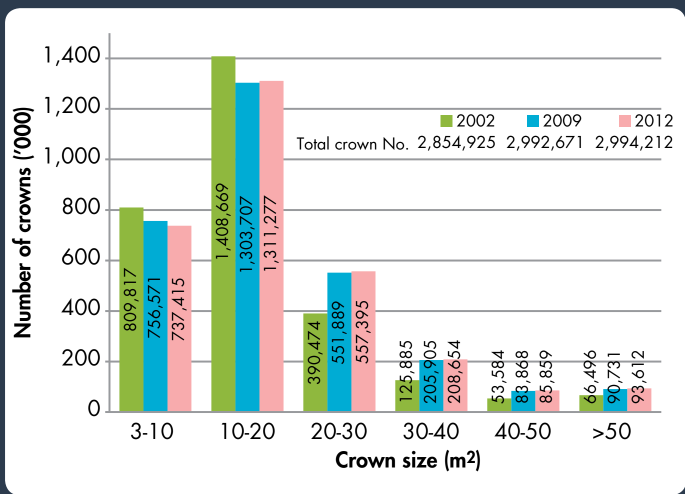


Table 15: **Change in CPA in the whole Kayar Khola watershed, individual CFs, and LHFs**

		CPA (ha)			Change in CPA (ha)	
Name	Total area (ha)	2002	2009	2012	2002–2009	2009–2012
Whole watershed	8,006	4,951	5,333	5,350	381	17
CFs						
Batauli	156	135	146	150	11	4.0
Chelibeti	65	61	61	65	0.5	3.4
Chitramkaminchuli	314	224	239	256	15	17
Deujar	279	210	226	226	16	0.8
Devidhunga	189	182	182	187	0.2	4.7
Dharapani	147	136	136	138	0.6	2.2
Indreni	172	149	149	155.	0.4	5.8
Jamuna	35	26	32	32	5.1	0.1
Janapragati	119	107	107	114	0.4	6.5
Jharana	35	30	31	33	0.8	1.7
Kalika	214	201	201	212	0.8	10
Kankali	92	78	80	88	2.8	7.8
Nibuwatar	329	295	299	301	3.7	3.0
Pragati	115	94	104	111	10	6.5
Samphrang	64	53	58	61	5.4	2.7
Satkanya	58	50	52	58	2.2	5.6
Total CFs	**2,382**	**2,030**	**2,104**	**2,187**	**74**	**82**
Total LHFs	**285**	**216**	**223**	**232**	**6.8**	**9.0**

Figure 19: **Change in tree crown size and number in Ludi Khola watershed**

Figure 20: **Change in tree crown size and number in CFs in Ludi Khola watershed**

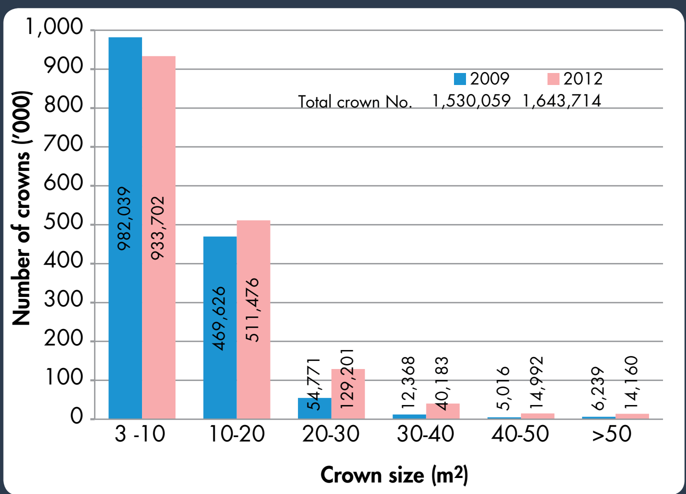


Table 16: **Change in CPA in the Ludi Khola watershed, individual CFs, and PF**

Name	Total area (ha)	CPA (ha) 2009	CPA (ha) 2012	Change in CPA (ha) (2009–2012)
Whole watershed	5,751	4,686	4,812	126
CFs				
Anpshwara Bhawanipakha	9.1	8.8	8.8	0.03
Badahare	26	22	25	2.8
Bagepani	68	67	67	0.2
Bhalukhola Soti	108	106	106	0.2
Bhangeristhan Ghantari	5.2	5.0	5.0	0.03
Birenchok	84	82	83	0.5
Chisapani	50	50	50	0.03
Gangate Bahunechaur	174	168	169	0.9
Ghaledanda Ranakhola	182	174	174	0.6
Goldanda	46	46	46	0.1
Kharkandepakha	48	46	47	0.5
Kharkopakho Bhekhpari	51	50	51	0.1
Kuwadi	92	91	91	0.6
Kyamundanda	59	58	58	0.1
Lamidanda	62	59	59	0.7
Laxmi Mahila	8.7	8.7	8.7	0.0
Ludi	17	16	16	0.0
Ludi Damgade	271	264	266	1.8
Mahalaxmi	64	60	63	2.5
Majhikhola Simredanda	6.0	5.4	5.4	0.0
Patalchanpe Mahila	8.2	7.6	7.9	0.4
Punche	18	18	18	0.3
Ram Laxman	13	12	13	0.2
Sandan Bisauni	51	49	50	1.0
Shikhar Bhanjyang	56	54	54	0.0
Shikhardanda	30	30	30	0.3
Sikhar	51	50	50	0.5
Siraute	60	58	59	0.7
Sitalupakha	5.7	5.6	5.5	0.0
Taksartari	89	87	88	1.0
Thokane Bhanjyang	76	75	75	0.4
Total CFs	**1,888**	**1,834**	**1,850**	**16**
Total PFs	**3.7**	**3.6**	**3.6**	**0**

Model for biomass estimation from CPA

The relationship between CPA and biomass was developed for the watersheds individually using directly measured data from field plots and the CPA results from analysis of the satellite images. Altogether 31 of the 51 sample plots in the Kayar Khola watershed used to develop the relationship with segmented crowns (see earlier section) were used for development of the equation, and 20 for validation; in the Ludi Khola watershed 33 sample plots were used to develop the equation and 18 for validation. CPA values were calculated from the GeoEye-1 satellite images for 2009. There were no species wise allometric equations available at plot level to relate DBH and height to biomass, hence the generalized equation recommended by Chave et al. (2005) for tropical moist hardwood forests was used. The wood specific gravities given by Chaturvedi and Khanna (1982) were used for each tree species.

$$AGTB = 0.0509 * pDBH^2H$$

Where; *AGTB* = above ground tree biomass (kg), *p* = wood specific gravity (kg/m^3), *DBH* = tree diameter at breast height (cm), *H* = tree height (m)

A very good linear relationship was obtained between CPA and biomass with R^2 values of 0.76 and 0.77, and RSME values of 64.4 and 47.6, for the Kayar Khola and Ludi Khola watersheds, respectively (Table 17, Figure 21 a,c). The equation was used to estimate the spatial distribution of AGB across each of the watersheds using a 1 ha spatial grid (100 x 100 m) and the results were then validated using the validation sample plots (Table 17, Figure 21 b,d). The total AGB in all forests, CFs, and LHFs or PFs, in each watershed was calculated using the model. The biomass data were then converted into carbon stock by applying a conversion factor of 0.47, as suggested by the IPCC (2006). Biomass and carbon production were calculated by dividing the values by the total forest area in the different units, i.e., watershed, CFs, LHFs. The results are shown in Table 18.

Table 17: **AGB linear equations for the Kayar Khola and Ludi Khola watersheds**

Watershed	Samples for model	Model	R^2	Samples for validation	R^2
Kayar Khola	31	AGB = 0.0543 * CPA - 62.078	0.76	20	0.84
Ludi Khola	33	AGB = 0.0441 * CPA - 18.226	0.77	18	0.87

Table 18: **AGB and carbon in the forests of the Kayar Khola and Ludi Khola watersheds**

Watershed		Forest area (ha)	Total AGB (t)	Total carbon (t)	Average AGB (production) (t/ha)	Average carbon (production) (t/ha)
Kayar Khola	Watershed	5,864	2,448,990	1,151,025	418	196
	CFs	2,322	1,240,013	585,203	534	252
	LHFs	233	96,114	45,174	412	194
Ludi Khola	Watershed	4,868	1,959,970	921,186	403	189
	CFs	1,853	771,607	362,655	416	196
	PFs	4	1,502	706	414	195

Change in AGB and carbon stocks

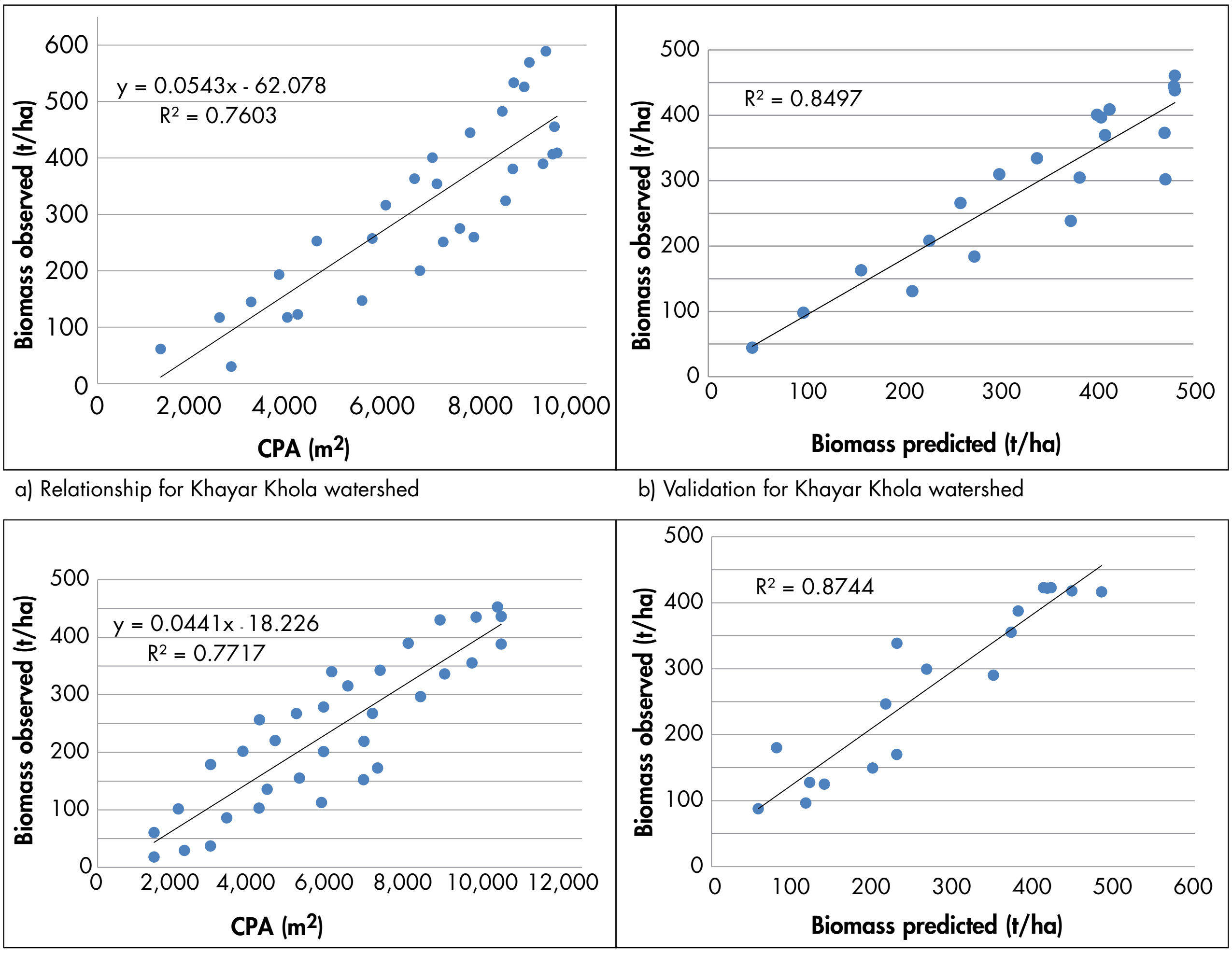
AGB was estimated from analysis of the delineated crowns in the satellite images for 2002 and 2012 (Kayar Khola) and 2012 (Ludi Khola) in the same way as described above using the linear equation developed using the 2009 data. Biomass (AGB) and carbon maps were prepared for each of the years analysed. The results for Khayar Khola are presented in Table 19 and shown in map form in Figures 22 (AGB) and 23 (carbon). The results for Ludi Khola are presented in Table 20 and shown in map form in Figures 24 (AGB) and 25 (carbon). Overall, forest AGB and carbon increased over time across both watersheds, as well as in the CFs, LHFs, and PFs, individually.

Comparison of Remote Sensing and Community Measured Carbon Stock Estimates

The REDD+ pilot project aimed to demonstrate the feasibility of applying the REDD+ payment mechanism in community forests in Nepal. REDD+ aims to reduce deforestation and forest degradation by linking sustainable forest management practices with economic incentives. The aim of the project was to show that local communities could carry out the procedures required under REDD+, and that the concerns of indigenous and marginalized people, women, Dalit, and other local groups dependent on forests could be addressed by involving them in designing and implementing a national-level REDD governance and payment mechanism that supports community forestry at grassroots level. The specific objectives included strengthening the capacity of civil society actors in Nepal to ensure their active participation in the planning and preparation of national REDD strategies; establishing a Forest Carbon Trust Fund that is sustainable and credible in the long run; and contributing to the development of REDD+ strategies that can effectively and efficiently monitor forest carbon flux in community-managed forests.

Forest carbon measurement was carried out annually in the community forests of the three watersheds from 2010 to 2013 to assess any change in forest carbon in forests with a different ecological base. Specifically, the

Figure 21: **Relationship between CPA and field-measured AGB; and between predicted and observed AGB (validation)**



a) Relationship for Khayar Khola watershed

b) Validation for Khayar Khola watershed

c) Relationship for Ludi Khola watershed

d) Validation for Ludi Khola watershed

measurements were used to train local communities in forest carbon monitoring and generate forest carbon data so that they could claim appropriate compensation for their efforts in forest conservation and avoiding forest degradation. Local resource persons, watershed-level REDD network members, and forest users were involved in the field data collection and analysis, thereby enhancing their knowledge about the effect of sustainable management of forests on forest carbon stocks. The methodology used for the field measurements is described in the following. The results were compared with the results obtained from the analysis of satellite images.

Table 19: **Change in AGB and carbon stock in Kayar Khola watershed from 2002 to 2012**

	2002	2009	2012
Watershed			
Forest area (ha)	5,583	5,864	5,892
AGB (t)	2,257,933	2,448,990	2,460,814
Carbon (t)	1,061,228	1,151,025	1,156,583
Average AGB (t/ha)	404	418	418
Average carbon production (t/ha)	190	196	196
CFs			
Forest area (ha)	2,167	2,322	2,354
AGB (t)	1,125,191	1,240,013	1,297,819
Carbon (t)	528,840	585,203	612,090
Average AGB (t/ha)	519	534	551
Average carbon production (t/ha)	244	252	260
LHFs			
Forest area (ha)	221	233	243
AGB (t)	89,382	96,114	101,613
Carbon (t)	42,010	45,174	47,758
Average AGB (t/ha)	405	412	419
Average carbon production (t/ha)	190	194	197

Figure 22: **AGB maps for Kayar Khola watershed in 2002, 2009, and 2012**

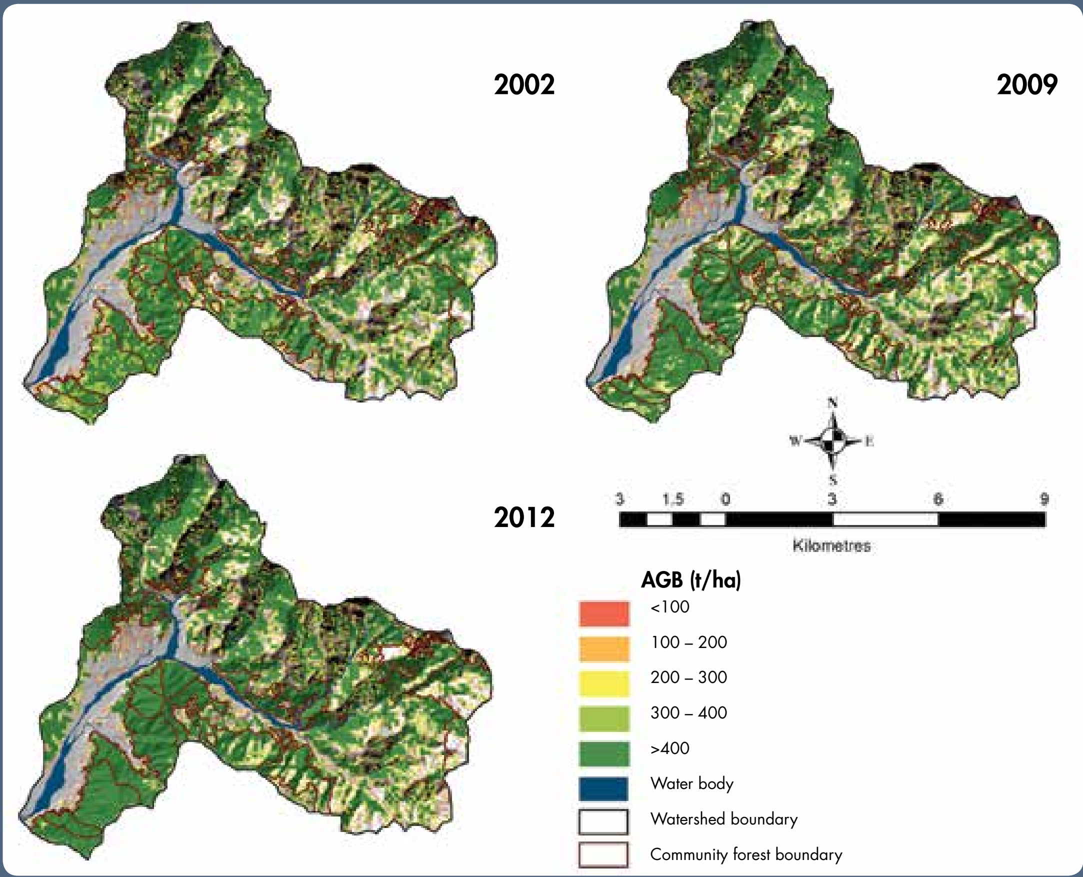


Figure 23: **Spatial carbon stock in Kayar Khola watershed in 2002, 2009, and 2012**

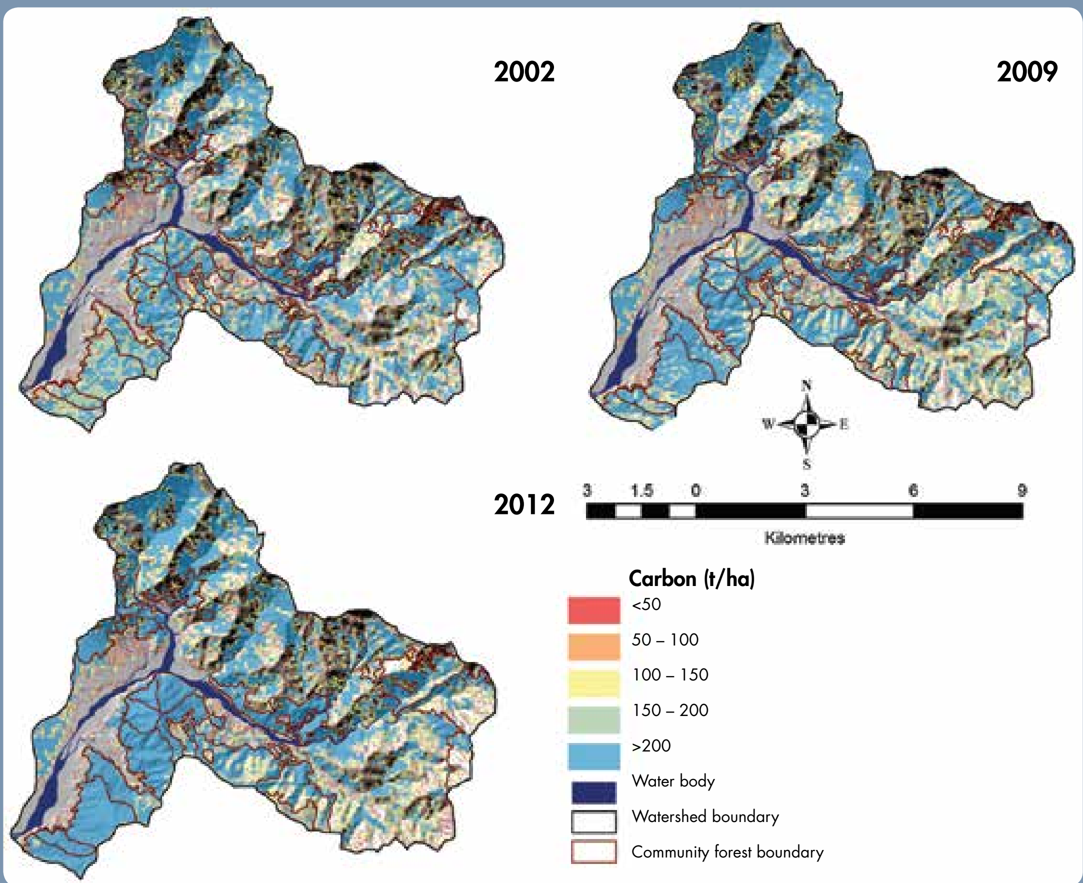


Table 20: **Change in AGB and carbon stock in Ludi Khola watershed from 2009 to 2012**

	2009	2012
Watershed		
Forest area (ha)	4,868	4,913
AGB (t)	1,959,970	2,015,823
Carbon (t)	921,186	947,437
Average AGB (t/ha)	403	410
Average carbon production (t/ha)	189	193
CFs		
Forest area (ha)	1,853	1,865
AGB (t)	771,607	781,205
Carbon (t)	362,655	367,166
Average AGB (t/ha)	416	419
Average carbon production (t/ha)	196	197
PFs		
Forest area (ha)	3.6	3.6
AGB (t)	1,502	1,529
Carbon (t)	706	718
Average AGB (t/ha)	414	415
Average carbon production (t/ha)	195	195

Methodology used for AGB measurement by local communities

Members of CFUGs carried out field measurements in permanent sample plots annually from 2009 to 2013. The measurements were designed to provide estimates of above and below ground biomass and ultimately total carbon stocks. The CFUGs adopted a design-based assessment sample extrapolation methodology for quantification and scaling up from plot level to the whole community forest.

Permanent circular sample plots (area 250 m^2; radius 8.92 m) were established for field measurement in all community forests. The position and number of plots was determined using the information on dense and sparse forest in the land cover maps extracted from GeoEye-1 2009 images. Tree AGB was determined by measuring the DBH (at 1.3 m) and height of all trees with DBH greater than or equal to 5 cm in a plot. Trees were measured using a diameter tape, clinometers, and linear tape or vertex-IV/transponder. They were marked starting from the edge and working inwards to prevent accidental double counting. Each tree was recorded individually,

Figure 24: **AGB maps for Ludi Khola watershed in 2009 and 2012**

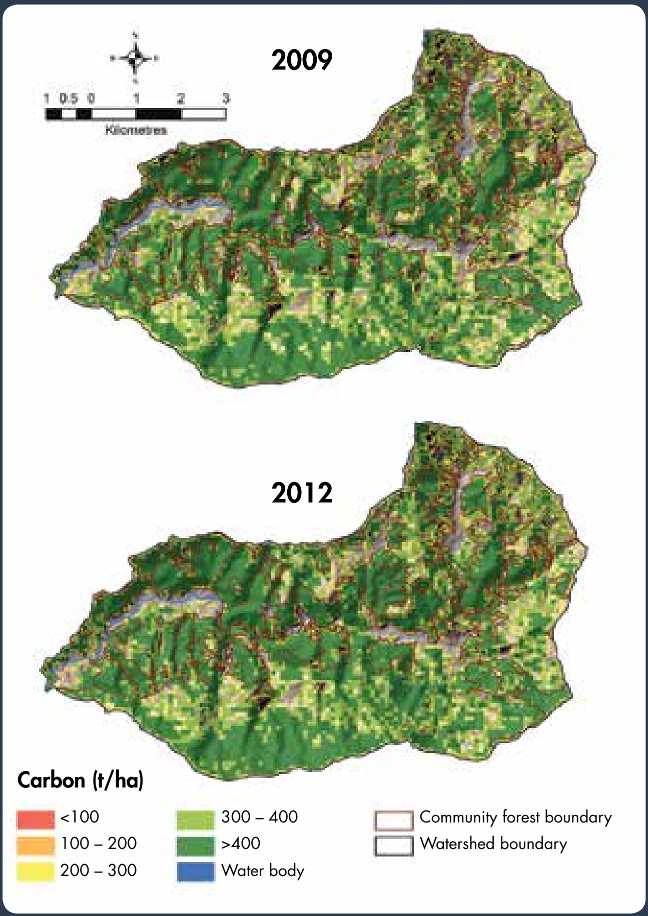
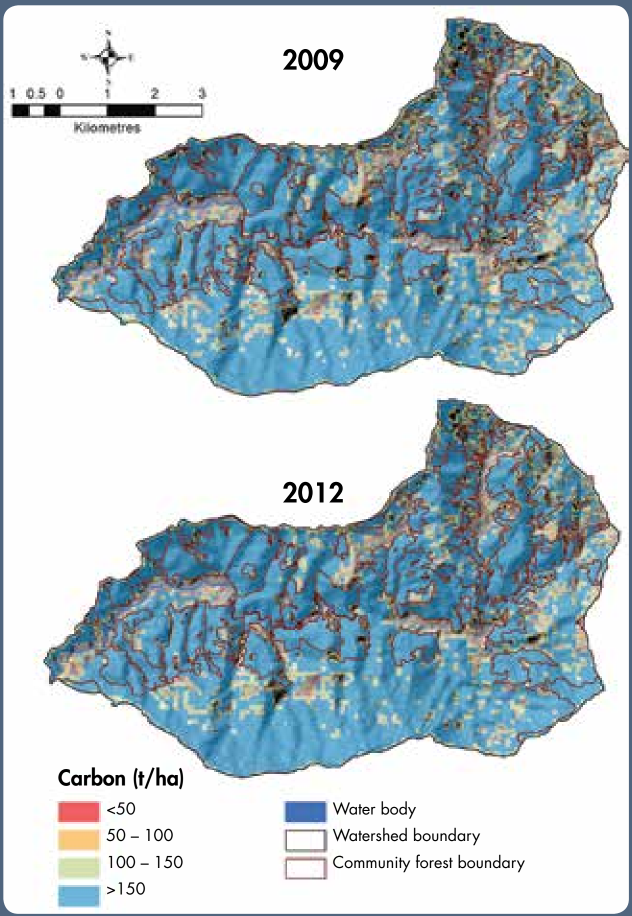


Figure 25: **Spatial carbon stock in Ludi Khola watershed in 2009 and 2012**



together with its species name. Trees on the border were included if more than 50% of their basal area fell within the plot; all the branches of trees classed as 'inside the plot' were included even if they extended outside the plot boundary. Branches overhanging the plot from trees outside were excluded. Standard forestry practice was adopted for trees of unusual shape. For stems that fork from the ground, each individual stem was measured separately but they were numbered by adding a letter suffix to indicate that they were part of the same tree. Care was taken to ensure that the diameter tape was put around the stem exactly at the indicated point of measurement.

Developing site-specific allometric equations lay outside the remit of the project. Instead, the allometric equation given by Chave et al. (2005) for tropical moist hardwood forests was used. Wood specific gravities for each tree species were taken from the values published by Chaturvedi and Khanna (1982) available under MPFS (1988). The sum of the AGB (in kg) of all individual trees in the sample plot was divided by the area of the plot to give average AGB density in kg m^{-2}. This value was then converted to tonnes per hectare (t ha^{-1}). Since the project area has both tropical and sub-tropical vegetation, the biomass value was converted into carbon stock by multiplying with the default carbon fraction of 0.47 as suggested by the IPCC (2006).

Comparison of remote sensing-based and field-based AGB values

As discussed above, optical remote sensing can provide values for AGB with only a small amount of data from a limited number of sample plots. Although the type of data it can provide is limited (e.g., no data on biomass of litter and soil), it has the advantage of being able to provide data on spatial changes over a large area in a timely and cost-effective manner. Thus the two methods – remote sensing and field plots – are complementary.

The AGB values derived from field-based measurement and remote-sensing analysis were calculated for 2009 and 2012 in each of the community forests in the two watersheds and compared to ascertain whether the results were in fact similar. The detailed results are shown in Annex 4. Individual results were compared, and the root mean square error calculated. The Kayar Khola watershed was 0.95 t/ha and in Ludi Khola watershed 1.66 t/ha, indicating a good correlation between the results at this detailed level. AGB values were only markedly over- and/or underestimated using the remote sensing based method in a very few community forests.

Forest Fire Mapping

Fire is a complex biophysical process with multiple direct and indirect effects on the atmosphere, the biosphere, and the hydrosphere. Forest fire is an important driver of forest change. It can be a disaster (at least for some years) for a forest-dependent community, but – as is now widely recognized – in some fire-prone environments fire disturbance is essential to maintain the ecosystem in a state of equilibrium.

Forest fire management is challenging. It can be difficult to detect forest fires at an early stage, especially in remote areas. An effective system is needed to detect and monitor fires as a basis for assessing the potential danger to life and property and the need for intervention. Forest fires also have an impact on forest biomass, and it is useful to have a system for identifying the number and extent of fire incidents when assessing biomass change for REDD+ activities. In view of their large-area repetitive coverage, satellite images can be useful for near real-time fire detection, monitoring, and assessment of the burned area.

Remote sensing methodology was used to detect and map forest fires as a part of the geospatial activities for the REDD+ pilot project. The Moderate Resolution Imaging Spectroradiometer (MODIS) sensors on board the Terra and Aqua satellites of NASA are already used extensively for detecting and monitoring forest fires across the globe. In the REDD+ pilot study, forest fire incidents within the three watersheds were assessed on a daily basis using MODIS images and mapped cumulatively from 2000 to 2014. Figures 26–28 show the location of all forest fire incidents in the three watersheds over this period.

Figure 26: **Forest fire incidents in Kayar Khola watershed from 2000 to 2014**

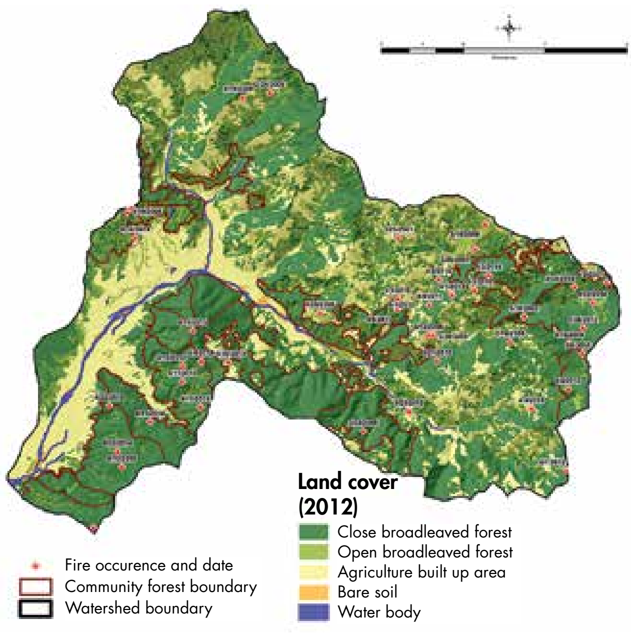


Figure 27: **Forest fire incidents in Ludi Khola watershed from 2000 to 2014**

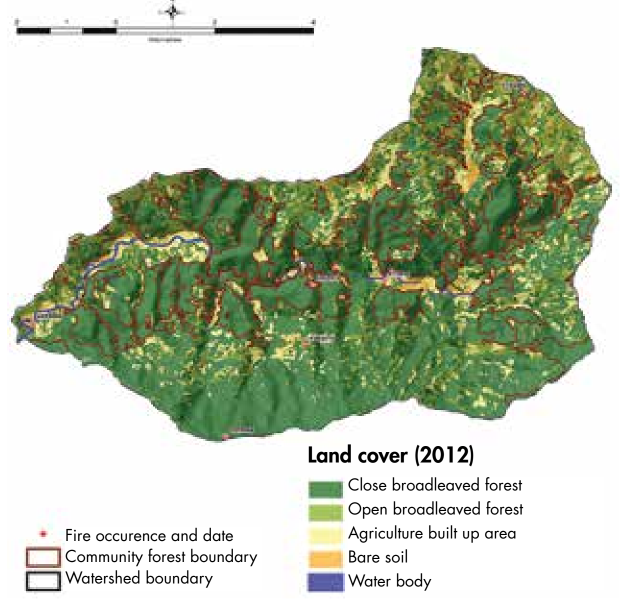
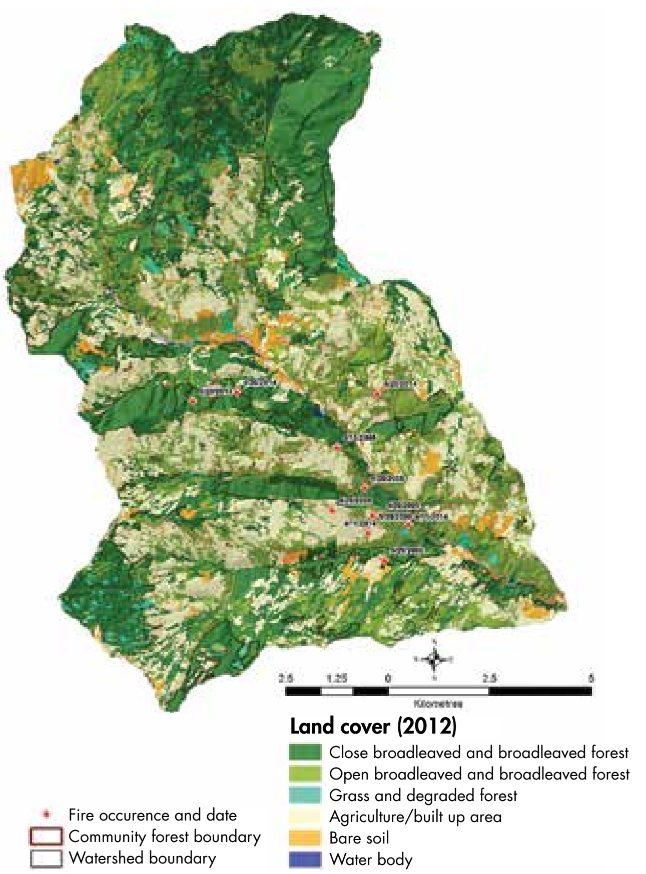


Figure 28: **Forest fire incidents in Charnawati watershed from 2000 to 2014**



Capacity Building and Research

One of the major objectives of the remote sensing component of the project was to engage partners and stakeholders through capacity building of staff in national and regional forestry institutes, mobilization and awareness campaigns for field staff and communities, and scientific research to investigate the application of different methods and tools. Some of the major events are described briefly in the following sections.

National level training

Two national level training courses in the 'Use of Geo-informatics for Mapping and Modelling Forest Carbon Stocks in Nepal' (basic introduction in 2010, advanced in 2011) were conducted for capacity building of national partners. The training courses were jointly organized with ITC-Netherlands. The participants (Figure 29) came from ANSAB, the Department of Forest, Department of National Parks and Wildlife Conservation, District Forest Offices of Chitwan, Gorkha, Dolakha, and Makwanpur, Kathmandu Forestry College, Nepal Federation of

Figure 29: **National level training participants in 2010 (above) and 2011 (below)**

Indigenous Nationalities (NEFIN), REDD Implementation Centre, Ministry of Forests and Soil Conservation, National Trust for Nature Conservation, Winrock International, and ICIMOD. Half-day field visits to a nearby forested area were arranged during the courses.

Climate change and carbon assessment training

A two-week training on 'Climate change and carbon assessment for the benefit of community forests in Central and Southeast Asia' was jointly organized with ITC-Netherlands for Central and Southeast Asian participants (Figure 30). The training was funded by the Netherlands Fellowship Programme (NFP). The training included both theoretical and practical examples. Hands-on exercises related to climate change, forest, and RS/GIS were also carried out by the participants. A two-day field visit to the Kayar Khola (Chitwan District) REDD+ site was organized to demonstrate forest measurements by the community as well as community involvement in the preservation of forest.

Awareness programme for CFUGs and support to national partners

ICIMOD, ANSAB, and FECOFUN organized awareness programmes jointly during the fieldwork for identifying watersheds and community forest mapping. The objective was to create awareness about the REDD+ programme among the forest communities and other concerned agencies. Participants came from the District Forest Offices, district FECOFUN Offices, CFUGs, political parties, NGOs, local resource persons, and media representatives.

Support was also provided to national partners for different components. The data and maps of open and closed forests were provided to ANSAB for sample design of fieldwork. A number of maps were prepared and printed in large format for use in the field. On-the-job training was provided to a GIS officer from ANSAB. Technical support on mapping and analysis was provided whenever requested by partners.

Figure 30: **Central and Southeast Asian participants in the climate change and carbon assessment training**

Figure 31: **Students from ITC-Netherlands who conducted research at the REDD+ sites**

Facilitating research

ICIMOD provided both moral and financial support for students to conduct research in the three watersheds. More than 15 students from ITC-Netherlands completed their graduation theses in 2010 and 2011 (Figure 31). A number of peer-reviewed papers based on the research are being published.

Conclusion

Of the 14.7 million hectares of land in Nepal, 5.83 million hectares are forested, and 1.65 million ha of this is managed by communities under the community forestry programme. As of 2012, 17,685 CFs have been formed with 2,177,858 households benefitting (DOF 2012) and a further 6,712 LHFs covering 38,997,358 ha of national forest are managed by 62,735 households. Overall, the rate of deforestation and forest degradation in Nepal has reduced considerably and the forest is improving, but at a local scale deforestation and forest degradation still takes place, often to fulfil the day to day requirements of local communities. REDD+ is being introduced as a way of reducing degradation and increasing forest health by compensating local communities for their efforts in maintaining and improving their forests.

The REDD+ pilot project is being implemented in three representative areas to pilot the concepts and practical approach of using financial benefits to encourage and facilitate community groups, and also, among others, to explore the use of geospatial data, tools, and methods to assess carbon stocks, quantify change, and prepare maps. The study shows that high resolution satellite images are very useful for forest measurement. The results indicate that community forests operating under the REDD+ model are indeed improving in terms of carbon stocks. Methods based on satellite imagery are relatively low cost and cover larger areas than traditional field inventories. Now it is even possible to perform biomass estimation at tree species level using high resolution WorldView-2 (eight spectral bands) satellite data.

A number of initiatives are being implemented at sub-national and national levels in different parts of the country to develop methods for data collection within the MRV in REDD+ framework and for greenhouse gas emission inventories and others. It is now vital to coordinate and integrate these different approaches and methods to develop an efficient, cost-effective, and reliable MRV system. ICIMOD, as a regional organization, has been disseminating information about the successes experienced in the four-year REDD+ project to regional member countries to strengthen and provide awareness among communities and institutions. Monitoring will continue in the three watersheds both by the communities and using geospatial technologies.

Site-specific community monitoring is reliable, effective, and economic. Local people and communities, as users of the natural resources in their vicinity, are usually familiar with the state of the forest, and, if they are actively engaged in forest management under REDD+, this knowledge could be very useful. The fact that there is a large workforce available at the community level means that data can be collected across scales not otherwise feasible and at regular intervals, for example, annually. In Nepal, CFUGs effectively manage community forests with government cooperation and guidance. Continual monitoring is essential to assess positive and negative changes in community forests. To support this, some CFUGs have been measuring plot-level forest stock on an annual basis. Such regular measurements are helpful for reporting robust improvements in forest cover for conservation payment mechanisms. In field measurements and photographs used for monitoring, a very small area the size of a single plot is in view. Aerial photographs or high resolution satellite images give a wider view of the entire community forest area during different time periods. Now, easily readable repeat satellite images are available, which can be used to detect changes in community forests. The use of satellite images minimizes the need for labour intensive, field data collection. Integrating satellite-based change assessments with annual measurements from permanent field plots monitored by the CFUGs can provide an accurate assessment for the entire community forest area.

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Annex 1: **Area of community, leasehold, and private forests**

The area of individual community, leasehold, and private forests in each watershed was calculated following delineation of the boundaries on the print outs of the satellite images and digitization of the maps.

Table A1.1: **Area of CFs in Kayar Khola watershed, Chitwan District**

CF Name	Area (ha)
Batauli	155.77
Chitramkaminchuli	314.02
Deujar	278.87
Devidhunga	191.79
Chelibeti	64.87
Dharapani	147.16
Indreni	172.17
Jamuna	34.53
Janapragati	118.84
Jharana	34.53
Kalika	213.77
Kankali	91.60
Nibuwatar	329.18
Pragati	115.48
Samfrang	63.90
Satkanya	58.28
Total area	**2,384.48**

Table A1.2: **Area of LHFs in Kayar Khola watershed, Chitwan District**

LHF Name	Area (ha)	LHF Name	Area (ha)
Aanp danda	7.20	Khani dhunga	2.57
Aanp gaira	3.73	Kotrang	10.32
Aanptari	3.93	Kuwapani	2.59
Ajingar	3.23	Laisirang	5.72
Argheli danda	3.17	Malayo Pakha	3.07
Babiyorang	4.54	Namuna	4.63
Badahar pakha	1.99	Niklang	0.90
Baghkhor	3.82	Nunilo pani	2.25
Bail danda	3.18	Ojheli Pakha	3.50
Bhalayo Pakha	3.74	Paireni pakha	2.32
Bhalu khane	5.25	Pandheri Khola	3.61
Chairang	3.81	Pandheri Pakha	5.26
Chaitya pakha	1.16	Purbeli	2.22
Chaudaha	5.81	Ranighat	3.00
Chautari danda	5.79	Ratmate	4.07
Chilaune paani	3.74	Rungtesh	4.00
Chisapani	4.04	Sajgaira	2.07
Chiuri gaira	5.81	Samini danda	2.14
Dalantaar	1.30	Sano bigauta Ga	3.27
Daringrang	3.84	Sano bigauta Ka	3.42
Devithan	2.09	Sano bigauta Kha	3.49
Dogara	1.15	Sanobhanjyang	3.17
Gaidaghari	11.97	Sarkaritari Ga	4.44
Girairang	5.11	Sarkaritari Ka	2.66
Glajboom	3.02	Sarkaritari Kha	2.27
Gorkhali danda	4.68	Saunepani	6.76
Gurans pakha	3.85	Sewange danda	5.95
Henka pakha	5.93	Sidhha nath	2.38
Indayo	3.59	Simal pakha	2.27
Irani danda	8.42	Simane pakha	0.69
Jal devi	3.27	Suga Bhanjyang	4.96
Jorsal pakha	1.78	Sulitar	4.44
Kalika	3.05	Tanglangyo	3.33
Kamire bhitte	1.79	Thulo bigauta	2.25
Karam danda	2.68	Thulo gaire	3.08
Kasara Pakha	6.10	Tirtire	6.41
Khagati pakha	2.48	Uttar himali	5.35
Total area			**284.87**

Table A1.3: **Area of CFs in Ludi Khola watershed, Gorkha District**

CF Name	Area (ha)	CF Name	Area (ha)
Anpshwara Bhawanipakha	9.14	Ludi	17.44
Badahare	25.78	Ludi Damgade	270.71
Bagepani	68.16	Mahalaxmi	63.96
Bhalukhola Soti	107.58	Majhikhola Simredanda	6.00
Bhangeristhan Ghantari	5.24	Patalchanpe Mahila	8.16
Birenchok	83.57	Punche	18.13
Chisapani	50.04	Ram Laxman	13.25
Gangate Bahunechaur	173.62	Sandan Bisauni	50.62
Ghaledanda Ranakhola	181.66	Shikhar Bhanjyang	55.49
Goldanda	45.99	Shikhardanda	30.36
Kharkandepakha	47.82	Sikhar	50.84
Kharkopakho Bhekhpari	51.15	Siraute	60.34
Kuwadi	92.27	Sitalupakha	5.69
Kyamundanda	58.72	Taksartari	89.31
Lamidanda	61.59	Thokane Bhanjyang	76.18
Laxmi Mahila	8.72		
Total area			**1,887.54**

Table A1.4: **Area of PFs in Ludi Khola watershed, Gorkha District**

PF Name	Area (ha)
Jaya Bdr. Khatri	0.08
Krishna Bbdr. Kuwar	0.75
Pradhumna Shrestha	1.38
Ishwor Shrestha	1.51
Total area	**3.72**

Table A1.5: **Area of CFs in Charnawati watershed, Dolakha District**

CF Name	Area (ha)		CF Name	Area (ha)
Amlekharka	6.60		Mahabhir	50.26
Barkhe Dandapari	35.40		Mahankal	39.38
Bhakare	104.43		Majhkharka Lisepani	174.18
Bhasmepakha	10.93		Mathani	28.28
Bhirmuni Devithan	5.98		Napke Yanmara	152.46
Bhitteri	542.64		Paleko Ban	1.49
Bhudha Bhimsen	41.97		Palung Mahila	10.28
Bichaur	47.71		Pauwa	58.64
Botle Setidevi	172.10		Pokhari	23.60
Charnawati	819.35		Ramite	13.60
Charnawati	55.12		Salleri	92.27
Chhitakunda	51.51		Sankha Devi	305.26
Chuche Dhungha	8.90		Sano Botle	35.06
Chyanedanda	64.86		Seti Devi	421.71
Chyase Bhagabati	30.32		Shivajang Bhumesthan	46.67
Devithan	43.94		Simpani	64.40
Dhande	29.17		Simsungure	33.35
Dhande Singhadevi	343.69		Sitakunda	141.31
Dimal	38.20		Srijana	264.20
Eklepakha	197.33		Sundari Mai	12.98
Gahate Baghkhor	5.54		Thangsa Deurali	124.37
Gairi Jungle	131.08		Tharlange	203.97
Golmeswor	215.18		Thumka Danda	40.78
Gothpani	23.50		Thutemane	23.60
Harisiddhimai	28.35		Timure Tinsalle	67.10
Jugedarkha	125.60		Sele Alambhir	57.33
Jyamire	70.01		Ghattepakha	6.08
Kalchhe	21.49		Kuktung khola	12.60
Kamalamai	71.81		Nurserypakha	5.81
Kopila	96.07		Setokhola Mahasthan	7.64
Kupri Salleri	42.03		Radhakrishna	5.55
Laligurans	35.53		Chitreshwor Mahadev	3.12
Lodini	50.67			
Total area				**6,094.30**

Table A1.6: **Area of LHFs in Charnawati Watershed, Dolakha District**

LHF Name	Area (ha)
Kalyankari	2.94
Kalidevi	2.22
Bhimsen	2.11
Muna	2.51
Janahit	2.57
Srijana	3.31
Setidevi	2.50
Harisiddhi	4.18
Gurase	4.82
Indrawoti	3.92
Buddha	6.27
Amala	7.43
Siddhi Ganesh	2.40
Sansarimai	4.77
Bhumethan	5.13
Total area	**57.08**

Annex 2: **Change in forest cover as seen in satellite images**

Figure A2.1: **Improvement in forest cover in Janapragati Community Forest in Kayar Khola watershed (Chitwan District) between 2002 and 2012**

Figure A2.2: **Deforestation due to trail expansion in Charnawati watershed (Dolakha District) between 2009 and 2012**

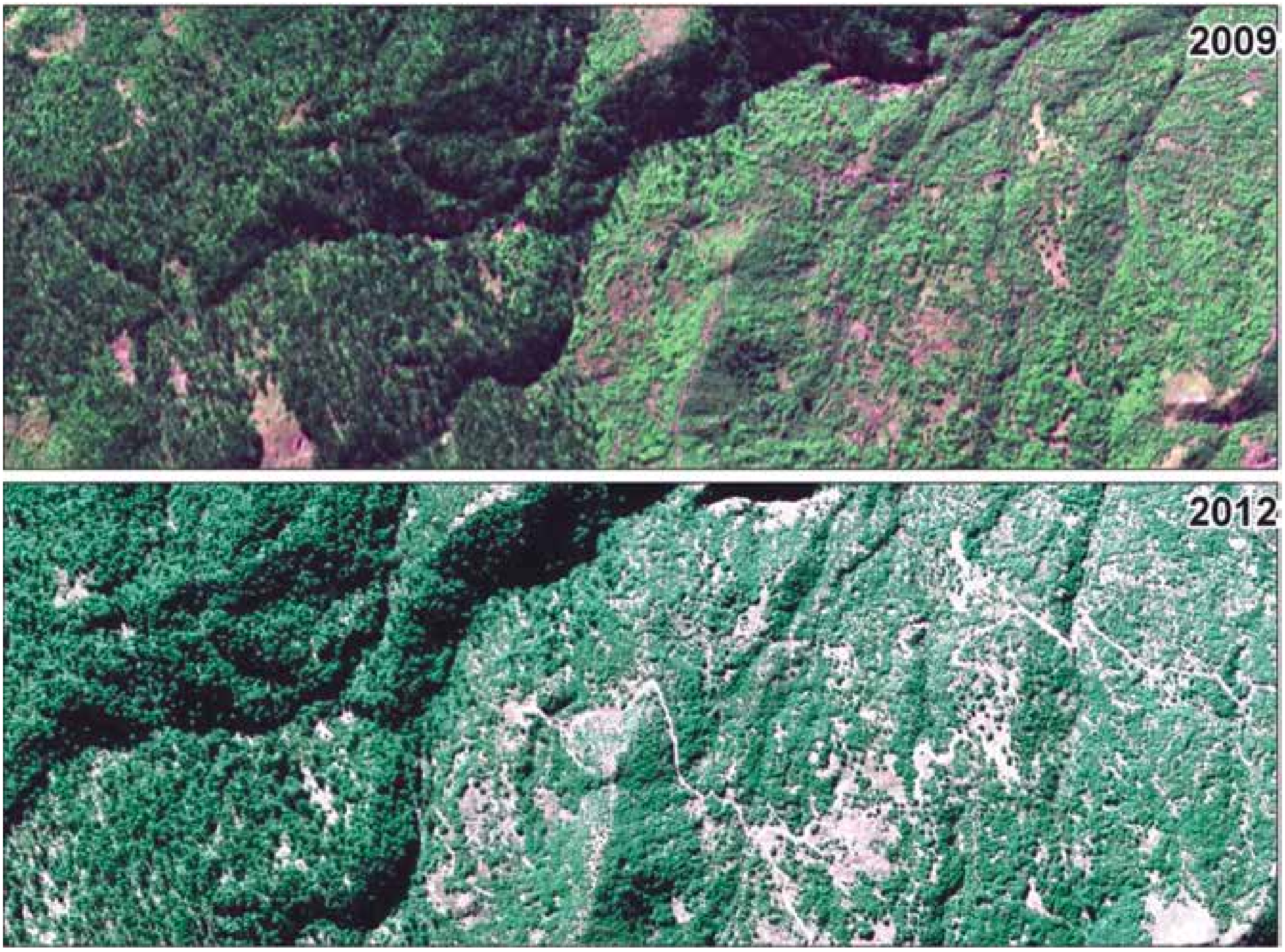
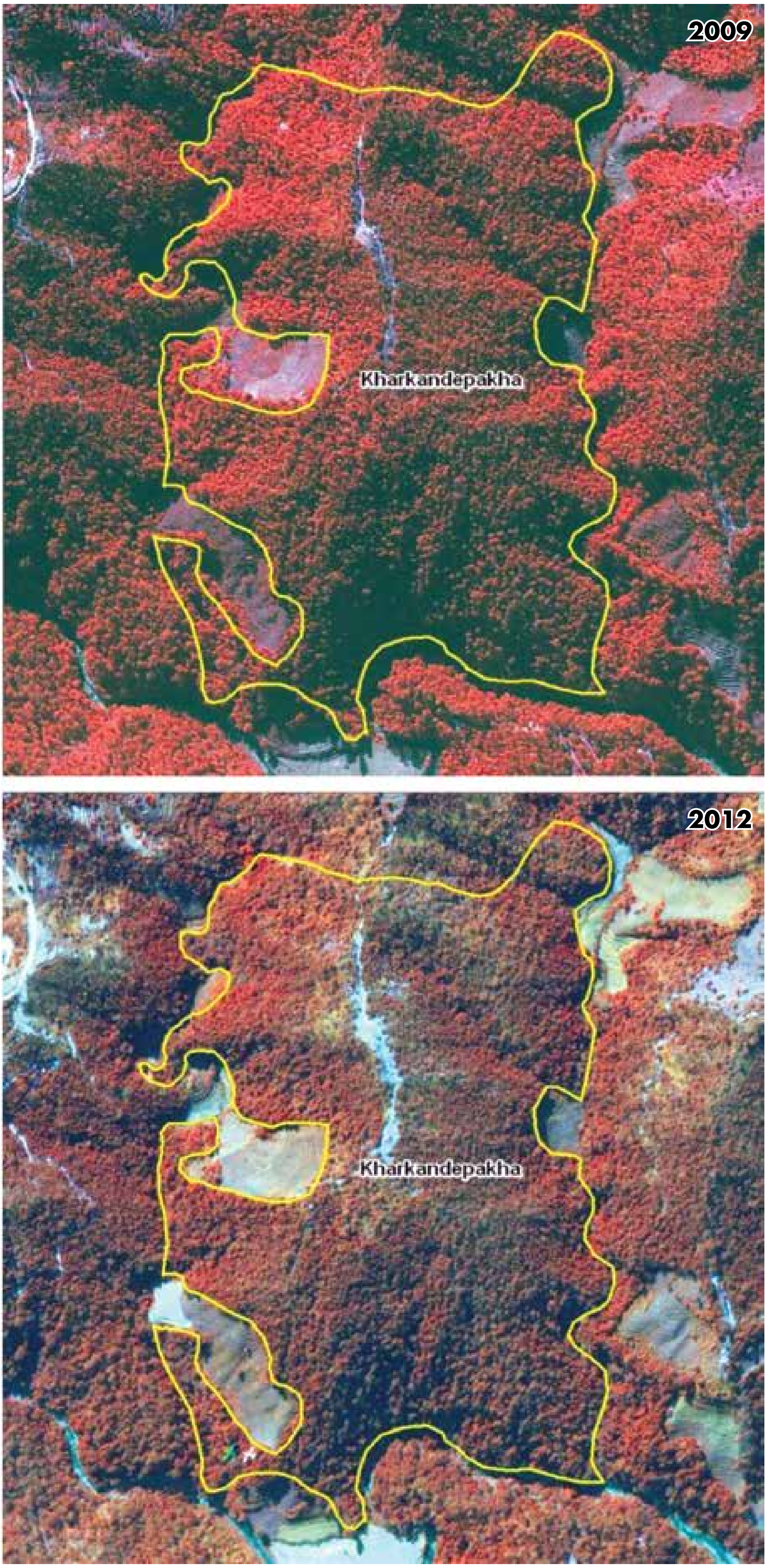


Figure A2.3: **Change in forest area and tree crown number in Kharkandepakha Community Forest in Ludi Khola watershed (Gorkha District) between 2009 and 2012**



Annex 3: **Location of permanent sample plots in community, leasehold, and private forests**

Figure A3.1: **Location of permanent sample plots in CFs and LHFs in Kayar Khola watershed, Chitwan District**

LHF name	Area (ha)
Aanp danda	7.2
Aanp gaira	3.73
Aanptari	3.93
Ajingar	3.23
Argheli danda	3.17
Babiyorang	4.54
Badahar pakha	1.99
Baghkhor	3.82
Bail danda	3.18
Bhalayo Pakha	3.74
Bhalu khane	5.25
Chairang	3.81
Chaitya pakha	1.16
Chaudaha	5.81
Chautari danda	5.79
Chilaune paani	3.74
Chisapani	4.04
Chiuri gaira	5.81
Dalantaar	1.3
Daringrang	3.84
Devithan	2.09
Dogara	1.15
Gaidaghari	11.97
Girairang	5.11
Glajboom	3.02
Gorkhali danda	4.68
Gurans pakha	3.85
Henka pakha	5.93
Indayo	3.59
Irani danda	8.42
Jal devi	3.27
Jorsal pakha	1.78
Kalika	3.05
Kamire bhitte	1.79
Karam danda	2.68
Kasara Pakha	6.1
Khagati pakha	2.48
Khani dhunga	2.57

LHF name	Area (ha)
Kotrang	10.32
Kuwapani	2.59
Laisirang	5.72
Malayo Pakha	3.07
Namuna	4.63
Niklang	0.9
Nunilo pani	2.25
Ojheli Pakha	3.5
Paireni pakha	2.32
Pandheri Khola	3.61
Pandheri Pakha	5.26
Purbeli	2.22
Ranighat	3
Ratmate	4.07
Rungtesh	4
Sajgaira	2.07
Samini danda	2.14
Sano bigauta Ga	3.27
Sano bigauta Ka	3.42
Sano bigauta Kha	3.49
Sanobhanjyang	3.17
Sarkaritari Ga	4.44
Sarkaritari Ka	2.66
Sarkaritari Kha	2.27
Saunepani	6.76
Sewange danda	5.95
Sidhha nath	2.38
Simal pakha	2.27
Simane pakha	0.69
Suga Bhanjyang	4.96
Sulitar	4.44
Tanglangyo	3.33
Thulo bigauta	2.25
Thulo gaire	3.08
Tir tire	6.41
Uttat himali	5.35
Total	**284.84**

CF Name	Area(Ha)
Batauli	155.77
Chelibeti	64.87
Chitramkaminchuli	314.02
Deujar	278.88
Devidhunga	188.99
Dharapani	147.16
Indreni	172.17
Jamuna	34.53
Janapragati	118.84
Jharana	34.53
Kalika	213.77
Kankali	91.6
Nibuwatar	329.18
Pragati	115.48
Samphrang	63.9
Satkanya	58.28
Total	**2384.48**

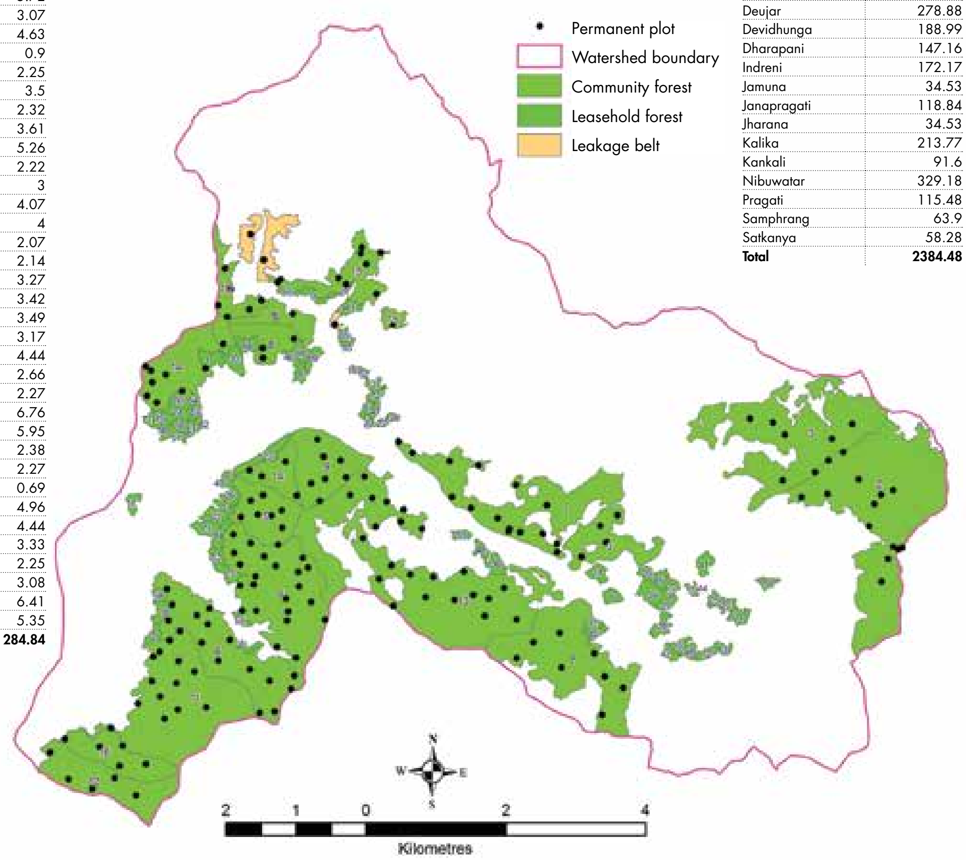


Figure A3.2: **Location of permanent sample plots in CFs and PFs in Ludi Khola watershed, Gorkha District**

CF Name	Area (ha)
Anpshwara Bhawanipakha	9.14
Badahare	25.78
Bagepani	68.16
Bhalukhola Soti	107.58
Bhangeristhan Ghantari	5.24
Birenchok	83.57
Chisapani	50.04
Gangate Bahunechaur	173.62
Ghaledanda Ranakhola	181.66
Goldanda	45.99
Kharkandepakha	47.82
Kharkopakho Bhekhpari	51.15
Kuwadi	92.27
Kyamundanda	58.72
Lamidanda	61.59
Laxmi Mahila	8.72
Ludi	17.44
Ludi Damgade	270.71
Mahalaxmi	63.96
Majhikhola Simredanda	6

CF Name	Area (ha)
Patalchanpe Mahila	8.16
Punche	18.13
Ram Laxman	13.25
Sandan Bisauni	50.62
Shikhar Bhanjyang	55.49
Shikhardanda	30.36
Sikhar	50.84
Siraute	60.34
Sitalupakha	5.69
Taksartari	89.31
Thokane Bhanjyang	76.18
Total	**1887.54**

Private forest owner name	Area (ha)
Jaya Bdr. Khatri	0.08
Krishna Bbdr. Kuwar	0.75
Pradhumna Shrestha	1.38
Ishwor Shrestha	1.51

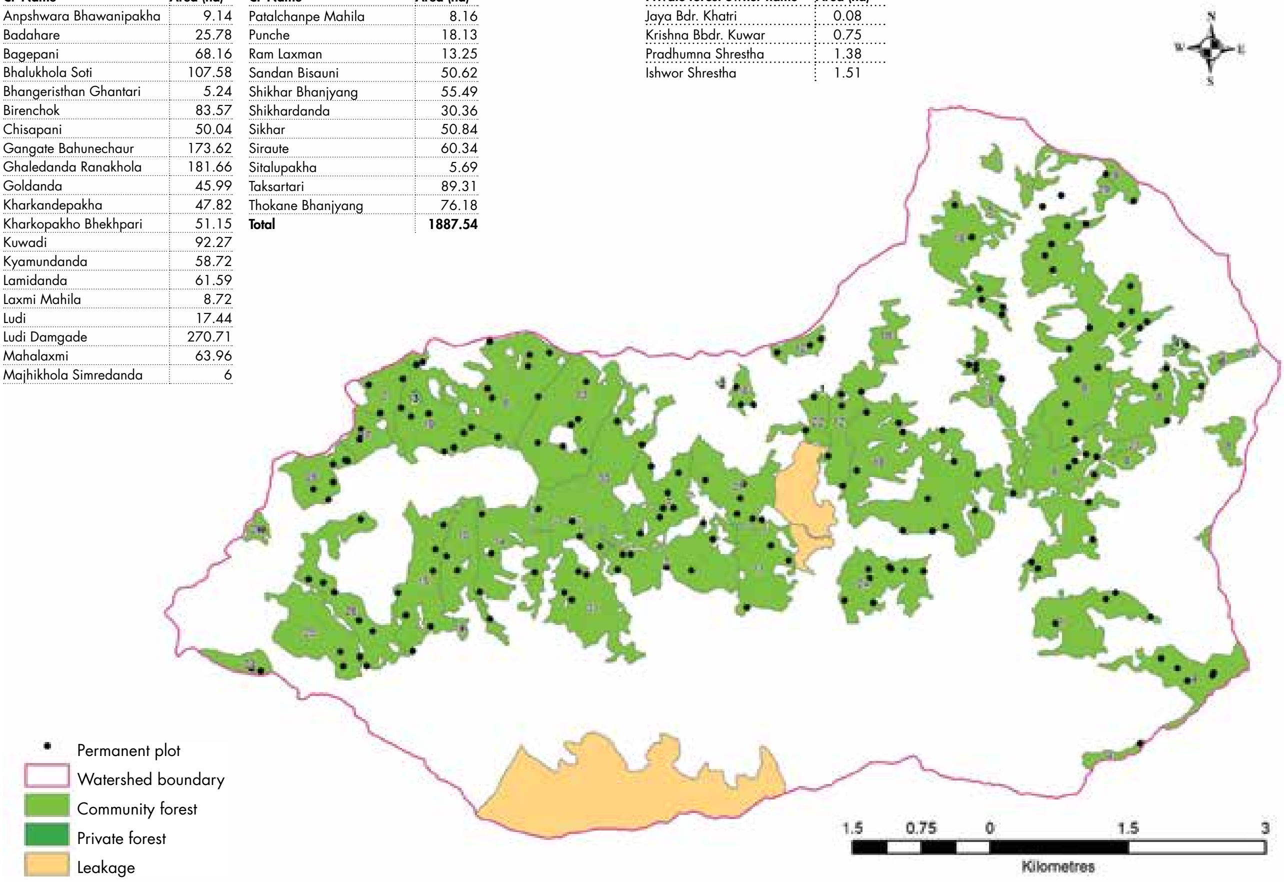
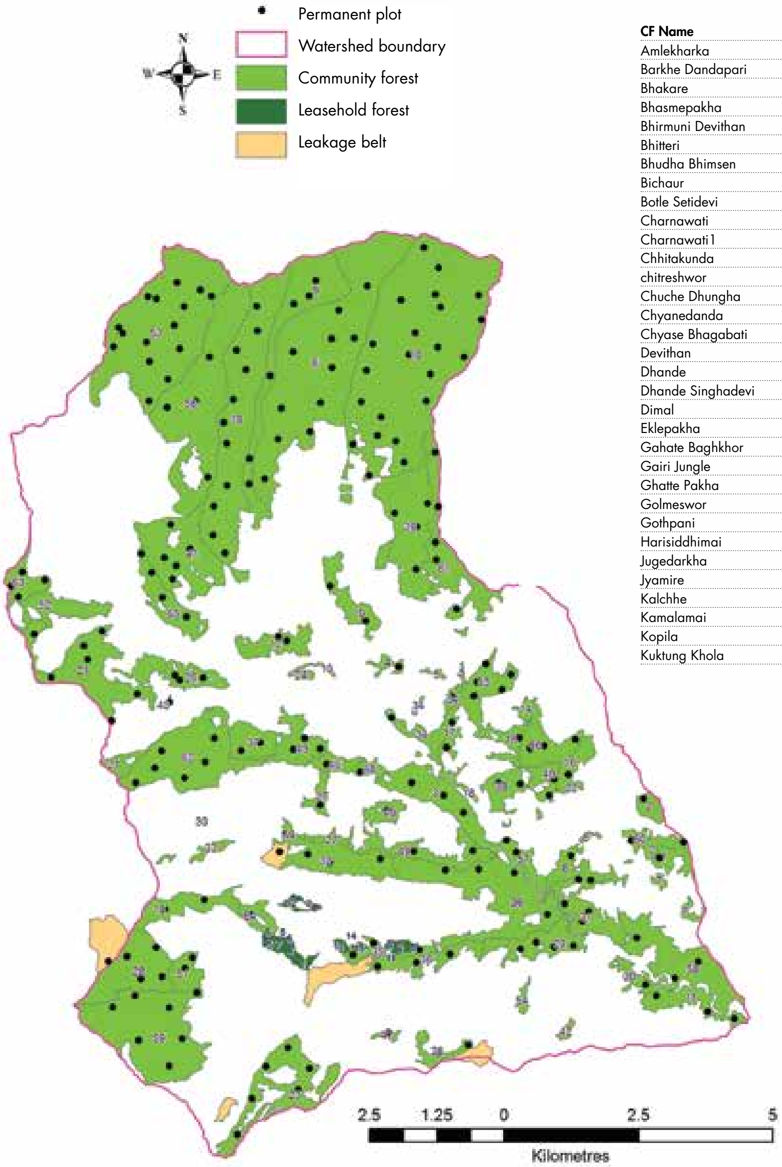


Figure A3.3: **Location of permanent sample plots in CFs and LHFs in Charnawati watershed, Dolakha District**

LHF Name	Area (ha)
Amala	7.43
Bhimsen	2.11
Bhumethan	5.13
Buddha	6.27
Gurase	4.82
Harisiddhi	4.18
Indrawoti	3.92
Janahit	2.57
Kalankari	2.94
Kalidevi	2.22
Muna	2.51
Sansarimai	4.77
Setidevi	2.5
Siddhi Ganesh	2.4
Srijana	3.31
Total	**57.08**



CF Name	Area (ha)	CF Name	Area (ha)
Amlekharka	6.6	Kupri Salleri	42.03
Barkhe Dandapari	35.4	Laligurans	35.53
Bhakare	104.43	Lodini	50.67
Bhasmepakha	10.93	Mahabhir	50.26
Bhirmuni Devithan	5.98	Mahankal	39.38
Bhitteri	542.64	Majhkharka Lisepani	174.18
Bhudha Bhimsen	41.97	Mathani	28.28
Bichaur	47.71	Napke Yanmara	152.46
Botle Setidevi	172.1	Nursari Pakha	5.81
Charnawati	819.35	Paleko Ban	1.48
Charnawati1	55.12	Palung Mahila	10.28
Chhitakunda	51.51	Pauwa	58.64
chitreshwor	3.12	Pokhari	23.6
Chuche Dhungha	8.9	Radha Krishna	5.55
Chyanedanda	64.86	Ramite	13.6
Chyase Bhagabati	30.32	Salleri	92.27
Devithan	43.94	Sankha Devi	305.26
Dhande	29.17	Sano Botle	35.06
Dhande Singhadevi	343.69	Sele Alambhir	57.33
Dimal	38.2	Seti Devi	421.71
Eklepakha	197.33	Setokhola Mahadevsthan	7.64
Gahate Baghkhor	5.54	Shivajang Bhumesthan	46.67
Gairi Jungle	131.08	Simpani	64.4
Ghatte Pakha	6.08	Simsungure	33.35
Golmeswor	215.18	Sitakunda	141.31
Gothpani	23.5	Srijana	264.19
Harisiddhimai	28.35	Sundari Mai	12.98
Jugedarkha	125.6	Thangsa Deurali	124.37
Jyamire	70.01	Tharlange	203.97
Kalchhe	21.49	Thumka Danda	40.78
Kamalamai	71.81	Thutemane	23.6
Kopila	96.07	Timure Tinsalle	67.1
Kuktung Khola	12.6	**Total**	**6094.32**

Annex 4: **AGB and carbon change in individual community forests**

Table A3.1: **Field-based and remote-sensing based AGB values in the community forests in Kayar Khola watershed in 2009 and 2012 and change over time**

Kayar Khola watershed

			Field based AGB						RS based AGB							
CF name	Total no of field sample plots	No. of field sample plots used	Total 2009 (t)	Av. 2009 (t/ ha)	Total 2012 (t)	Av. 2012 (t/ha)	Annual change (t)	Annual change per ha	Total 2009 (t)	Av. 2009 (t/ ha)	Total 2012 (t)	Av. 2012 (t/ha)	Annual change (t)	Annual change per ha	Difference annual change (t)	R^2
Batauli	15	11	3,873.15	352.10	3,895.23	354.11	7.36	0.67	3,883.26	353.02	3,917.06	356.10	11.27	1.02	0.36	0.13
Chitramkaminchuli	14	8	1,639.53	204.94	1,852.50	231.56	70.99	8.87	1,664.86	208.11	1,873.62	234.20	69.58	8.70	-0.18	0.03
Deujar	11	9	3,016.15	335.13	3,075.33	341.70	19.73	2.19	3,051.04	339.00	3,104.26	344.92	17.74	1.97	-0.22	0.05
Devidhunga	30	29	12,931.54	445.92	12,990.13	447.94	19.53	0.65	12,982.21	447.66	13,235.16	456.38	84.32	2.91	2.26	5.09
Dharapani	15	13	5,361.57	412.43	5,421.76	417.06	20.06	1.54	5,428.09	417.55	5,488.97	422.23	20.29	1.56	0.02	0.00
Indreni	8	6	2,110.68	351.78	2,187.88	364.65	25.73	4.29	2,143.34	357.22	2,205.79	367.63	20.82	3.47	-0.82	0.67
Jamuna	3	3	1,108.11	369.37	1,118.03	372.68	3.31	1.10	1,111.42	370.47	1,133.41	377.80	7.33	2.44	1.34	1.80
Janapragati	10	7	1,747.81	249.69	1,819.56	259.94	23.92	3.42	1,765.87	252.27	1,852.81	264.69	28.98	4.14	0.72	0.52
Jharana	6	5	2,013.51	402.70	2,031.35	406.27	5.95	1.19	2,020.88	404.18	2,038.34	407.67	5.82	1.16	-0.03	0.00
Kalika	14	7	2,355.69	336.53	2,383.48	340.50	9.26	1.32	2,392.01	341.72	2,434.02	347.72	14.00	2.00	0.68	0.46
Kankali	5	4	927.68	231.92	947.41	236.85	6.58	1.64	975.08	243.77	983.36	245.84	2.76	0.69	-0.95	0.91
Nibuwatar	22	21	8,900.92	423.85	9,083.08	432.53	60.72	2.89	8,942.85	425.85	9,080.94	432.43	46.03	2.19	-0.70	0.49
Pragati	12	7	1,899.60	271.37	1,951.34	278.76	17.25	2.46	1,969.84	281.41	2,004.77	286.40	11.64	1.66	-0.80	0.64
Samfrang	10	6	2,454.06	409.01	2,463.94	410.66	3.29	0.55	2,443.32	407.22	2,481.75	413.63	12.81	2.14	1.59	2.52
Satkanya	5	4	1,079.22	269.80	1,112.74	278.18	11.17	2.79	1,102.71	275.68	1,139.99	285.00	12.43	3.11	0.31	0.10
Total	180	140	51,419.22	337.77	52,333.75	344.89	20.32	2.37	51,876.78	341.67	52,974.26	349.51	24.39	2.61	3.58	
													Sum of square difference			13.40
													RMS error (t/ha)			0.95

RMS = root mean square

Table A3.2: **Field-based and remote-sensing based AGB values in the community forests in Ludi Khola watershed in 2009 and 2012 and change over time**

Ludi Khola watershed

			Field based AGB						RS based AGB							
CF name	Total no of field sample plots	No. of field sample plots used	Total - 2009 (t)	Av. -2009 (t/ha)	Total - 2012 (t)	Av. - 2012 (t/ha)	Annual change (t)	Annual change per ha	Total - 2009 (t)	Av. - 2009 (t/ha)	Total - 2012 (t)	Av. - 2012 (t/ha)	Annual change (t)	Annual change per ha	Difference annual changes (t)	R^2
Badhare	3	2	803.70	401.85	804.89	402.44	0.40	0.20	864.43	432.21	866.47	433.24	0.68	0.34	0.14	0.02
Bagepani	7	4	1,395.75	348.94	1,395.75	348.94	0.00	0.00	944.47	236.12	976.93	244.23	10.82	2.70	2.70	7.32
Bhalukhola Soti	11	8	3,260.42	407.55	3,270.31	408.79	3.29	0.41	3,176.12	397.01	3,195.69	399.46	6.52	0.82	0.40	0.16
Birinchowk	7	7	2,774.36	396.34	2,805.82	400.83	10.49	1.50	2,643.01	377.57	2,660.38	380.05	5.79	0.83	-0.67	0.45
Chisapani	7	5	1,999.74	399.95	2,061.83	412.37	20.70	4.14	1,978.73	395.75	2,074.98	415.00	32.09	6.42	2.28	5.19
Gagatepakha Baunechaur	16	12	4,644.68	387.06	4,778.48	398.21	44.60	3.72	4,237.95	353.16	4,467.34	372.28	76.46	6.37	2.66	7.05
Ghaledanda Rana Khola	20	18	7,024.81	390.27	7,129.03	396.06	34.74	1.93	7,390.52	410.58	7,606.85	422.60	72.11	4.01	2.08	4.31
Goal Danda	5	4	1,521.95	380.49	1,684.14	421.03	54.06	13.52	1,600.63	400.16	1,729.98	432.49	43.11	10.78	-2.74	7.49
Kharkande	2	2	757.55	378.78	813.04	406.52	18.50	9.25	804.05	402.03	870.16	435.08	22.04	11.02	1.77	3.13
kharko Pakha Damgade	7	5	2,083.94	416.79	2,086.71	417.34	0.92	0.18	2,171.71	434.34	2,188.90	437.78	5.73	1.15	0.96	0.92
Kuwadi	6	5	2,104.47	420.89	2,122.99	424.60	6.17	1.23	2,216.18	443.24	2,266.72	453.34	16.85	3.37	2.13	4.56
Kyamun Danda	4	3	1,260.73	420.24	1,272.94	424.31	4.07	1.36	1,128.27	376.09	1,162.96	387.65	11.56	3.85	2.50	6.24
Lami Danda	7	4	1,652.17	413.04	1,675.37	418.84	7.74	1.93	1,640.91	410.23	1,692.81	423.20	17.30	4.32	2.39	5.72
Laxmi Maila	3	2	817.47	408.74	847.47	423.74	10.00	5.00	851.68	425.84	871.99	436.00	6.77	3.38	-1.62	2.61
Ludi	3	3	1,147.15	382.38	1,177.15	392.38	10.00	3.33	1,258.23	419.41	1,301.72	433.91	14.50	4.83	1.50	2.25
Ludidamgade	23	21	8,432.55	401.55	8,425.33	401.21	-2.41	-0.11	8,566.35	407.92	8,683.55	413.50	39.06	1.86	1.97	3.90
Mahalaxmi	10	9	3,588.98	398.78	3,791.41	421.27	67.48	7.50	3,531.11	392.35	3,668.49	407.61	45.79	5.09	-2.41	5.81
Majikhola Simre Danda	1	1	399.05	399.05	429.05	429.05	10.00	10.00	332.88	332.88	367.19	367.19	11.44	11.44	1.44	2.07
Pungche	1	1	422.77	422.77	435.77	435.77	4.33	4.33	448.62	448.62	463.96	463.96	5.12	5.12	0.78	0.61
Ramlakshuman	2	2	527.55	263.78	572.78	286.39	15.07	7.54	648.43	324.22	694.07	347.04	15.21	7.61	0.07	0.00
Sandan Bisauni	9	8	3,186.53	398.32	3,306.31	413.29	39.93	4.99	3,269.96	408.74	3,428.55	428.57	52.86	6.61	1.62	2.61

Shikar danda Ludipakha	6	6	2,266.33	377.72	2,273.63	378.94	2.44	0.41	2,289.23	381.54	2,299.50	383.25	3.42	0.57	0.16	0.03
Shikhar	6	5	2,102.25	420.45	2,172.25	434.45	23.33	4.67	2,133.96	426.79	2,212.64	442.53	26.23	5.25	0.58	0.34
Shikhar Bar Bhanjyang	3	3	1,228.29	409.43	1,338.29	446.10	36.67	12.22	1,144.92	381.64	1,265.34	421.78	40.14	13.38	1.16	1.34
Sirautae	7	5	2,061.54	412.31	2,071.54	414.31	3.33	0.67	2,049.86	409.97	2,054.12	410.82	1.42	0.28	-0.38	0.15
Taksatari	3	3	1,265.16	421.72	1,268.32	422.77	1.05	0.35	1,264.34	421.45	1,265.41	421.80	0.36	0.12	-0.23	0.05
Thokne Bhanjyang	7	5	1,941.83	388.37	1,945.11	389.02	1.09	0.22	1,719.52	343.90	1,732.70	346.54	4.39	0.88	0.66	0.44
Total	186	153	60,671.72	395.09	61,955.70	406.26	15.85	3.72	60,306.06	392.36	62,069.43	405.96	21.77	4.53		
													Sum of square difference			74.77
													RMS error (t/ha)			1.66

RMS = root mean square

About ICIMOD

The International Centre for Integrated Mountain Development, ICIMOD, is a regional knowledge development and learning centre serving the eight regional member countries of the Hindu Kush-Himalayas – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan – and based in Kathmandu, Nepal. Globalisation and climate change have an increasing influence on the stability of fragile mountain ecosystems and the livelihoods of mountain people. ICIMOD aims to assist mountain people to understand these changes, adapt to them, and make the most of new opportunities, while addressing upstream-downstream issues. We support regional transboundary programmes through partnership with regional partner institutions, facilitate the exchange of experience, and serve as a regional knowledge hub. We strengthen networking among regional and global centres of excellence. Overall, we are working to develop an economically and environmentally sound mountain ecosystem to improve the living standards of mountain populations and to sustain vital ecosystem services for the billions of people living downstream – now, and for the future.

ICIMOD gratefully acknowledges the support of its core donors:
The Governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Switzerland, and the United Kingdom.

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ISBN 978 92 9115 344 2