Multi-Scale Forest Biomass Assessment of the Hindu Kush Himalayan Region

Scope and Challenges of Geospatial Applications

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Forest resource conservation through community-based programmes has become an integral part of forest management in the Hindu Kush Himalayan (HKH) region. Reliable baseline assessment and monitoring strategies at multiple scales are needed to generate optimal supply–demand resource scenarios for effective use of forest resources and to leverage carbon mitigation benefits through mechanisms like the Clean Development Mechanism (CDM) and Reducing Emissions from Deforestation and Forest Degradation (REDD). There is a critical need for forest biomass assessment and monitoring at multiple scales using ground and space-based protocols. However, the use of geospatial information systems is still at an early stage due to the lack of a uniform and consistent methodological framework and varying capacity of countries in the HKH region. This paper describes the available geospatial datasets and models relevant for the region; the current status of assessment levels and needs at HKH regional, national, and local levels; and areas of research to strengthen geospatial applications for multi-scale biomass assessment.

Keywords: Hindu Kush Himalayas (HKH), REDD+, multiple scales, and geospatial applications

Introduction

In the debate on greenhouse gas (GHG) emissions as the prime cause for the perceptible global warming, forest carbon flux assessment has gained the attention of researchers and practitioners alike. The roles played by terrestrial ecosystems in the global carbon (C) cycle, and especially the role of intact forests as a carbon sink, and of deforestation and forest degradation as a GHG source, have been widely recognized as crucial since the 13th session of the Conference of the Parties (COP 13) to the United Nations Framework Convention on Climate Change (UNFCCC) in Bali in 2007, and publication of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in the same year (IPCC 2007). This is mainly due to the early estimations that deforestation and degradation of forest ecosystems contributes up to one-fifth of the world's total anthropogenic GHG emissions. Carbon sequestration was also reported to be a potentially effective mitigation method to counter global warming at a lower cost than that of the massive energy conservation and innovation adjustments needed to reduce the use of fuel in high-energy world economies.

Forests play an important role in the global carbon cycle, and both influence and are influenced by climate change. Forest ecosystems contain more than half of all terrestrial carbon and account for about 80% of the exchange of carbon between terrestrial ecosystems and the atmosphere (FAO 2010). At the same time, 14 million hectares of global forest cover is lost annually (FAO 2010). The future global trend of pressure on the remnant forest cover can be gauged from the fact that five billion new middle class consumers are expected by 2030 (Cotula 2011). This will mean a marked increase in the demand for energy, food, material, and consumables that is driving forest conversion, and especially in the five commodities considered to be closely linked with widespread deforestation: palm oil, soy, beef, leather, timber, and biofuels.

In the Hindu Kush Himalayan (HKH) region, the system of agriculture, forest, and other land use (AFOLU) constitutes an important component of livelihoods and means of support for creating and safeguarding more climate-resilient livelihoods. AFOLU-based systems support around 70% of fuel and fodder demand in the region, and their CO_2 mitigation potential is also thought to be significantly high. However the current low investment and lack of innovation to improve the productive interface between forest-dependent people and sustainable forest ecosystem services do not augur well for addressing climate change. There are currently four key opportunities for renewing the role of forests as an effective and efficient carbon sink:

- **Putting a price on ecosystem services.** Economic valuation of all forest products and services
- **Incentivizing for carbon sink services.** Creating innovative financing mechanisms and markets for carbon sink services
- **Encouraging investment in sustainable forest management.** Proactive management to sustain forest ecosystem goods and services.
- **Strengthening governance.** Improving forest governance

Validated research on carbon flux potential and measurement is needed as a basis for achieving these opportunities for forest carbon management; tracking and monetizing carbon sinks using simple carbon flux monitoring methodologies is essential. The extent of deforestation and degradation is considered to be a primary measure for carbon mitigation strategies and there is a critical need for assessment and monitoring of forest extent and biomass at multiple scales using ground and space-based protocols. Satellite-based monitoring of deforestation is largely proven technically, but the establishment and application of operational forest cover monitoring systems has a long way to go in most of the HKH countries. The use of geospatial information systems remains at an early stage due to the lack of a uniform and consistent methodological framework and varying capacity within different countries. At present, degradation assessments and monitoring focusing on forest biomass are generally performed through community- and state-owned ground-level monitoring systems.

The diverse forestry initiatives in the region require methodologies and approaches to bring value addition to geospatial systems (remote sensing and in-situ measurements) in order to meet biomass assessment and mitigation compliance procedures, and to support uncertainty control and seamless scaling up and integration into sub-national and national frameworks. This paper describes the available geospatial datasets and models relevant for the region; the current status of assessment levels and needs at HKH regional, national, and local levels; and areas of research to strengthen geospatial applications for multi-scale biomass assessment.

Forest Sampling and Biomass Estimation: Data Requirements and Models

The precise estimation of forest biomass depends on efficiency at three stages of the quantification process: design, estimation, and inference. The design stage means selecting the design for data gathering; the estimation stage involves selecting and using estimators for the parameters of interest, i.e., population means and totals; and the inference stage analyses the accuracy of these estimators, i.e., calculation of standard errors and confidence levels. In natural forested ecosystems, selected features are typically identified by their location. Thus forest biomass sampling needs a spatial perspective: sampling in space. There are two scientifically based approaches for sampling and extrapolating from a sample to an entire population: design methods and model-based methods. The principle difference between them lies in the source they use for randomness.

Design-based estimation: Geospatial data and methods

In classical design-based sampling theory, the source of randomness is the probability introduced by the sampling design to the various subsets of a population. Inference rests on the stochastic structure introduced by the sample selection. Hence one of the important ways of enhancing the efficiency of design is to develop a reliable stratification of a complex population and optimally sample subpopulations. Satellite remote sensing provides precise stratification in terms of forest crown density, forest types, communities, and species formations which can form the basis for reducing the strata variance and making precise estimates. This becomes more relevant in the context of the high degree of variability in spatial distribution of vegetation types across the HKH region. Spatial explicitness in the estimates can be brought out at the desired scale and accuracy using a geographical information system (GIS) by accounting for the strata proportions and value of the category of interest per unit area for a given strata. However, the resolution of spatial explicitness depends on the details of stratification and intensity of ground sampling.

Different forest types vary significantly in terms of the ratio of below and above ground biomass, annual increment, and biomass density, which determine the standing biomass levels. Kaul et al. (2010) have described how forest type information was used in different studies related to the assessment of forest carbon pools in India. Precise delineation of the boundaries of the groups of different types, single species formations, and mixed species formations, offer a unique opportunity for developing spatially balanced sampling designs, improving the precision of the field sampling, and attributing appropriate biomass expansion factors (BEF) at the national, state, or bioclimatic zone level to improve the precision of the estimates.

Spatially explicit forest type products suitable for use at HKH regional level are available as open-source databases from global land cover and vegetation products (Annex, Table A1), and spatially explicit forest type databases using satellite and ground-based information suitable for use in national and sub-national level biomass estimations exist for China and India (Annex). While significant information on forest composition exists from ground surveys in the other countries in the HKH region, there is a lack of spatially explicit forest type databases that can be used for forest biomass estimation and management.

The relationship between forest crown cover and biomass is strongly established and has been widely used at different scales. The forest crown density (percentage) is delineated using widely available medium resolution satellite data and used as a stratification input for ground inventory in estimations at national and sub-national levels. The different forest cover parameters available as open-source products and relevant for biomass estimation at different scales are presented in the Annex (Table A1). The crown projected area (CPA) delineated using very high resolution satellite data has been found to provide reliable information on forest basal area and the number of trees at forest stand level. Several studies have been published using this technique across different parts of the HKH region at the research level; the approach needs to be integrated in regular operational sub-national and local level assessments. Several national and sub-national biomass inventories over different parts of the HKH region have been developed using design-based models with remote sensing data.

Model-based estimations: Geospatial data and methods

Forest structure and biomass often exhibit nonlinear variations across space and variable interactions across temporal and spatial scales. Hence, the traditional methods of uniform extrapolation of field-based sample biomass estimates over larger areas suffer from a large uncertainty. In addition, spatially explicit estimates can potentially provide good insights for carbon monitoring, leakage, additionality, and prediction of biomass over time, as a function of change due to land cover and land use. With the advent of availability of multi-resolution satellite data, powerful data mining, and self-learning algorithms, there has been a paradigm shift from simple area-based extrapolation methods to model-based extrapolation.

In the model-based approach, the inference rests entirely upon the validity of the model describing the real world. All the randomness in this inference is due to the population and not the sampling method, as in the design-based approach. Where the design-based approach requires independent selection of units, the model-based approach considers the independence of the sampling units, and thus spatial correlations between the sampling units need to be taken into account. Even when models are used in the design-based approach, the validity of inference is ensured by the sampling design and not by the validity of the model.

In this context, remote sensing based spatial information, geostatistical tools, and non-parametric tools provide an effective means to develop robust models. Remotely sensed reflectance data based on the physiognomy, composition, and phenology of vegetation are used as a proxy to estimate the biomass. The reflectance regulated by physiognomy and composition is understood using high resolution satellite data, and the phenology is quantified using high temporal resolution and medium spatial resolution satellite data. The model-based approaches relate the spatial variability of forest spectral reflectance across each unit (pixel) of the remotely sensed image with field-based biomass, and develop a model that associates the biomass value for each pixel. This results in development of spatially explicit biomass as a function of the resolution of the satellite data used, hence the model can be developed from local to regional and national scales. As a result of these advantages, estimation of forest volume and biomass using satellite reflectance-based models has recently been drawing attention.

Qingxi and Feng (2003) used a multi-regression equation and neural network model to estimate the forest biomass on the southern side of the Xiaoxing'an Mountains. The model was established using TM imagery, together with 232 plots of forest inventory data, including environmental and biological factors, to develop the regression equation. Using forest inventory data for three inventory periods (1984–1988, 1989–1993, and 1994–1998) and synchronous NDVI (Normalized Difference Vegetation Index) data, Piao et al. (2005) developed a satellite-based approach for estimating China's total forest biomass carbon stocks. Karna et al. (2015) developed a high resolution, species-specific crown projected area and diameter model to estimate forest carbon over mid-Himalayan tracts of Nepal. Several such models have also been presented in different articles in this publication. These techniques have an enormous potential to use multi-resolution data and develop multiphase sampling approaches to integrate local measurements at national scales.

Forest allometry

Information is needed on volume equations, biomass expansion factors, and specific gravity of wood for estimation of above and below ground biomass, assessing the commercial and non-commercial parts of biomass, and other calculations. Biomass expansion factors are used to convert stand volume to above ground biomass and account for non-commercial components such as branches, twigs, bark, stumps, and foliage. The IPCC, FAO, Forest Survey of India (FSI), and Forest Research Institute of India have been publishing extensive information on these parameters in the form of reports. As part of the National Carbon Project of India under the ISRO-GBP programme, an effort was made to develop a database with specific volume equations and general equations for 753 regional species based on Forest Research Institute and FSI publications. Specific gravity data have been collected for 16,400 species in Asia. The specific gravity of 86 fuelwood trees and shrubs growing on wasteland and degraded sites has been added. In Nepal, allometric equations are mainly available for community forests with low diameter at breast height (DBH); these equations can produce errors in biomass and carbon estimation for bigger trees.

Multi-scale Assessment Systems

HKH regional level assessment

One of the critical challenges in the transboundary HKH mountain system is managing carbon sequestration and biodiversity within and among geographic regions, and estimating the effects of 'natural' disturbances on carbon storage and flux. Scaling of biogeochemical processes to regions, continents, and the world is also critical for understanding feedback between the biosphere and atmosphere in the analysis of global change. It is necessary to have this type of understanding on the interplay between forest ecosystem structure and function at the HKH regional scale, considering the high degree of latitudinal and altitudinal control of climate over the region. Studies along these lines could provide scientific evidence on the patterns of biomass change and associated drivers to support transboundary management.

Some of the diverse geospatial datasets available on forest distribution and biomass levels developed using multi-sensor remote sensing data are listed in the Annex (Table A1). These datasets contribute to understanding of patterns and drivers of change at a regional scale. The spatial distribution patterns of forest carbon at different latitude and altitude and under different disturbance regimes over the HKH region are shown in Figures 1 and 2. The forest patches (high disturbance regime) were identified using landscape metrics at half degree resolution grid level. The carbon estimates were generated for the HKH region using the global carbon datasets from Kindermann et al. (2008) at 20 x 20 km resolution.

Figures 1 and 2 show that the variation in forest carbon is greater along the latitudinal gradient than along the elevation gradient. This indicates a possible role of forests in land surface climatology along the latitudinal gradient. The high variability of patch forest carbon (disturbed regime) at different elevations may be due to anthropogenic and environmental heterogeneity, the total carbon in patch forest is also very small compared to forest overall. Understanding of the role of disturbance regimes on carbon sequestration in relation to landscape gradients could provide useful information for transboundary management at the landscape level.

Figure 3 shows the relationship between species diversity and level of basal area in deciduous forests in India in 25 bioclimatic zones. The graph shows three distinct groupings: in Group A, basal area increases with species diversity; in Groups B and C, basal area also increases with species diversity but at different threshold levels. These distribution patterns indicate how dominant species, bioclimatic and local topographic factors, and disturbance regimes control growth and species diversity. Sal mixed ecosystems in the lower elevation regions of the Himalayas have a high basal area but low diversity, whereas the mixed forest deciduous systems have a low basal area but high diversity. The spatial delineation of such zones using remote sensing and ground based data would help in demarcating zones that are more or less resilient to disturbance and climate change impacts.

Figure 1: **Forest and patch forest area and carbon stocks at different latitudes in the HKH region**

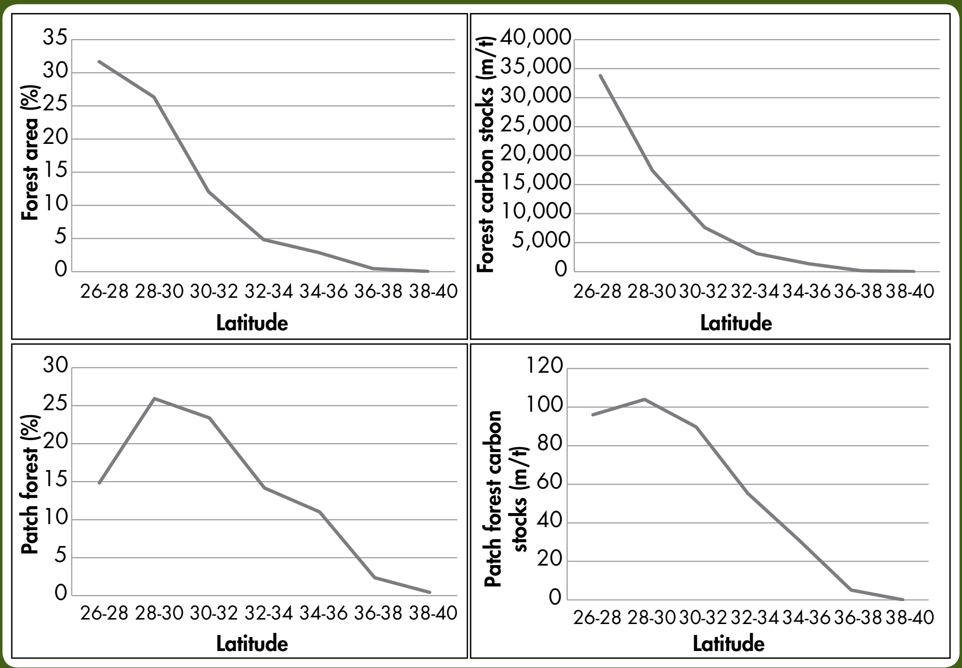


Figure 2: **Forest and patch forest area and carbon stocks at different elevations in the HKH region**

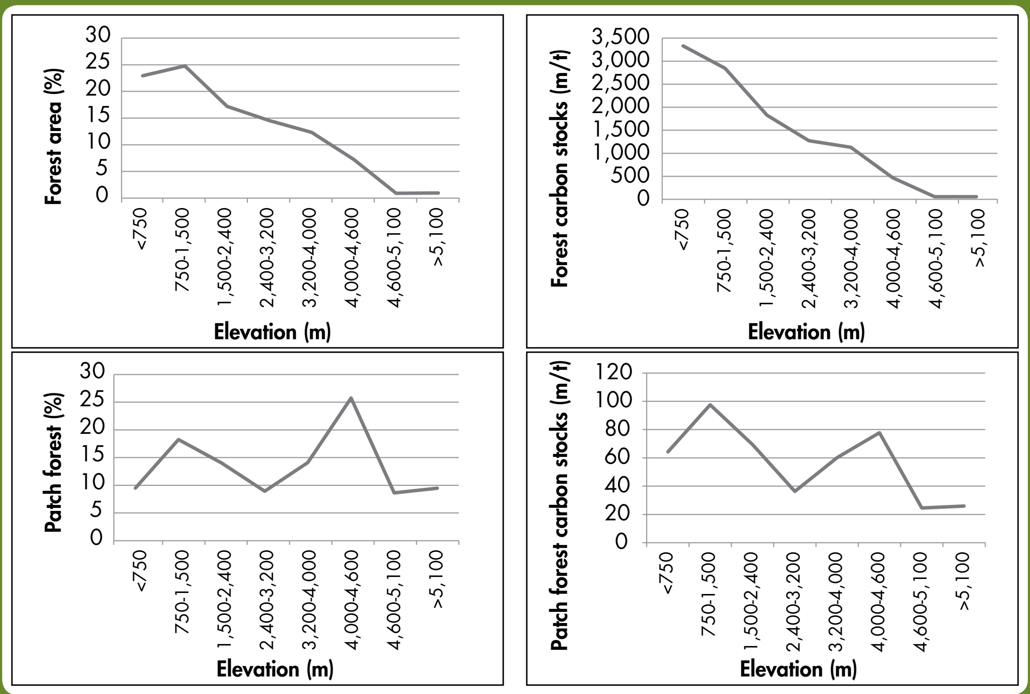
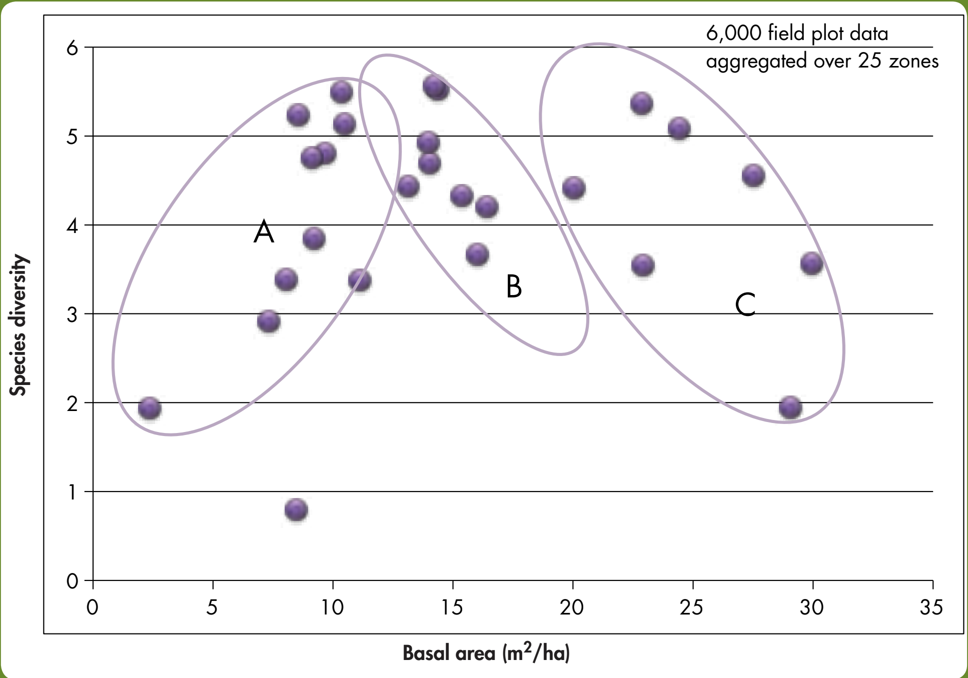


Figure 3: **Species diversity and basal area of deciduous forests in India**



National and sub-national level biomass assessments

Currently, assessment of forest growing stock is done at national and sub-national levels. National growing stock estimates are developed using national-level multi-source forest inventories. In order to address sustainable forest management, the national forest inventories are made exhaustive in terms of parameters and data collected across the entire country. Most of the national inventories follow systematic sampling with fixed grids and proportional temporary and permanent sample points chosen for data collection.

In view of this complexity, national inventories involve intensive field sampling and are thus time and cost intensive. The estimates are generally planned over a five-year time interval. However due to time and cost constraints, biomass assessments in most HKH countries, apart from China and India, have not been carried out at regular intervals. Equally, national-level growing stock estimates over a large country do not provide realistic sub-national scenarios, while the next lower level assessments done at the district level are designed with district-specific requirements in terms of sampling design and time.

Low cost and rapid national and sub-national forest monitoring systems which can address deforestation and biomass changes are increasingly being developed. Such monitoring systems could provide consistent temporal databases that would enable estimation of historical forest cover change, as well as an operational mechanism for monitoring forest at specified intervals on a regular basis. Such a coherent operational system would go a long way towards measuring and reporting changes in deforestation and/or forest degradation (biomass changes), in forest carbon conservation, and on carbon stock enhancement or reduction activities for GHG inventories and forest reference emission level estimates.

The contribution of geospatial approaches in developing low cost and rapid forest monitoring systems in the HKH region is immense. Forest cover monitoring is carried out operationally at regular intervals in China and India using remotely sensed satellite data. The International Centre for Integrated Mountain Development (ICIMOD) is developing harmonized time series forest cover databases and establishing operational systems for forest cover monitoring in association with the remaining countries under the NASA supported SERVIR-Himalaya initiative. However, efforts to develop monitoring systems for low forest biomass as a proxy for forest degradation still have a long way to go.

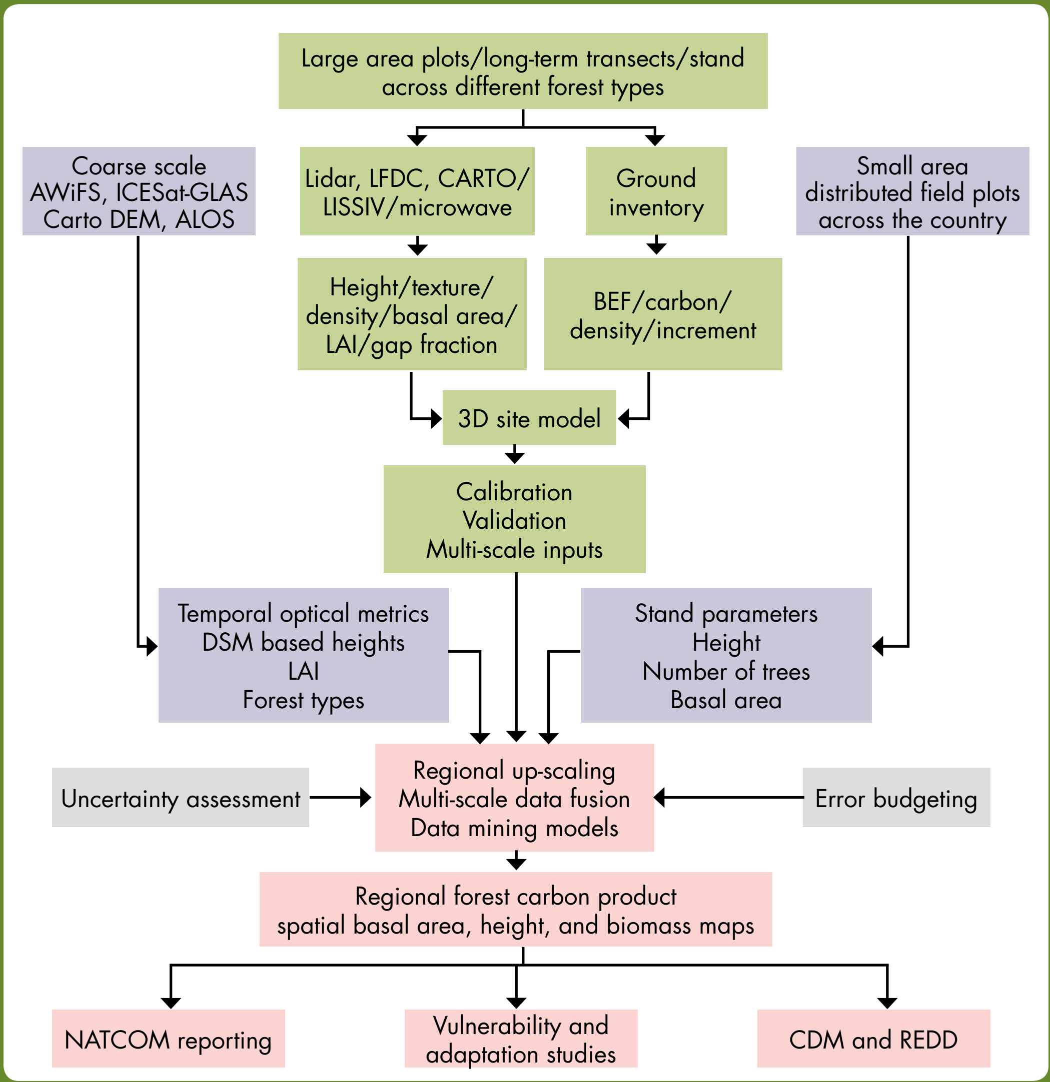
The studies carried out over China and India to develop satellite reflectance-based biomass models are also worth mentioning. Piao et al. (2005) developed a satellite-based approach for estimating China's forest total biomass carbon stocks using forest inventory data for three inventory periods, 1984–1988, 1989–1993, and 1994–1998, together with synchronous satellite based NDVI (Normalized Difference Vegetation Index) data. Region-specific spectral models are being developed across India as part of the ISRO National Carbon Project. The remote sensing models initially depend on more intensive ground data for model calibration and validation. The standardized models then provide spatially explicit biomass estimates based on reflectance data perceived as a function of change in land cover class and physical growth of forests.

These kinds of models have greater relevance where forest undergoes dynamic changes due to deforestation, reforestation, and afforestation under different anthropogenic interventions. Intensive ground data and high resolution satellite-based quantification of sites of dynamic change, followed by synoptic coarse scale assessment at a landscape scale and integration of the two scales of information to develop a national level framework for biomass assessment, could be explored as the basis for a cost and time effective national level monitoring system. Figure 4 shows a conceptual framework of this type which is being tested in Nepal.

Local scale assessments

Community forest management has been increasing in the HKH region as a process for sustainable management of forest resources. The success of community forest management lies in the fact that the local people receive tangible benefits from the conservation efforts they make. Tangible benefits are particularly clear from programmes like those under the Clean Development Mechanism and Reducing Emissions from Deforestation and Forest Degradation (REDD+). Effective monitoring of conservation efforts and their results has become a mainstay for payment mechanisms, and evolving REDD+ monitoring, reporting, and verification (MRV)

Figure 4: **Multi-scale national assessment framework**



as a cost and time effective, locally implementable mechanism has become a challenge. The synergistic use of local ground measurements and adoption of low cost geospatial systems to develop synoptic scale of understanding offers a potentially viable system to be tested. In the following, we describe our experience of local scale monitoring of pilot REDD+ sites in Nepal.

Ground based participatory monitoring of REDD+ project sites

Since 2009, ICIMOD and partners Federation of Community Forestry Users Nepal (FECOFUN) and Asia Network for Sustainable Agriculture and Bioresources (ANSAB) have been implementing a pilot REDD+ project in collaboration with local communities in three watersheds in Nepal covering more than 10,000 ha of forested area under community management. This pilot project, funded by the Norwegian Agency for Development Cooperation (Norad), looked at why and how a community can be involved in MRV.

The pilot project facilitated a sub-national level MRV system in which monitoring responsibilities were devolved to local communities through a participatory method with an opportunity to seek guidance and supervision from the district forest office (DFO). MRV is the single most important activity for performance-based forest management and determines the scale of payment and incentives. Community-based monitoring is a data source for MRV (Danielsen et al. 2011). The involvement of local communities in forest monitoring promotes a feeling of ownership, and motivates people to take on REDD+ responsibilities with performance-based forest management.

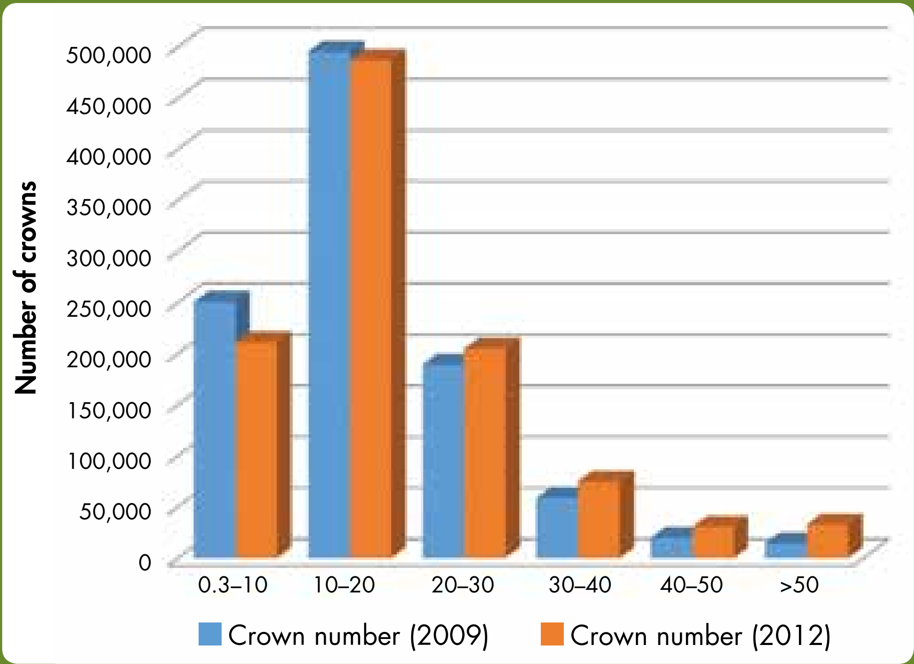
The project developed forest carbon stock measurement guidelines following IPCC 2006 Good Practice standards, and trained and supported community forest user groups to carry out forest measurements. Other authors have noted that local MRV may be cheaper than, and as accurate as, national-level alternatives (Puliti 2012) and that collecting data on their own forests engages local communities and reduces the costs of technology and experts (Dangi 2012). The communities in the project proved able to measure stock using standard forest inventory methods; mapping this methodology was tried, and shown to work, in several countries including India, Tanzania, Senegal, and Papua New Guinea. The communities carried out diameter measurement, boundary delineation, and species identification in permanent monitoring plots laid down at the project sites more effectively than outside professionals, and their involvement in monitoring activities also enhanced transparency (IGES 2012).

Low cost scientific tools: The potential of geospatial systems

The requirements in the REDD+ MRV process such as completeness, consistency, and correctness depend on spatial explicitness of the given observation or estimate from which they are developed. Plot-based low intensity ground monitoring has a limited scope to address certain critical components of community forest programmes such as additionality, leakage, and persistence, as such changes need to be evaluated at the landscape scale. Thus it is helpful to complement the limited permanent field plot-based carbon monitoring with more spatially explicit forest structure and biomass based monitoring using multi-resolution remotely sensing data.

Time series satellite data at 1 m resolution can provide information on detailed changes in crown size, number of crowns, crown overlap function, crown shadow, and crown gaps, and such satellite images are freely available through Google Earth and very low cost Indian satellite systems. Figure 5 shows some typical results for change in crown number over time. The monitoring of forest canopy morphology using such data could provide meaningful information on degradation or improvement of forest. CPA–basal area models using very high

Figure 5: **Change in tree crown size over time**



resolution data are also very useful for predicting basal area and biomass over an entire project site to quantify the dynamics of change even outside the permanent monitoring plots.

Pilot studies over selected sites have proven the usefulness and scientific feasibility of using geospatial data to provide a low cost monitoring system. The results are presented in another paper in this volume (Gilani et al. 2015). Efforts are being made to develop easily readable and understandable value-added geospatial products, and to carry out capacity building of local users in the use of such products in participatory forest monitoring.

Emerging Research Areas and Challenges

Enhanced forest biophysical data generation

The key challenges in regional and national level forest carbon estimation include optimizing field sampling, developing spatially consistent estimations, controlling uncertainty due to errors from allometry, sampling design, ensuring the quality of predictor and response variables, and using robust models for extrapolation. Remote sensing of forest biomass, which is directly correlated with carbon stored in forests, holds one of the keys to addressing these challenges at different scales. Since biomass is a three-dimensional metric, precise estimation requires biophysical measures addressing horizontal (e.g., canopy density/cover) and vertical (e.g., canopy height) structural characteristics of the vegetation. The availability of high temporal large swath optical sensors like MODIS, SPOT, and AWiFS have enabled understanding of horizontal vegetation structure and the relationship with above ground biomass using parametric and non-parametric models. However, these models are constrained by the large volume of field inventory data required for training the model, and the availability of repeat measurements for time domain biomass assessments.

During the last decade, the scope for generating more biophysical information in the horizontal and vertical domains and estimating biomass has improved enormously due to the launch of very high resolution optical sensors, and airborne and space-borne microwave and Lidar systems. Very high spatial resolution optical systems have the potential to provide details on canopy morphology which can be related to biomass. Airborne microwave and Lidar systems have been used across the world to retrieve stand height and estimate biomass. Saatchi et al. (2011) prepared biomass carbon estimates over three tropical continents using tree height information based on GLASNOST and optical temporal metric information based on MODIS using data mining models. It is generally expected that measurement of above ground biomass (AGB) will become dominated over the next five years by methods that combine radar, Lidar, and optical data, which can provide spatial consistency in the estimates and optimize field inventories. The open-source satellite data currently available, their use, and comparative assessment in terms of cost, are summarized in the Annex (Tables A2, A3).

Uncertainty assessment and control

The uncertainties in assessing biomass and change can be grouped into three classes: spatial characterization, temporal characterization of forest cover and standing biomass, and use of precise ground-based forest allometric databases. Because of the high degree of spatial and temporal variability in rainfall, topography, and biotic disturbances, both forest type and standing biomass differ appreciably across space. Any national level estimate suffers at times from inaccuracy because of the inadequacy in accounting for spatial heterogeneity in terms of forest condition (crown density), forest type, and standing biomass. Uncertainty in important variables in the ground-based data such as biomass expansion factors, specific gravity of wood, annual increment, and wood extraction (fuelwood, thinning, logging, and others) also induce a large uncertainty in forest carbon stock assessment.

The challenges in carbon pools and flux estimates lie in the extent to which the degree of uncertainty can be reduced. The errors that can accumulate include: measurement errors at plot level; errors due to allometric relationships; sampling errors; and model prediction errors. Currently, carbon pool estimates rely on field measurements and are subject to measurement uncertainties. A shift towards multi-sensor remote sensing based biomass estimations with optimal field sampling is urgently needed. Remote sensing and ground-based Lidar systems help in intensive site characterization to develop models for biomass estimation and validation. These approaches would facilitate production of periodic biomass assessments using satellite data and limited ground information and reduce uncertainty. With the advent of the availability of geospatial tools and digital databases, spatially balanced field sampling designs could be evolved using multiple layers of information to reduce errors in sampling. Currently, design-based models are used to develop regional and national estimates. Spatially disaggregated model-based estimation methods would help in optimizing errors during scaling up.

Conclusion

The use of diverse open-source data and tools in the HKH region for multi-scale biomass monitoring needs to be strengthened both in scientific terms and in improved capacity building. Development of scientific understanding on the relationship of forest biomass to different ecosystem processes at a regional level using consistent geospatial datasets will help support transboundary management. The increasing integration of community-based field biomass monitoring systems into national monitoring systems through a geospatial framework for scaling up will facilitate the optimization of national level reference emission level inventories. Value-added remote sensing products that can be understood by local level stakeholders will help to reduce the transaction costs involved in the REDD+ MRV mechanism.

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Annex

Table A1: **Useful open-source geospatial products for biomass estimation**

Geospatial Product	Satellite	Scale	Resolution (m)	Use
Land cover	MERIS	Regional	250	Vegetation stratification-forest type, forest crown cover
Land cover	MODIS	Regional	1,000	Vegetation stratification-forest type, forest crown cover
VCF Fields	MODIS	Regional	500	Works as proxy of biomass stratification
Ecoregion map	MODIS	Regional	10,000	
Deforestation	MODIS	Regional	500	Useful in estimation of temporal biomass changes
Phenology	MODIS	Regional	1,000	Useful in biomass estimation models
LAI	MODIS	Regional	500	Useful in biomass estimation models
Stand height	GLASNOST	Regional	500	Useful in biomass estimation models
Biomass	MODIS,GLASNOST	Regional	0.5x0.5	Useful in regional scale analysis
Deforestation	Landsat TM	National	30	Useful in estimation of temporal biomass changes
Land cover	Landsat TM	National	30	Forest stratification and field design development
Land cover change	Landsat TM	National	30	Useful in estimation of temporal biomass changes

Table A2: **Geospatial open-source datasets for biomass estimation**

Open Data	Satellite Sensor	Resolution (m)	Interval	Scale	Output
Multispectral reflectance data	MODIS	500	Fortnight	Regional	Forest cover, gap fraction,
	MERIS	500		Regional	Broad types
	MISR	500		Regional	
Vegetation index	MODIS	500	Fortnight	Regional	Seasonality, annual growth
	MERIS	250		Regional	
	MISR	500		Regional	
Multispectral reflectance data	Landsat TM	30	Month	National	Forest crown density, type, seasonality
Multispectral reflectance data	IRS AWiFS	56	5 days	National	
Very high resolution satellite data	Google Earth	1	> 1 year	Local	Crown projected area, age class
	Bhuvan	2.5	> 1 year	Local	Stand height
Allometric data	IPCC				Volume/biomass equations, BEFs
	FAO				
	Geowiicki				
Terrain data	SRTM	90			Elevation, slope, and aspect information
	ASTER	30			
	CARTODEM	10			

Table A3: **Cost comparison – satellite data**

	Satellite/Sensor	Resolution (m)	Swath (km)	Price per sq.km (USD)
Method 1	LISS-IV	5	70 (192 USD)	0.15*
	CARTOSAT -1	2.5	27 (129 USD)	1.02*
	CARTOSAT -2	1	9.6 (104 USD)	<1*
Method 2	RapidEye	5	77	1.28*
	IKONIOS	1		15
	GeoEye-1	0.5	15.2	40
	WorldView-2	0.5	16.4	32
	QuickBird	0.5	16.5	40

* Archive data price, may increase for new acquisitions