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The overall goal of this NASA funded project is to synthesize existing research efforts on LCLUC to detect and quantify LCLUC and their impacts on biogeochemical cycles in SSEA region over the past three decades. While a great amount of research has focused on individual LCLUC-related efforts in ground-based measurements, remotely-sensed observations, land change processes, and modeling assessment of LCLUC impacts on terrestrial biogeochemical cycles, the objective of this project is to systematically synthesize these efforts, because different LCLUC- related efforts are interconnected.

As part of this research, we have accomplished the following 3 major objectives that we originally proposed:

Objective 1: *Understand the major land cover and land use (LCLU) transition activities in the study region*.

Objective 2: *Advance our understanding of the causes of land cover and land use change.*

Objective 3: *To improve our understanding of the historical effects of land cover change dynamics on the quantities and pathways of terrestrial carbon and nitrogen fluxes*.

Over the last year we produced 10 journal articles and gave various presentations at national and international conferences. ***All these papers and presentations acknowledged financial support of this grant*** *(see the list of journal articles and presentations at the end of this document.*

In the following we describe our major accomplishments under each objective:

1 Synthesizing the Existing Satellite and Ground Based Data Sets to Understand the LCLUC Dynamics of Various Countries in SSEA Region

We started by synthesizing existing studies and the remote sensing data sets for LCLUC in the SSEA. In addition, we are also making use of numerous local scale studies and national-scale forest inventory and agricultural census data to estimate the rates and geographic patterns of change in forest cover, cropland and land-cover change. We originally proposed that we will synthesize existing data, but for most countries LCLUC data at a country or regional scales is not available in the literature. However, we compiled the information in collaboration with several local scientists in the SSEA countries and are working on producing joint publications. Our approach is to study LCLUC transition activities on a country by country basis within the study region. We have made substantial progress in synthesizing the LCLUC dynamics for Bangladesh, Bhutan, India, Indonesia, Nepal and Pakistan, which we are reporting here. For the remaining couries, our research is in the preliminary stage and we hope to make substantial progress for the rest of the countries in the coming year.

1.1 Bangladesh

The major land-cover in Bangladesh consist of 59% agriculture, 11% forests, 17% fisheries and wetlands and 13% other land use categories such as urban, tourism, commercial areas (Islam 2006). Forests are second most important land-cover. On the basis of geographical location, climate, topography, and management principles, the forests of Bangladesh can broadly be classified into: hill forests, unclassified state forests, mangrove forests, coastal forests and home gardens.

A review of the literature on LCLUC and landscape management was conducted to investigate the sustainability of different land-cover types, particularly for the forests in Bangladesh. In addition, we collaborated with scientists at ICIMOD, Nepal and Bangladesh Forest Division to get the deforested area information for hill forests, particularly for the Chittagong hilly area of Bangladesh (Figures 2 and 3).

Table 1: Land cover changes in Bangladesh (Uddin and Gurung, 2010)

Land Cover	LCOV 1977	LCOV 2000	Change (1977-2000)	Remarks
Waterbodies	9818.11	17618.6	-7800.49	Increased
Bare Land	6163.69	6831.99	-668.3	Increased
Agriculture	103664.12	102119.63	1544.49	Decreased
Closed Forest	8357.45	2961.5	5395.95	Decreased
Open Forest	4790.39	6163.77	-1373.38	Increased
Shrubland	2177.63	3760.25	-1582.62	Increased
Mangrove Forest	4122.23	4117.53	4.7	Decreased
Grass Land	5595.14	1115.49	4479.65	Decreased

In a study conducted by Uddin and Gurung (2010), area coverage by each land cover type were compared for the years 1977 and 2000 (Table 1). The comparison between the two years indicated an increase for waterbodies, bare land, open forest and shrub land. On the other hand, there was a decrease in the areas for agriculture, closed forest and mangrove forest.

Shortage of land is becoming an increasing problem. More than 50 % of farmers have become landless and many of them settle in undeveloped areas (Rahman 2008). Around 220 ha of arable land is lost daily to uses such as road construction, industry, houses, etc. (Islam et al., 2004). Several studies reported a reduction of land for cattle grazing, mortality of trees and other vegetation (Ahmed 2011).

According to Reddy et al. (2016), the three largest land cover include agricultural land (62.2%), plantation and forest. In the past eight decades (1930-2014), 39.1% forests have decreased (Figure 1), majority of which occurred during 1930-1975. The highest net annual rate of deforestation was 0.75% during the years 2006-2014.The rate of afforestation increased during 1975-1985 however decreased in the later time periods (1995-1995, 1995-2006, 2006-2014). Despite different conservation policies, there is an increasing trend in deforestation, especially in the dense forests as compared to open forests indicating a threat to high biomass systems. In Bangladesh, the annual deforestation rate is 1-3.3%, which is 2-5 times higher than the deforestation rates in South Asia region (Reddy et al., 2016).

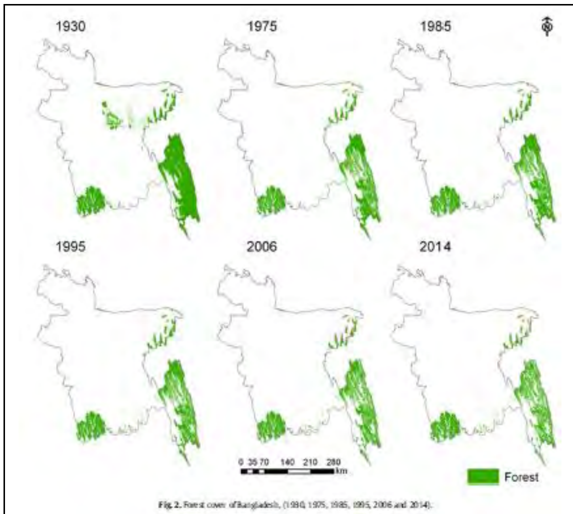

Figure 1: Forest cover in Bangladesh (1930-2014) (Reddy et al., 2016).

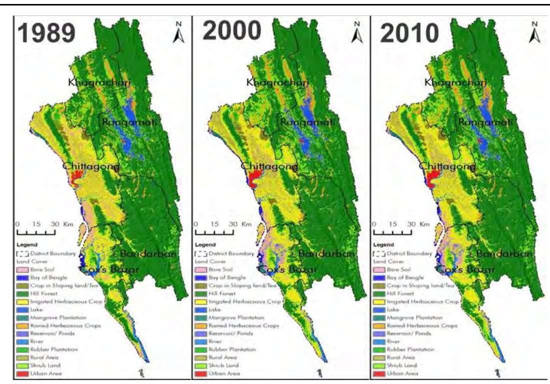

Figure 2: Landsat images for forested area in Southeastern part of Bangladesh for years 1989, 2000 and 2010 (Courtesy: Hammad Gilani of ICIMOD)

In a study carried out by ICIMOD Nepal using Landsat images for years 1989, 2000 and 2010 (Figure 2), the LCLUCs were estimated for or the Chittagong hilly area of Bangladesh. The results show that Chittagong area forest land decreased by 1,105.66 km^2 (or 9.9% of the total forest area) over the period 1989-2000 and 3,726.55 km^2 (31.2% of the total area) over the 2000 – 2010 (Figure 2). This suggests that the rate of deforestation had increased more than three times. According to Figure 3, land cover changes show an increasing trend in urban area in the Chittagong district for the time period during 1989-2010. Similarly, there is an increase in bare soil in Cox's Bazar while a decrease is observed in bare soil in the Chittagong area. Additionally, there is an increase in shrub land in the Khagrachari district (Figure 2).

According to the National Forest and Tree Resources Assessment 2005-2007, approximately 10% of the surface area of the country remains forested (BFD, 2008). Rahman et al. (2015) suggest that 93% of Bangladesh's forests are lost or degraded. The protected area network of the country, which consists of 1.4% of the surface area,

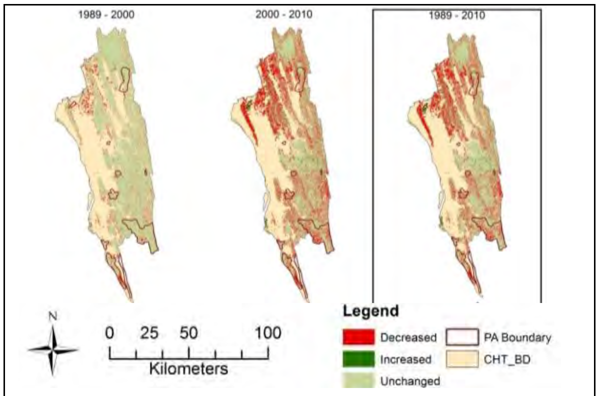

Figure 3: Change in forested area in Southeastern part of Bangladesh (1989-2010). The area shown in polygons are the PA (Protected Area) boundaries (Courtsey: Hammad Gilani of ICIMOD)

is one of the smallest in the world. Even though the current deforestation rate is relatively low (less than 1% per annum), Bangladesh is at a major risk of losing its remaining forest resources and associated biodiversity unless the trend is reversed (FAO, 2009). Results reveal that with the current rate of deforestation, in less than two decades little or no forest cover will exist in Bangladesh.

Shrimp/prawn farming is one of the fastest growing industries as it commands a leading position in the world market through its high demand and competitive international price (Hossain et al. 2013). It is the second largest export industry in the country. The main two areas of shrimp production are in the southwest comprising of 80% of the produce (Khulna, Satkhira, Bagerhat) and southeast comprising of 20% (Chittagong, Cox's bazar) (Alam et al., 2005). According to Islam et al. (2015), the highest land loss during 1989–2010 was observed for single cropland (52.2%), whereas the highest gain (45.1%) was achieved in shrimp area for the three areas of interest (Ganges Tidal Floodplain, Young Meghna Estuarine Floodplain and Chittagong Coastal Plain) included in the study.

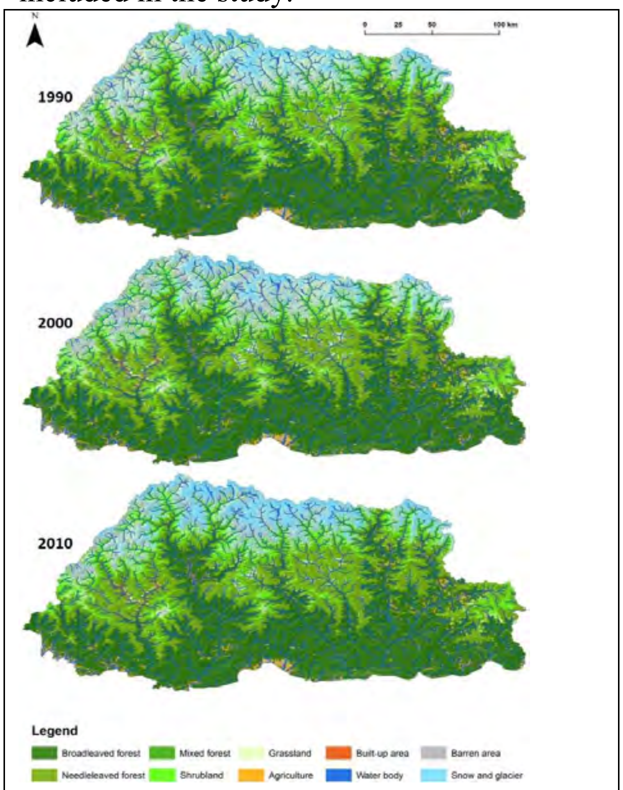

Figure 4: Landsat-based land cover maps for Bhutan for the years 1990, 2000, 2010.

1.2 Bhutan

Bhutan is a landlocked country in the eastern Himalayas. The population in 2005 was 634,982, giving an overall population density of 16 persons per km^2; 69% live in rural areas and 31% in urban areas. According to Bhutan's Department of Forests and Parks Services, Ministry of Forest and Agriculture, 19,677 km^2 of land (51% of the total area) has protected status, 16,396 km^2 in nine protected areas and 3307 km^2 in twelve biological corridors (areas set aside to connect one or more protected areas and conserved and managed for the safe movement of wildlife).

Land cover maps covering the whole of Bhutan were developed separately for 1990, 2000, and 2010 based on the Landsat images (Figure 4). Three classes of forest were used: broadleaved, needle leaved, and mixed. In 2010, percent of total area covered by: total forest 70%, shrubs 10%, meadows 4 %, agriculture land 3%, and the rest of the land 13%.

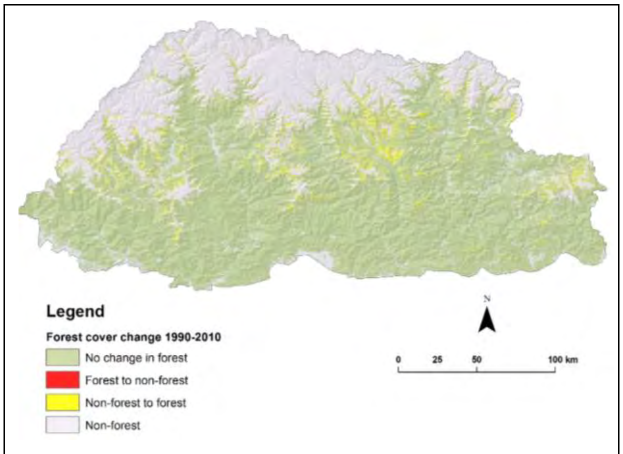

Figure 5: Forest cover changes in Bhutan (1990-2010)

The satellite maps suggest that the area for all three forest class increases in small amount from 1990 to 2000 and from 2000 to 2010, with an overall increase in forest area from 67 to 70% of total land over the whole period. There was a small change in "forest to non-forest" from 1990 to 2000, zero between 2000 and 2010, and close to zero (-2 km^2) over the whole period. The change in "non-forest to forest" was marked with a net increase of 1174 km^2 between 1990 and 2010, equivalent to an average annual increase of 59 km^2 or 0.2%.

Figure 5 shows the spatial distribution of forest change from 1990 to 2010. The change from non-forest to forest, mostly due to regeneration through planting, is easily observed and is spread across the country; the deforestation areas are difficult to identify. The greatest increase in forest was observed in Bumthang (277 km^2), followed by Wangdue Phodrang and Trashigang, and the least in Tsirang (1 km^2).

The data for all other classes showed a small increase in area over the twenty-year period apart from shrub land and grassland, which showed a decrease. The change in built-up area was negligible (0.01%). The changes in "grassland" and "others" ("water body", "barren area", "snow and glacier") were highly dependent on season and the time of satellite data acquisition. With rapid development, urbanization has taken place mostly in the agricultural land which further reduces the limited agricultural land e.g. Khuruthang and Bajo towns.

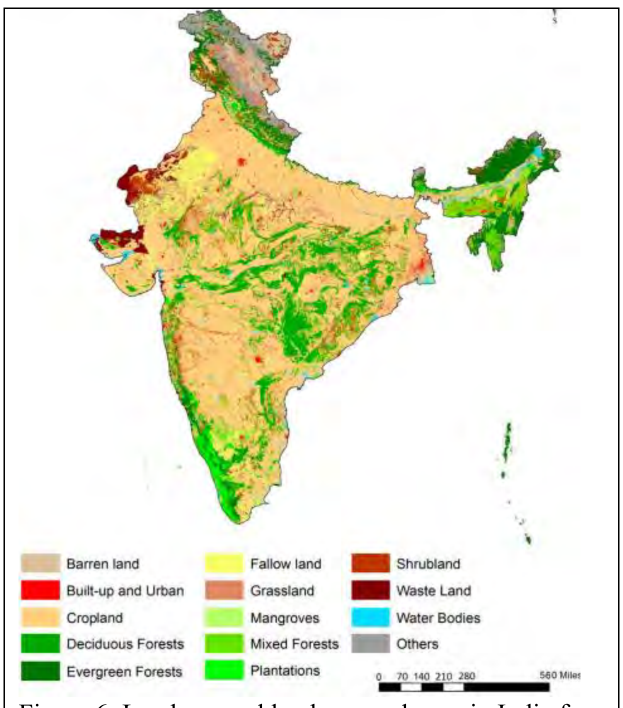

Figure 6: Land use and land cover classes in India for 2005 (Roy et.al 2015)

1.3. India

India has experienced significant LCLUC over the past few decades. The pressure on India's land resources is expected to further intensify in the future, with the growing economy and human population, expected increase in demands for animal products, and climate change. At the same time, India being one of the ten most forest-rich nations of the world, has received increasing attention under the REDD+ (Reducing Emissions from Deforestation and Forest Degradation) mechanism to protect its forests to help mitigate climate change, preserve its rich biodiversity, and support ecosystem services. In recent studies, we have examined the dynamics and spatial determinants of land change in India by integrating decadal land cover maps (1985-1995-2005) from a wall-to-wall analysis of Landsat images with spatiotemporal socioeconomic database for ~630,000 villages in

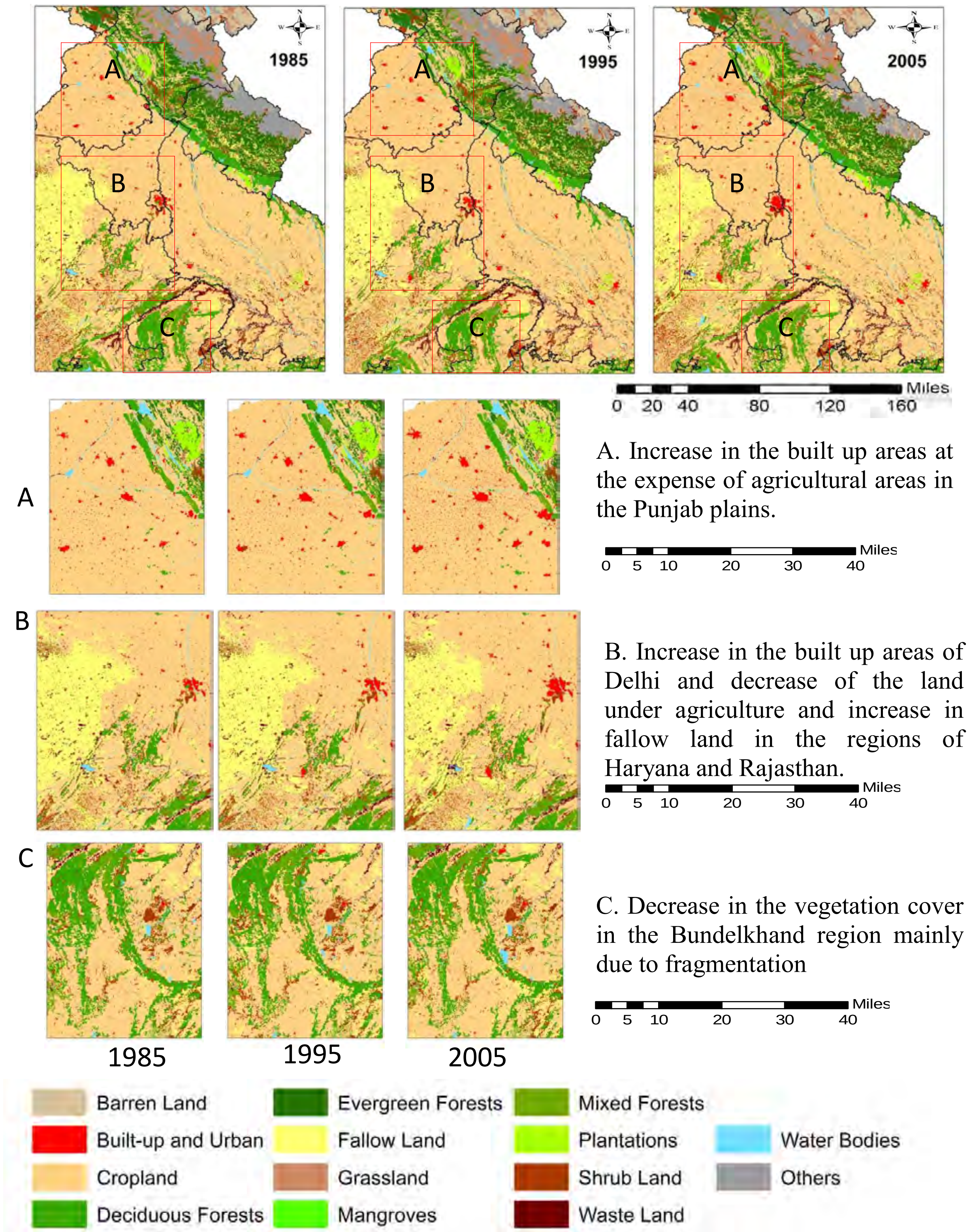

Figure 7. Land cover and land use changes in north western India over two decades (1985–2005).

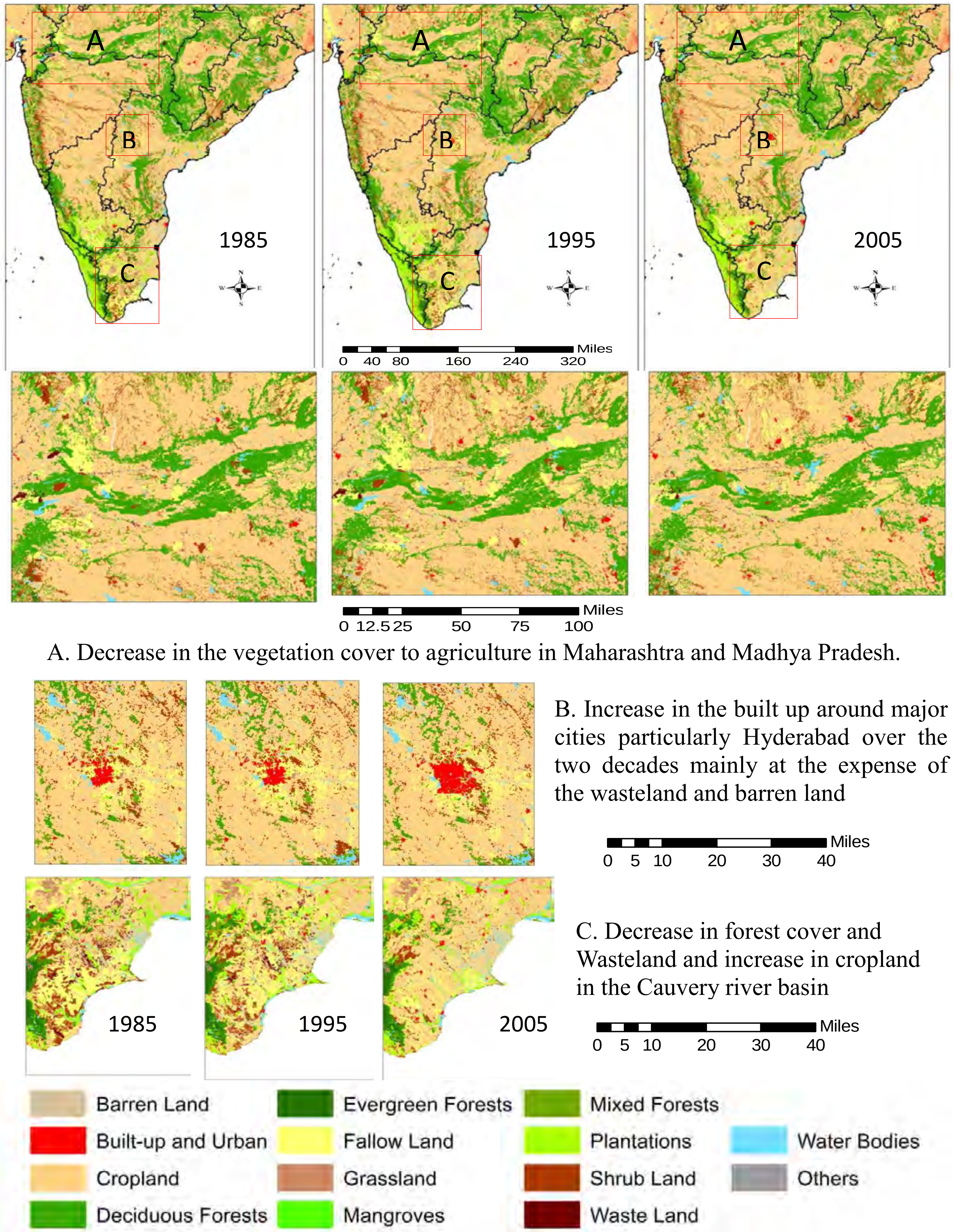

Figure 8: Land use and land cover changes in south India over the two decades (1985–2005).

India. As a starting point, we used the comprehensive satellite data, ground truth surveys, supplementary information and toposheets to prepare the 2005 LCLU map (Figure 6), which was subsequently used as a reference to prepare 1995 and 1985 LCLU maps.

Our analysis shows that the LCLUC in India has undergone important changes between 1985 and 2005 (Figures 7 and 8). The total area that has changed during 1985–2005 is 0.10% of the total geographic area of the country (~340,932 km^2). During this period, there has been a continuous decrease in land cover in the form of forests with concomitant increase in cropland and built-up area. Between 1985 and 2005, of the 11 major LULC classes, a considerable increase has been recorded in agriculture (47.55%–49.34%) and built-up areas (1.03%–1.44%), whereas significant decrease was noticed for forests (23.25%–22.18%), and wastelands (2.57%–2.27%). Within different forest classes, areas under mixed forest, savannah/woodlands/scattered trees, and mangroves have shown marginal increase.

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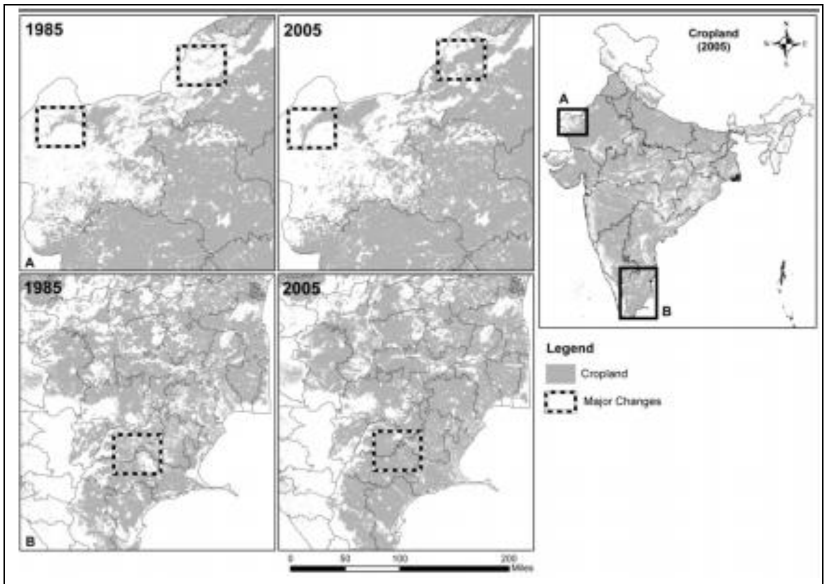


Figure 9: Increase in crop land during 1985 to 2005 in western India and east coast of south India.

There has been a progressive expansion in agricultural cropland and intensification with management inputs (Figure 9). The irrigation projects have contributed to the intensification of agriculture to meet the local and global market demands with more focus on cash crop cultivation. The present study reports considerable decrease in cropland area in 1985 due to deficit in rainfall during 1984–1986 compared to 1995 and 2005 (Table 2). During 1995 and 2005, there has been an increase in the crop area due to high number of good monsoon years showing high correlation between cropping area and annual precipitation; thereby, confirming the monsoon-dependent agriculture system in the country.

Another substantial change in the land use over the decade is the steady increase in built-up area of about 13,219 km^2 at the expense of the agricultural land. The built-up area has increased by 6000–7000 km^2 in each decade of the study period. The geographical built-up area has increased from1.03% in 1985 to 1.22% in 1995 and then to 1.44% in 2005. The changes between 1995 and 2005 are more prominent than the period between 1985 and 1995 as seen in Table 2. The increase in built-up area between 1995 and 2005 is more prominently observed in the north-western plains and in the peninsular India.

Table 2: Overall extent of land use land cover classes in India over the years 1985, 1995 and 2005.

Land Use/Land Cover Classes	Area					
	km^2			%		
	1985	1995	2005	1985	1995	2005
Built-up and Urban	34,019	40,090	47,239	1.03	1.22	1.44
Cropland	1,558,712	1,556,346	1,614,921	47.55	47.45	49.34
Fallow land	252,073	266,671	221,136	7.68	8.13	6.77
Forest	764,143	745,173	729,262	23.25	22.67	22.18
-Deciduous broad leaf forest	264,071	241,647	224,101	8.03	7.35	6.82
-Deciduous needle leaf forest	53,358	53,130	56,583	1.62	1.62	1.62
-Evergreen broad leaf forest	187,749	185,083	178,646	5.71	5.63	5.43
-Evergreen needle leaf forest	20,314	20,077	19,346	0.62	0.61	0.59
-Mixed forest	150,163	149,523	147,284	4.57	4.55	4.48
-Mangrove	4120	4525	4579	0.13	0.14	0.14
-Savannah/woodlands/scattered Trees	84,368	91,188	98,723	2.57	2.77	3.01
Plantations	77,493	77,956	78,560	2.36	2.37	2.38
Shrub land	182,860	188,342	192,873	5.56	5.63	5.65
Grass land	54,553	56,604	61,595	1.66	1.62	1.66
Barren land	65,484	71,250	69,855	2.00	2.17	2.13
Waste land	84,414	78,649	74,355	2.57	2.40	2.27
Water bodies [1]	116,119	121,148	114,856	3.55	3.69	3.50
Others [2]	97,152	91,636	92,522	2.96	2.79	2.82

Notes: [1] Includes Aqua Culture, Water bodies, and Permanent Wetlands; [2] Includes Salt Pan, Snow and Ice.

Additionally, there was a steady decrease in forest area in both central India and parts of northeast India between 1985 and 2005. The areas under mangroves show a considerable increase during 1985–1995 and nominal increase during 1995–2005 due to various coastal protection legislations/ordinances formulated by the Government of India. A significant increase in plantation was noticed in the peninsular India and western Himalaya. It shows the success of state sponsored programs to meet the resource demand as well as to increase the green cover as per the national forest policy. These plantations are carried out in forest gaps, wastelands, and on agriculture fields under agro-forestry programs.

1.4. Indonesia

Indonesia covers the third largest tropical rainforest and also is the third largest emitter of greenhouse gases (USAID, 2010). About 85% of the greenhouse gases in Indonesia are a result of land use related activities- about 37% due to deforestation and 27% due to peat fires (National Council on Climate Change, 2010). Indonesia surpassed the deforestation rate in the Brazilian Amazon forest in 2012, marking it as the country with the highest deforestation rate (Wijeya et al., 2015). The causes of these high deforestation rates include conversion of forest to shrub/open land, agricultural land, oil palm and forest plantation, and mining (Wijeya et al. 2015).

From 1990 to 2012, Indonesia lost 18.3% (20.7 Mha) of its forests. Deforestation in Sumatra and Kalimantan contributed to 41.5% (8.6 Mha) and 37.5% (7.8 Mha) of total national deforestation (Wijaya et al., 2015). Indonesia experienced an average annual increase of 47,600 ha of primary forest cover loss, which is more than any other SSEA country's increase in annual forest cover loss (Margono et al., 2014). During 1990-2000, 48% (5.8 Mha) of forests were converted to shrub lands, whereas 15.6% (1.8 Mha) and 14.5% (1.7 Mha) of the forests were deforested, due to subsistence agriculture activities and for the expansion of estate crops especially, oil palm, and sometimes mixed with rubber plantations (Wijaya et al. 2015). In Kalimantan, for example, the conversion of degraded forest to shrub land is mostly due to extensive and severe fires occurred as a result of El Niño (1997-1998) (Gunarso et al. 2013).

Sumatera and Kalimantan currently produce about 50% of the oil palm plantations in the world and the government of Indonesia plans to expand the plantations on the Eastern side (Ramdani and Hino 2013). During the 1990-2000s, the oil palm plantations expanded to occupy 1.4 million ha (16% of the total provincial area) and during 2012, the plantations covered 1.6 million ha (20% of the total provincial area) (Ramdani and Hino 2013) (Figure 10).

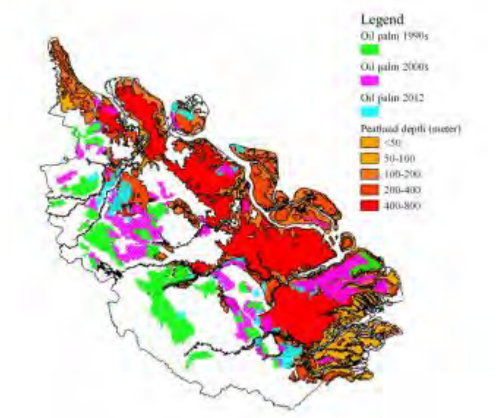


Figure 10:Development of oil palm on peat lands (Ramdani and Hino 2013)

About 52% (4.5 Mha) of forests were converted to shrub land and 16.5% (1.4 Mha) forests were deforested as open land from 2000-2012. Indonesia is one of the countries that has had major land changes due to oil plantations over the last two decades (Gunarso et al. 2013). It was noted that more than 50% of post-forest land use were shrubs or open land which were not immediately used for economic uses (Wijaya et al. 2015) (Figure 11). The overall trend in increasing wetland primary forest loss was greater than lowland primary forest cover loss. Of the annual increase in primary forest loss over the study period, 25,700 ha occurred in wetlands and 20,900 ha in adjacent dry lowlands (Margono et al. 2014).

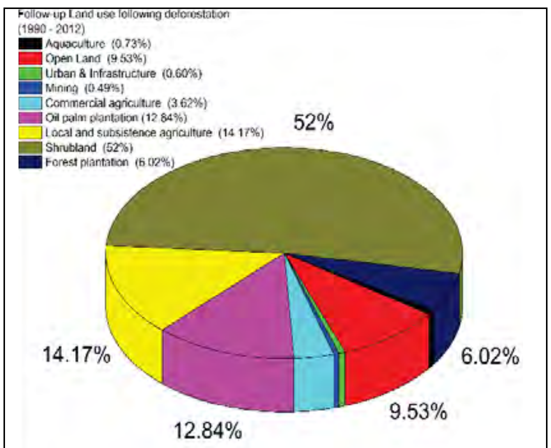


Figure 11: Land use following deforestation in Indonesia (Wijeya et al., 2015)

1.5. Nepal

In Nepal, various patterns have been observed as land use changes in terms of landscape and social changes (Uddin et al. 2014). Nepal has been divided in three physiographic regions: Mountains, Hills and Terai (UN-REDD 2014). It is further divided into districts and village development committees (VDCs). Forest is the most prevailing form of land cover contributing to 39.09% to the total geographical area (Uddin et al. 2014). Other land uses include agriculture (21%), non-cultivated land (7%), grassland (12%) and others (20%) (DFRS/FRISP, 1999).

The annual rate of forest area decrease is 2.7% and increase of shrub land is 12.7 % (CBS 2008). Consequently, it has a population of 26.5 million, with a growth rate of 1.35% per annum, according to 2011 Nepal census (Uddin et al. 2014). Nepal has set an example in implementing innovative forest conservation policies through community forestry programs over the years (KFC 2013). However, there is still a need for land cover and land use change research (Uddin et al. 2014). In 1978, the Government of Nepal (GoN) implemented a forest management technique that was community based. This initiative was promoted as a means to reduce the widespread deforestation and also to sustainably manage the forestry supplies used on a regular basis (KFC 2013). The study conducted by Uddin et al. (2014), covers the entire country (falls between latitudes 26°22'N to 30°27'N and longitudes 80°04'E to 88°12'E) to look at the land cover and land change. 39.1% of Nepal is under national forest cover. Table 3 shows the land cover statistics of Nepal (Uddin et al., 2014). Additionally, the study also noted that there is significant variability in terms of land cover within physiographic regions (Figure 12).

Land cover statistics of Nepal.

Class name	Area Km^2	%
Broadleaved closed forest	21,200	14.40
Broadleaved open forest	14,137	9.61
Needleleaved closed forest	13,934	9.47
Needleleaved open forest	8267	5.62
Shrubland	5008	3.40
Grassland	11,634	7.90
Agriculture area	43,910	29.83
Barren area	15,678	10.65
Lakes	45	0.03
Rivers	837	0.57
Snow/glaciers	12,062	8.20
Built-up area	469	0.32
Total	147,181	100.00

Table 3: Land cover statistical data for Nepal (Uddin et al., 2014)

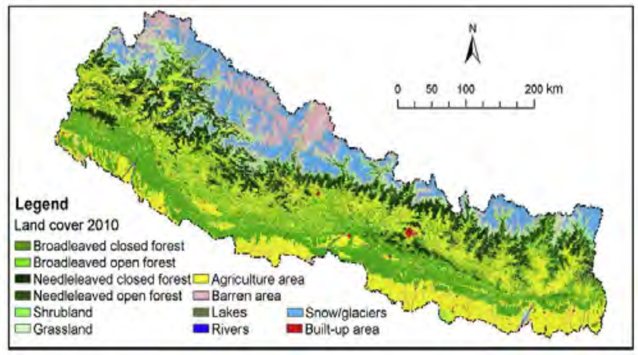


Figure 12: Land cover distribution in year 2010 (In collaboration with ICIMOD)

According to Table 4, it can be seen that the trends in forest areas decrease over the years (1964-1999). It should also be noted that between 1978/79 – 1999, the forest area is decreasing from 45.5% to 29% while the shrub land increased from 4.7% to 10.6% suggesting a conversion from forest to shrub land (UN-REDD 2014). Despite the trend observed above, there are studies that suggest that there was an increasing trend in the forested areas in the Hilly regions.

Table 4: Forest and shrub land coverage in Nepal (UN-REDD, 2014)

Report produced by:	Year	Forest		Shrubland		Total	
		000ha	%	000ha	%	000ha	%
Forest Survey and Research Office (FSRO)	1964	6402	45.5	-	-	6402	45.5
Land Resource Mapping Project (LRMP)	1978/79	5616	38.1	689	4.7	6285	42.8
Master Plan for the Forestry Sector (MPFS)	1985/86	5424	37.4	706	4.8	6210	42.2
National Forest Inventory (Department of Forest Research and Survey, DFRS)	1999	4268	29	1560	10.6	5828	39.6

Unlike the increasing deforestation trends usually observed over time, a study in Dolakha district of Nepal shows increasing trends of forest cover between 1990 and 2010. As seen in Figure 13, the forest area for all the three clusters in the study show increasing trend of forest cover between 1990 and 2010.

Of the 14.7 million hectares of total forest area in Nepal, communities manage 1.65 million hectares (DoF, 2012). In a study conducted by Mbaabu et al. (2014), the research estimated and compared above ground biomass and carbon stock between two types of forest management systems in Nepal: government-managed and community-managed.

Most recently ICIMOD carried out the study using uniform 30 m spatial resolution Landsat images with following objectives (Gillani et al., 2016): (1) Land cover maps for 1990, 2000 and

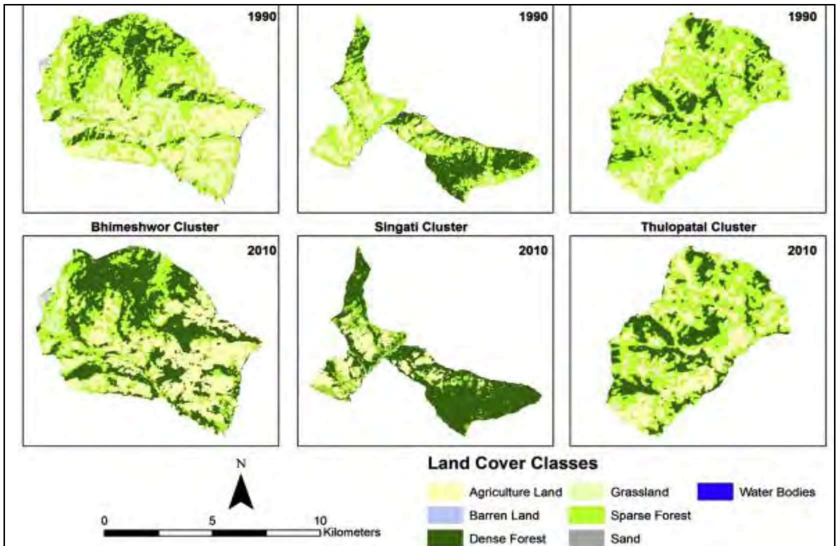


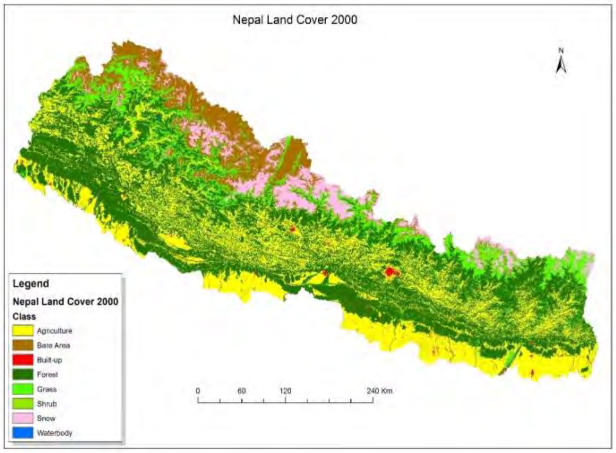
Figure 13: Land cover change analysis in three areas in Dolakha district (Mbaabu et al., 2014)

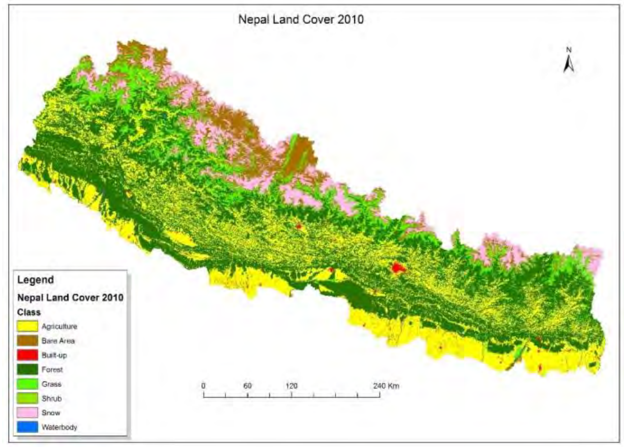
2010 using Landsat imagery (30 m); (2) Deforestation and afforestation at the national and sub-national levels, (3) Bivariate analysis – district level map: Deforestation (2000-2010) vs. Population (2011) and Afforestation (2000-2010) vs. Area covered by community forests (2011).

The study area covers the whole of Nepal (Figure 14). At the national level, eight land cover classes (forest, agriculture, grassland, shrub land, barren area, built-up area, waterbody and snow & glacier) were mapped and compared (Figure 14). The result shows forest is the dominant land cover in Nepal covering almost 40% of the total area in all the years 1990 (59,181 km^2), 2000 (57,714 km^2) and 2010 (57,538 km^2). From 1990 to 2000, the forest area has declined by 2%, i.e. by 1467 km^2 whereas, from 2000 to 2010 it has declined only by 0.12% i.e. 176 km^2. Other significant land cover classes are agriculture and barren land. Agriculture area covered 28% to nearly 30% of total area from the year 1990 (41,979 km^2), 2000 (43,562 km^2) to 2010 (43,910 km^2). The agriculture area continuously increasing by 1.08%, 0.23% from the year 1990 to 2000 and 2000 to 2010. Similarly, increasing trends 0.07%, 0.12% from the year 1990 to 2000 and 2000 to 2010 observed in shrubland class. Barren area covered 10% to 12% of total area from the years 1990 (14,751 km^2), 2000 (18,091 km^2) to 2010 (15,678 km^2). The grassland was also found to increased from the year 1990 to 2000 and decreased from the year 2000 to 2010.

1.6 Pakistan

In Pakistan, the current forest cover extent and deforestation rates are contentious among different stakeholders. According to the first comprehensive remote sensing based national land cover assessment, under the Forestry Sector Master Plan (FSMP), the forest area accounted as 3.59 million ha which is 4.1 % of total land area of Pakistan (GOP, 1992). Out of this 3.59 million ha, about 67% percent of forest area exist in the provinces of Khyber Pakhtunkhwa (1.49 million ha), the administrative region Gilgit-Baltistan (0.66 million ha) and the state of Azad Jammu and Kashmir (0.26 million ha) in the western Himalaya. Taking FSMP study as baseline the national forest and range resource study observed that annual deforestation in natural forests was 27,000 ha during 1990-2000 giving annual decline of 0.7%. The Global Forest Resource Assessment reported forest cover to be 2.5 million ha, 2.1 million ha and 1.7 million ha for year 1990, 2000 and 2010 respectively hence the forest cover change rate during the first decade was -1.6 % per annum and during the second decade was -2.0 % per annum (FAO, 2010). Similarly, the World Bank referred Pakistan's total forest cover as 2.2 % of the land area of the country in its reports (World Bank, 2010).





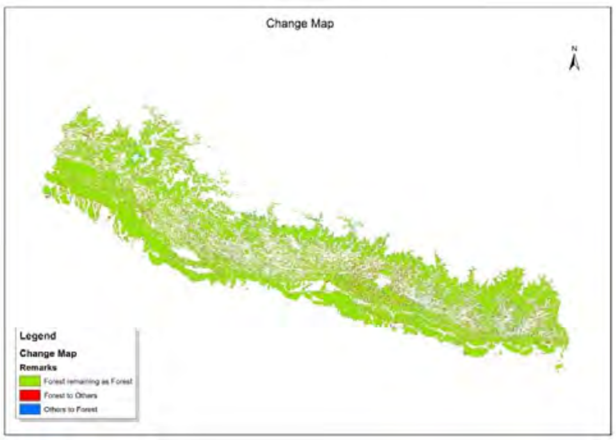


Figure 14: :Land cover classes (2000 and 2010) and land cover change map in Nepal

So, far there is not a systematic study of wall-to-wall mapping of land cover for the entire country. However, we have, in collaboration with Hammad Gilani from ICIMOD, Nepal, produce reliable large scale datasets on forest cover extent and change trends through wall to wall mapping of time series forest cover in the mountain region of western Himalaya, Pakistan (Figure 15). Here we discussed the preliminary findings of this study.

Geographically, the study area is extreme north of Pakistan lying between 31° 30′ - 37° 00′ Northing and 69° 00′ - 77° 30′ Easting in the extreme north of Pakistan. It comes under three administrative units including the Khyber Pakhtunkhwa (KP) province, the administrative unit Gilgit-Baltistan (GB) and the state of Azad Jammu and Kashmir (AJK). The total area covered in the study is approximately 18,260,000 ha (GB=6,900,000 KPK=10,170,000 and AJK=1,190,000) which is 23% of the total area of Pakistan sustaining approximately 67% of the total forest cover of Pakistan.

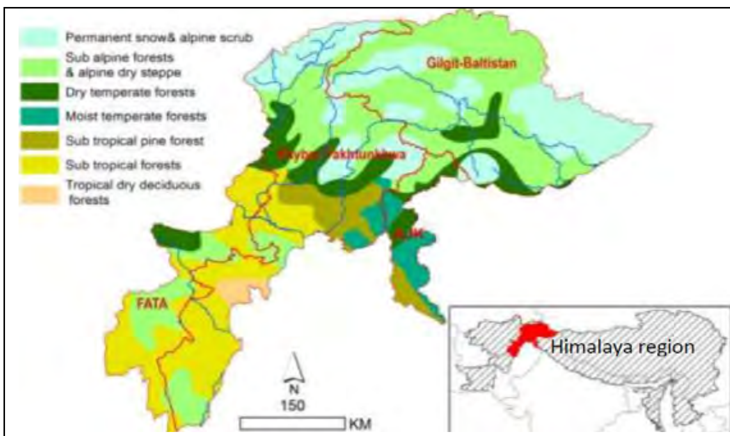


Figure 15: Study area and forest of the region

Land cover maps for three different years (1990, 2000, 2010) with 14 land cover classes were prepared for each three provinces. The land for the region was primarily classified 14 classes (Figure 16) including six forest cover classes (dense coniferous forest, sparse coniferous forest, dense mixed forest, sparse mixed forest, sparse broadleaved forest) and five non-forest cover classes (grassland/shrubs, alpine grassland, agriculture, bare soil/rocks, snow/glaciers/ice, water bodies). Transition from forest to non-forest was taken as deforestation and dense forest to sparse forest was taken as degradation. Change in forest cover classes was quantified using the output layers of land cover for three different years (1990, 2000, and 2010). Changes other than forest were not extensively investigated due to limited available data.

According to recent land cover map, in general there is 12% forest, 36% rangelands (grasses, shrubs etc.), 12% agriculture area, 40% bare area and only 1% of the surface area is covered with water. However, this cover distribution is not uniform across the space (provinces and districts) as study area belongs ecological regions. Generally, the land cover distribution is in accordance with the ecoregions where extremely high altitude (~ >4500m) is dominated with snow/ice and bare rocks, in the high altitude between 3000m to 4500m is dominated with grasses/shrubs (Montane grasslands and shrubs land), mid altitude 2000m -3000m is dominated with temperate conifer and subtropical conifer forest, low altitude < 2000m has significantly high agriculture areas in comparison to other elevations (Figure 17).

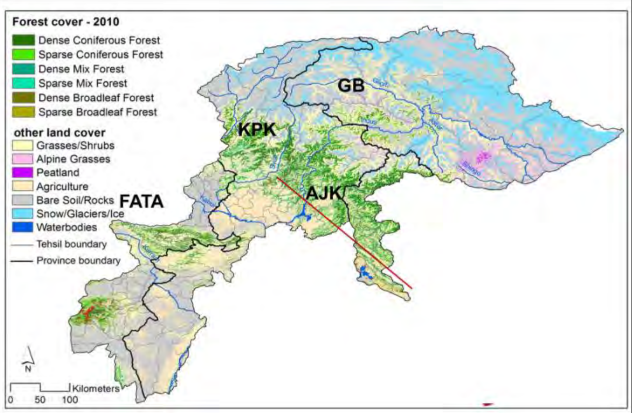


Figure 16: Landsat-based land cover types in Pakistan for year 2010.

There are high variations of forest cover distribution across the landscape. AJK has the highest forest cover percentage which mostly comes under the Himalayan moist temperate mix forest. The KPK province has the largest areas of forest cover. The GB has minimum forest cover area among all the administrative units of the study as large area.

In terms of comparison of deforestation during two time periods, a total forest loss of 74,613 ha was observed during 1990-2000 whereas 95,598 ha loss was observed during 2000-2010 which clearly shows an increase of deforestation during the second period.

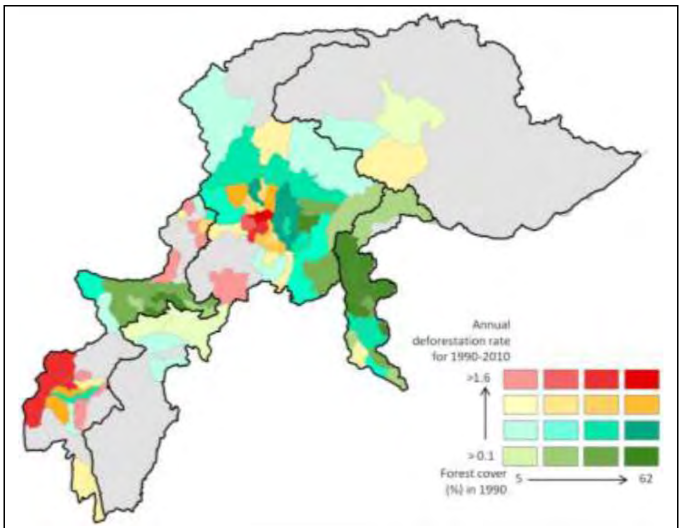


Figure 17: Bivariate map showing deforestation hot spots.

This deforestation can be linked to the security conflict in the area which started arising in 2001 and continued until recently. In some cases, the deforestation rate has decreased during the 2nd period of assessment which mainly includes North Waziristan, Upper Dir and Bajor. While looking at the inter-class changes, it is observed that the most of the deforested areas are transformed into grasses/shrubs and very small fraction of broadleaf forest areas has been changed into agriculture land. It is also evident that, thinning of dense forest (conversion of dense forest into sparse forest) is also high, along with complete destruction of forests.

2. Causes of Land Cover Conversions

We categorize causes of LCLUC into direct and underlying causes. Direct causes include urbanization, agricultural land expansion, commercial logging and conflict. Underlying causes of LCLUC are typically population pressure coupled with poverty.

2.1 Bangladesh

The major cause of deforestation in Bangladesh is due to agricultural expansion, principally through shifting cultivation in the hill forests. Rapid human population growth also has intensified pressure on forest resources throughout the country (see Figure 18 for the human population growth over the last two decades in Chittagong hilly area of Bangladesh). Forests are depleted by commercial timber exploitation and gradual conversion into pastures, and cultivated fields. Besides these, forest encroachment, extensive firewood collection, forest fires and illegal logging all contribute to deforestation in the country (BBS, 2010).

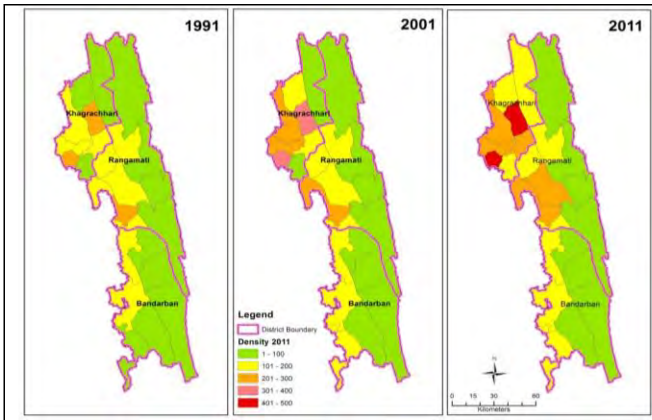


Figure 18: Map showing increasing population density over the years 1991, 2001 and 2011 in Southeastern Bangladesh (Courtsey: Hammad Gilani of ICIMOD, Nepal)

Moreover, existing forest policy in Bangladesh has a number of limitations. Most notable is that, although it vaguely commits to 'extend the scope of poverty alleviation and forest-based rural development', this policy excludes an implementation plan on how its goal will be achieved (ADB, 2004). Land tenure issues, social stratification, patronage, that influence in the sustainable forest management have not been addressed in the policy thus failed to motivate people who are involved in growing annual crops by slash-and-burn in large areas of the unprotected forest which does not require any investment in land (Rasul, 2005). In the Chittagong Hill Tracts of Bangladesh (Figure 18), shifting cultivation is the main farming system in the forest communities and the practice is intertwined within the sociocultural identity of the people (ADB, 2004). Historically, shifting cultivation practices included a fallow period between 15-20 years, to allow rejuvenation of soil fertility and forest regrowth. Although, government has assigned protected area (see PA Boundaries in Figure 3), however, due to failed policies forest area also reduces in these areas over the period 1989-2010.

2.2 Bhutan

Bhutan's low population and the general absence of overdevelopment contributed to its forest preservation. Because of terrain, more accessible forests had been overcut whereas remote forests remained largely in their natural state through the early 1990s. Progressive government-sponsored forestry conservation policies help manage its forest land. By 1989, Bhutan had developed nine other forest and wildlife preserves, also mostly along the southern border with India. In the face of increasing denuded hillsides, private logging was banned in Bhutan. One of the immediate results of forestry sector regulation, however, was a sharp decrease in revenues since the late 1970s. In 1991, the government, with assistance from UNDP and the World

Wildlife Fund (WWF), established a trust fund for environmental conservation aimed at producing up to US$1 million per year for training in forestry and ecology, surveying forests, reviewing and implementing management plans for protected areas, and supporting government environmental offices, public awareness programs, and integrated conservation and development programs. Currently, domestic timber harvesting remains legal though subject to strict regulation and inspection.

There are about 35.1 million people representing 24% of the total population living in coastal areas. Agricultural development in the coastal area is a challenge due to its poor soil fertility, heavy soil texture, short winter season and poor polder management. Due to these challenging conditions, many farmers have switched over to salt farms and/or shrimp culture from traditional agriculture (Redowan et al., 2014)

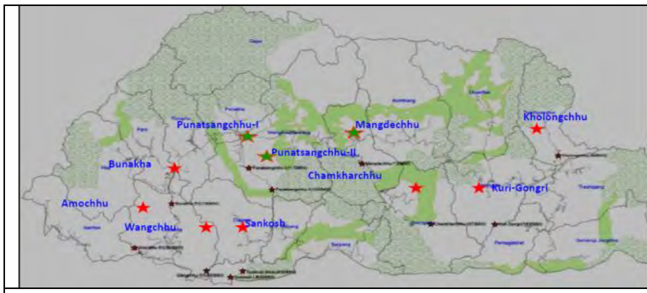


Figure 19: Projects under 10,000 MW development initiative in Bhutan (Courtesy: Lobjang Dorji of Bhutan Forest Services)

Bhutan faces challenges in its urban environments due to increased urbanization, industrialization, and economic development. Through 2011, many relatively urban areas lacked designated landfills and effective waste disposal systems, prompting residents to burn garbage, dump it, or simply dumping it nearby ground. In 2012, unsound disposal of waste reached 52% of generated waste.

In the late 2000s, Thimphu experienced steady growth despite water shortages. Areas downstream from Thimphu along the Wangchu River deteriorated significantly because of human waste and refuse. During November of 2011, in an effort to combat downstream degradation, waste outlets were converted into collection chambers, and refuse collection programs were instituted in the area.

Bhutan plans to exploit the vast potential of its high peaks and running rivers promise to transform it from an isolated backwater into one of the world's fastest growing economies. It aims to install 10,000 MW of hydropower by 2020 (Figure 19), 80% of which will be sold to India. So far it has exploited only 5% of its potential, but the long-term plan envisages 74 dams in cascades across the country.

2.3 India

We have investigated the spatial determinants of three broad LCLUC that are central to land use planning in India: cropland-fallow land conversions, forest area losses, and forest area gains (Meiyappan et al., 2016). We quantify the (spatial) determinants by estimating spatial logistic regressions between land-cover conversion estimates and hypothesized socioeconomic and biophysical factors grounded through local case studies. We estimate regression models specific to land-cover conversion, at both national scale and for sub-national hotspots. We evaluate and reinforce our regression results through collective evidence from synthesis of 102 case studies (Figure 20) that incorporate field knowledge of the causes of LCLUC mainly through social surveys and local expertise.

Our synthesis indicates that the three LCLUC (cropland fallow land conversions; forest area losses; and, forest area gains) are driven by different combinations of factors. It indicates that fallow land is mainly associated with: labor shortage (migration driven by new income opportunities), lack of infrastructure (irrigation and electricity) and access to capital, and cropland fragmentation (smaller average farm size). Reclamation of fallow land depends mainly on critical support services (e.g. access to markets and capital), level of education (knowledge to reclaim land), and village infrastructure (mainly irrigation). Illegal forest encroachment (for cropland expansion due to low productivity), wood extraction for subsistence, industrial exploitation, and cattle overgrazing, are common causes of forest loss. Unlike cropland fragmentation that drives fallow land, no case studies suggested that forest fragmentation drives forest loss. Regarding forest area gains, only three case-studies were designed to consider passive forces (regrowth following land abandonment), with other studies focusing on factors that influence the effectiveness of participatory forest management programs (e.g. Joint Forest Management). The prominent socioeconomic factors of forest area gain identified from our regression analysis are echoed in our synthesis (involvement of local community, education/awareness, and effective forest protection).

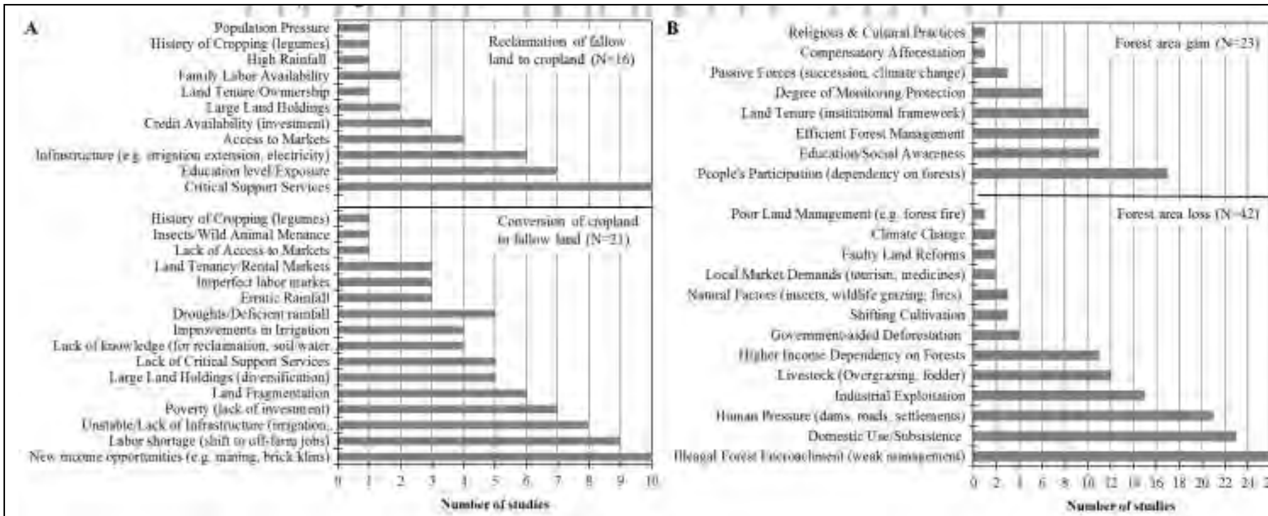


Figure 20: Frequency distribution of the causal factors identified from the synthesis of 102 case studies. (A) Conversions from cropland to fallow land and vice-versa, and (B) forest area losses and gains.

During the post liberalization period, a wide-spread spatial changes in main male agricultural (wage) laborers and male marginal cultivators (main + marginal), primarily driven by urbanization and better income opportunities (relatively less strenuous and more stable non-agricultural jobs) was observed. During 1995- 2005, we find areas converted from cropland to fallow land had substantially lower male main agricultural labor and total (main + marginal) male marginal cultivators (semi-arid hotspots) compared to counterfactual buffer villages. These results imply that availability of labor is an emerging factor in determining fallow land. We also find positive association between fallow land and proportion of main female cultivators, indicating gender-biased labor markets.

Causal factors uncommon at national scale can be most important regionally. For example, both our study and the synthesis literature report wood extraction for construction materials as a main determinant of forest loss. Some factors can also behave differently in individual cases. For example, different case studies show opposing effects on how education affects fallow land. Education (proxies: literate population, availability of educational facilities) causes a shift to off-farm jobs, thus increasing fallow land. In contrast, with education, farmers perceive higher returns to investment on land, invest more on resource conservation, and have better access to information leading to fuller land utilization. Such heterogeneity is concurrent and important to recognize; in such cases, our statistical analysis covering the entire region helps identify the dominant effect.

Wastelands have already been consistently reclaimed to cropland, with support from both public and private initiatives e.g. through building Indira Gandhi Canal and Integrated Wasteland Development Programs. Concurrently, farmers have fallowed much larger areas of existing cropland, representing an undesired tradeoff to wasteland reclamation.

Cropland expansion into forest was observed to occur in areas of low agricultural productivity. Therefore, improvements in agriculture sector can itself help reduce the pressure on forests. A compounding issue is our results show prominent positive association between forest loss and the economic dependence of village communities on forests across many regions. Currently, ~173,000 villages in India depend on forest for subsistence due to lack of alternative economic opportunities. The on-going and future planned privatization of afforestation programs in India tends to maximize corporate profits, with little space for community involvement.

Additionally, India recorded a positive trend in gross forest area gain over time. The gross forest area gains in 1995-2005 were 24% higher than the preceding decade, compensating for the increased gross forest area loss during 1995-2005 (Figure 21). Reversion of cropland and shrub land together explain 65% (1985-1995) and 78% (1995-2005) of gross forest area gain. gross forest area gains were positively associated with state administrative divisions, mined-out areas, density of forestry workers, and density of community workers. The identified state administrative divisions typically have larger amount of forest inundated to water bodies (irrigation projects), and forest diverted to built-up land (e.g. roads, industries). Both state administrative divisions and greening of mined-out areas indicate compensatory afforestation by respective state governments to partly compensate for forest loss.

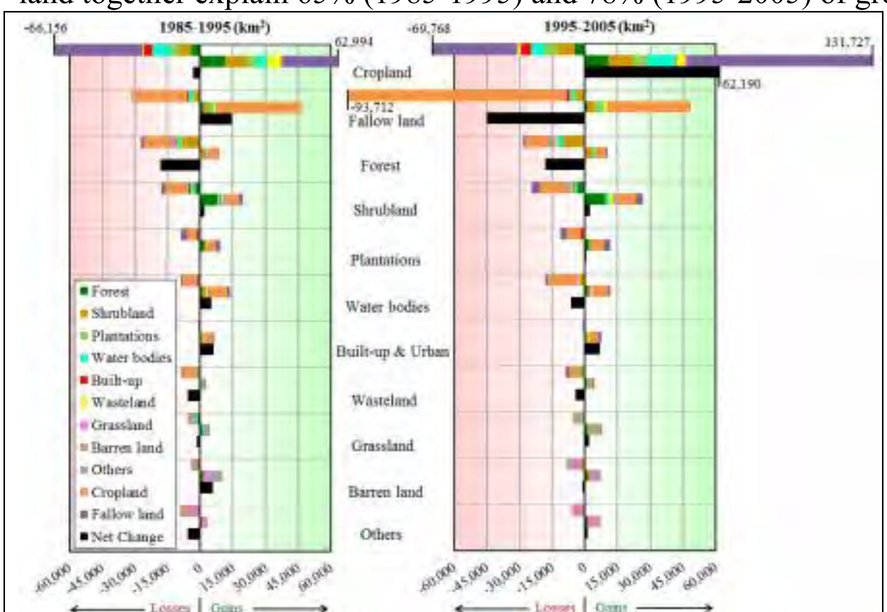


Figure 21: Gross gains, gross losses, and net changes in land use and land cover areas at aggregate national scale for the two decades (km^2/decade): 1985-1995 and 1995-2005. Aqua culture and permanent wetlands is included within "Water bodies". "Others" category include Salt Pan, Snow and Ice.

The forestry workers are employed by forest department, and are a proxy for level of protection and control. These workers are typically involved in forest maintenance, wildlife protection, fire observations, and interface with tourism, among others. Community workers help with restoration efforts (e.g. greening firewood and fodder) by involving forest department and local communities.

2.4 Indonesia

Even though Indonesia recently implemented a deforestation moratorium in 2011, it has not been as effective as it was intended to be and most of the increasing primary forest loss was found in production forests (Margono et al. 2014).

This alarming rate of land conversion in Indonesia brings attention toward improvements in land and forest governance (Toumbourou 2014). Unclear land tenure, influences on policy making and regulations, ineffective land use planning are some of the drivers which are further increasing the deforestation rates (Toumbourou 2014). Several policies and laws are introduced through the government in order to reduce deforestation. However, these laws have not been implemented effectively. An important concern is the presence of illegal logging activities in protected or conserved areas (Pagiola, 2000). United Nations Environment Programme (UNEP) estimates that Indonesia loses US$ 3 million revenues due to illegal logging (UNEP, 2007).

The increasing rate of forest degradation was caused due to illegal logging activities during 1990-2010 within protection and conservation forests compared to other forest land uses (Margono et al. 2012). Figure 22 depicts the changes in the Sumatra region for the years: 1990, 2000, 2005 and 2010. It can be observed that the eastern side of the region lost most of its intact primary forest, major changes can be seen from 1990-2000. The total forest loss from 1990-2000 was 7.54 Mha and considering the degradation during 2010, about 35.7% of the primary forest in 1990 was lost. According to the study conducted by Margono et al. (2012), the first decade of analysis (1990–2000) contributed 72% of forest loss and 83% of forest degradation in Indonesia. For the second half of the study, the rate of loss of forest was half of that during the first decade. Additionally, the primary degraded forest areas are also decreasing over the time period. The fact Indonesia had the highest rate of deforestation in 2012 brings into question the potential effectiveness of the government mandated restrictions such as the moratorium (Margono et al. 2012).

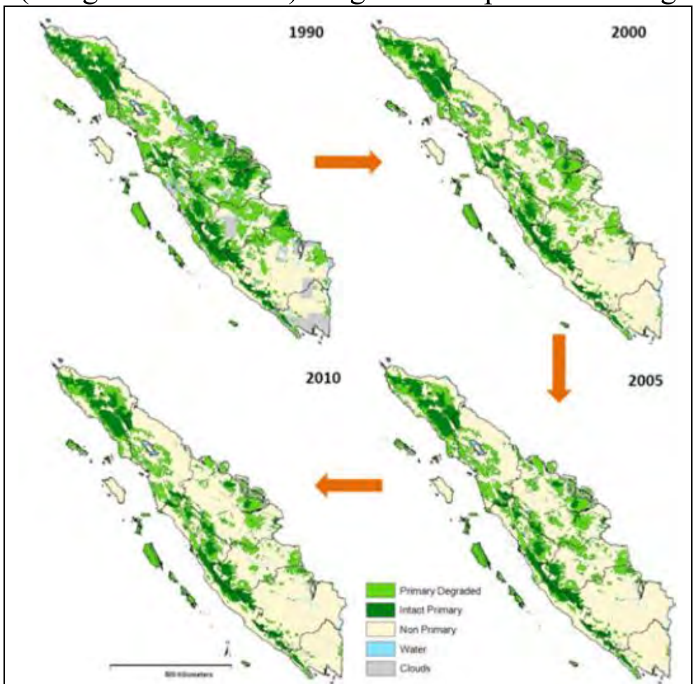


Figure 22: Sumatra Primary forest extent and change for the years: 1990, 2000, 2005 and 2010.

It is predicted that the natural forest resources may be depleted by the 2020s according to current increasing trends of deforestation (Shimamoto et al. 2004). In addition, even with legislation in Indonesia, the issue of deforestation persists. In the beginning of 2011, the Governments of Indonesia and Norway established a memorandum of understanding with a commitment of US$ 1 billion (The REDD desk 2016). Indonesia implemented a deforestation moratorium as a part of this commitment however the following year it experienced the highest rates of lowland as well as wetland primary forest loss (Margono et al. 2014). There are efforts being made to improve national forest extent and its change due to deforestation and degradation of forest by the Ministry of Forestry and the Indonesia Space Agency as a part of the Indonesia National Carbon Accounting System, although no national scale products have been publicly available yet (Margono et al. 2012). In analyzing forest cover through satellite imagery, cloud cover is often a major problem especially because Indonesia does not have a seasonally cloud-free window Margono et al. 2012). The land markets of Indonesia are considered to be poorly managed as a result of weak land administration, burdensome formal land- development process and corruption (USAID 2010). Similarly, some studies suggest that the growing oil plant productions are one of the primary reasons of higher deforestation rates however some studies have found that these oil palm plantations are instead taking place such as logged forest, shrub land, and rubber agroforest (Tarigana et al., 2015). Again, the region of focus can make a difference in determining what the driving cause of deforestation is. It is therefore necessary to point out what are the major causes of forest conversion throughout the country in the last two decades and predict its further implications if the same trend carries on.

2.5 Nepal

According to Niraula et al. (2013), the top five factors drivers of deforestation and forest degradation in Nepal were agricultural expansion, wood extraction (commercial and household), road and infrastructure construction, wild fires and grazing, and natural conditions and calamities.

Around 84% of the households in Nepal use fuel wood on a day to day basis (CBS, 2011) of which forests provide over 80% of the supply (WECS, 2010). The primary source of livelihoods is land and 76% or more homes are involved in agricultural activities (CBS 2012). In addition, there has been an increasing demand for forest land and resources. A projection of future projections for timber demand and supply is given in Table 5 (UN-REDD 2014) as population trends are increasing and the demand for more resources are most likely to rise. Also, road construction, especially along forest areas and tracts, pose a threat as it eases the access to forest resources ultimately leading to degradation and deforestation of the forest area.

Table 5: Future projections for timber demand and supply in Nepal (given in million m^3) (UN-REDD 2014)

Year	2011		2020		2030	
Ecological region	Demand	Supply	Demand	Supply	Demand	Supply
Terai	1.46	1.15	1.67	1.53	2.23	2.13
Hills	1.72	1.81	1.87	2.32	2.33	3.2
Mountain	0.19	0.22	0.21	0.27	0.25	0.35
Total	3.37	3.18	3.75	4.12	4.81	5.68

Similarly, Jacquet et al. (2015) conducted a tudy to look at land egradation and land bandonment due to the n-going outmigration :end and land ıanagement practices in a sub-watershed area Kaski District. There is an increasing trend of people, mostly young men, migrating to urban areas or abroad in search of labour. Most families then migrate downstream to easily access facilities. As a result, land cover changes due to problems such as spread of invasive species (Jacquet et al. 2015). On the other hand, the downstream areas face pressures of population increase which leads to intensive land use, reduction of vegetation cover, riverbank erosion and so forth (Jacquet et al. 2015).

The increase in forest areas in the hilly region of Nepal can be explained by the study conducted by Niraula et al. (2013). It reflects the success of community-based forest management in the mid-hills of Nepal despite a high population growth rate of 2.3% per year from 1990 to 2010. The forest has been restored at a rate of about 2% per year. Community based forest management resulted in sustainable and efficient use of forest resources, an increase in tree plantation, and a decrease in use of slash-and burn agricultural practices and forest fires (Niraula et al. 2013). Another factor that may have had an influence on the land cover is migration to urban areas during the decade long political conflict from 1996-2006 (Niraula et al. 2013).

2.6 Pakistan

According to Pellegrini (2007), deforestation in the northern Pakistan is taking place mainly because of institutional failure and there is a need to implement proper forest management rules. According to Khan (2009), historical analysis complemented with satellite images, highlights the role of resource rights in forest protection. While considering ongoing fuel wood demand (Häusler et al., 2000) observed that the forest in the region will cease to exist in 2027. Supplies from plantation, agricultural and range-lands will only cover 21 % of the total demand at this point in time and an uncovered demand/supply gap of 8.8 million m^3 in 2027 will continue to grow to 13.6 million m^3 in 2050 of which again only 21 % can be covered by local woody bio-mass supplies. With the increase in timber demand, decrease in agriculture areas and shrinkage of land holding the local people may also see small scale tree cutting as income generation activity [Fischer et al., 2010]. Shaheen et al. (2011) observed immense deforestation due to excessive fuel-wood consumption in the Bagh district of Azad Jammu and Kashmir. The losses due to Himalaya's degradation are not confined to the region itself but also badly affect the environment and economy of the adjoining plains of Indus basin through the disturbances in the hydrological cycle and contributing in soil erosion, siltation, floods and desertification. The incidence of floods in the Indus river system has been more severe and more frequent in the past 25 years than during the previous 65 years, mainly owing to increased surface runoff and accelerated erosion in the Himalayan mountains (TSRHR 1987).

According to Pakistan Water Strategy, the country needs to raise water storage of 18-million-acre foot by 2050 where 30 percent of this is only for replacement of storage loss due to siltation. The current study is first systematic effort for wall to wall forest cover mapping and deforestation assessment of 60% of the forest areas of Pakistan. Results from this study provide important insight to the deforestation patterns which can facilitate in developing appropriate forest conservation and management strategies in the country. Careful analysis of this variation may provide insights into land-change dynamics, both causes and consequences and identification of deforestation of hotspots. Moreover, these statistics are available at the local administrative units, which can provide the basis for regular monitoring of deforestation in the area.

3. Synthesis of the Terrestrial Ecosystem Model Results for LCLUC CO_2 Emissions

It is widely acknowledged that a key uncertainty in LCLUC emissions stems from uncertainties in estimating historical changes in areal coverage between forests, croplands and grassland, though the uncertainties have narrowed with time mainly due to improved data from satellites and inventories. Further uncertainty stems from incomplete understanding of all the processes affecting the net flux of carbon from LCLUC, different approaches adopted to calculate emissions, and data related uncertainties. In this task we have synthesized the state-of-the-art understanding of the contribution of LCLUC to anthropogenic emissions of CO_2, with specific references to the SSEA. The specific objectives of this study are: (1) to estimate the terrestrial carbon Net Biome Productivity (NBP= Net Ecosystem Production (NEP) – Land Use Change Emission (E_{LUC}) – Fire Emissions due to non-LUC activities (E_{FIRE})) and its components (NEP, E_{LUC}, E_{FIRE}) for SSEA and that for each contributing country (Bangladesh, Bhutan, Brunei, Cambodia, India, Indonesia, Laos, Malaysia, Myanmar, Nepal, Pakistan, Philippines, Singapore, Sri Lanka, Thailand, and Vietnam) within SSEA for the period 2000-2013; and (2) compare the terrestrial carbon budget (in terms of NBP) of SSEA and the countries within SSEA to the fossil fuel emissions. We use multiple data products; including fossil fuel inventory data, and remote sensing data products for fire emissions; and the results of dynamic global vegetation models (DGVM) (or bottom-up models), atmospheric inversion models (or top-down models) and book-keeping model to estimate the carbon fluxes and terrestrial carbon budget for SSEA and each country within SSEA.

3.1 Methods

We use multiple data products; including fossil fuel inventory data, and remote sensing data products for fire emissions; and the ensemble of 9 different dynamic global vegetation models (DGVM) (or bottom-up models) results, ensemble of 5 atmospheric inversion model (or top-down models) results, and a bookkeeping model result to estimate the carbon fluxes, particularly the flux related to LCLUC and terrestrial carbon budget.

The 9 DGVMs (or bottom up models) are: CLM4.5 (Oleson et al., 2013), ISAM (Jain et al., 2013), JULES (Clark et al., 2011), LPJ (Sitch et al., 2003), LPJ_GUESS (Ahlström et al., 2012) , LPX (Stocker et al., 2014), ORCHIDEE (Krinner et al., 2005), VEGAS (Zeng et al., 2005) and VISIT (Ito et al., 2012). These models used the protocol as described by the carbon cycle model intercomparison project (TRENDY) (Sitch et al., 2015).

The E_{LUC} term already accounts for fire emission due to LULCC activities, such as deforestation. In order to account for fire emissions due to non-LULCC activities (E_{FIRE}), such as lightning induced fires, we obtained carbon emissions from fires from the Global Fire Emissions Database version 4.1, which includes small fire burned area (GFED4s) (van der Werf et al.,2010).

In order to compare DGVM models estimated NBP for the 2000-2013 period, which uses bottom up modeling approach, we used NBP estimates based on the following 5 atmospheric inversions (or top-down models): ACTM (Patra et al., 2011), CCAM (Rayner et al., 2008), GELCA (Ganshin et al., 2012), JMA_CDTM (Sasaki et al., 2003), and CarbonTracker-Europe (Peters et al., 2007). In addition, country specific LCLUC emissions estimated based on DGVMs are compared with a bookkeeping method (Houghton, 2010).

3.2 Results

3.2.1 NEP

The DGVM model results suggest that NEP for SSEA increased from a sink of 414 TgC yr^{-1} in the 1980s to 489 TgC yr^{-1} and 542 TgC yr^{-1} in the 1990s, and the 2000s, respectively, and had a 1980-2013 absolute growth rate of 5.8 TgC yr^{-1} (Figures 23). The increase in NEP over the period 1980-2013 has mainly been attributed to the carbon dioxide fertilization effect due to the incremental increase in atmospheric carbon dioxide concentrations. All countries had positive absolute growth rates (increasing sink; decreasing source) except Bangladesh, Bhutan, and Nepal. Bangladesh had the least absolute growth rate (-0.04 TgC yr^{-1}) and the Indonesia had the greatest normalized growth rate (3 TgC yr^{-1}).

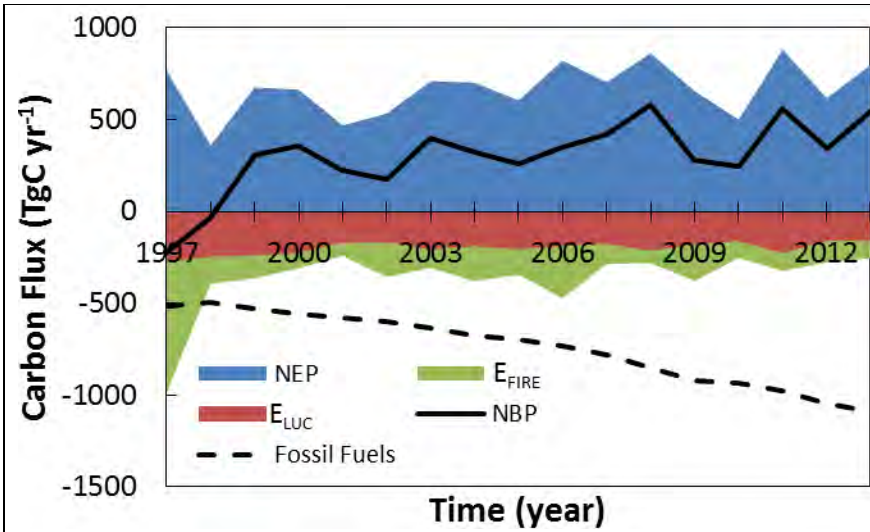


Figure 23: Cumulative components of the terrestrial carbon budget (NEP, E_{LUC}, E_{FIRE}) NBP, and fossil fuels for the period 1997-2013. Positive values are a land sink of carbon and negative values are emissions to the atmosphere. Net ecosystem productivity (NEP; dark blue) and land use change emissions (E_{LUC}; red) are the average of TRENDY models estimates. Fire emission estimates due to non-land use change activities (E_{FIRE}; green) are from the Global Fire Emissions Database version 4 (van der Werf et al.,2010). Net biome productivity (NBP; solid line) is the difference between emissions from the land sink, NEP, and the land sources, E_{LUC}, and E_{FIRE}. Fossil fuel emission (dashed line) is sourced from the Carbon Dioxide Information Analyses Center (CDIAC) database.

3.2.2 LCLUC Emissions

The DGVM models estimate land use change emissions (E_{LUC}) for SSEA were a net source in the 1980s, 1990s, and 2000s with mean annual emissions of 199 TgC yr^{-1}, 304 TgC yr^{-1}, and 244 TgC yr^{-1}, respectively. Every country, except Indonesia and Sri Lanka, had lower carbon emissions in the 2000s than in the 1990s (Figure 24). In all three decades, Indonesia had the highest emissions with increasing trend and the emissions contributed to 32%, 30%, and 39% of the total SSEA emissions for the 1980s, 1990s, and 2000s, respectively. Malaysia had the second largest emissions due to land use change in the 1980s (24 PgC yr^{-1}, 12%) and 2000s (14 PgC yr^{-1}, 6%) (Figure 24). In the 1990s, India had the second greatest emissions (32 PgC yr^{-1}, 10%). However, India experienced the greatest decrease in emissions (26 TgC yr^{-1}, 80%), whereas Indonesia experienced greatest increase in emissions (3 TgC yr^{-1}, 4%) between the 1990s and 2000s.

Indonesian and Malaysian deforestation is primarily due to logging and the expansion of oil palm plantations (Wicke et al., 2011; FAO, 2010). From 1980 to 2013, 11 Mha, 6% of Indonesia's total land area, had been converted from forest to cropland (Klein Goldewijk et al, 2011). In contrast, in India reforestation/afforestation policies practiced by India's Ministry of the Environment and Forests in the 2000s have decelerated the rate of deforestation (Reddy et al., 2015). On the regional scale, deforestation (due to conversion of forest to cropland and pasturelands) was the major driving factor of LULCC emission over the last three decades. The deforestation rates for SSEA region in the 1980s, 1990s, and 2000s were 1.25 Mha^{-1}, 0.93 Mha^{-1}, and 0.82 Mha^{-1}. Part of the deforestation effect is compensated by the forest regrowth in the regions which were the greatest in the 1980s (0.36 Mha yr^{-1}) (Figure 25) mitigating part of the carbon emissions associated deforestation. Likewise, the 2000s had a forest regrowth of 0.16 Mha yr^{-1} with a majority (81%) of regrowth due to the abandonment of cropland.

The LULCC estimates from the bookkeeping method for the 2000s are within the uncertainty range of the DGVM models for SSEA and 11 of 14 countries (Figure 25). Additionally, the book keeping model results are consistent with TRENDY with respect to the decadal trend for SSEA – an increase from the 1980s to the 1990s followed by a decrease from the 1990s to the 2000s. Differences may be due to different land use and land use change inputs and different modeling approaches.

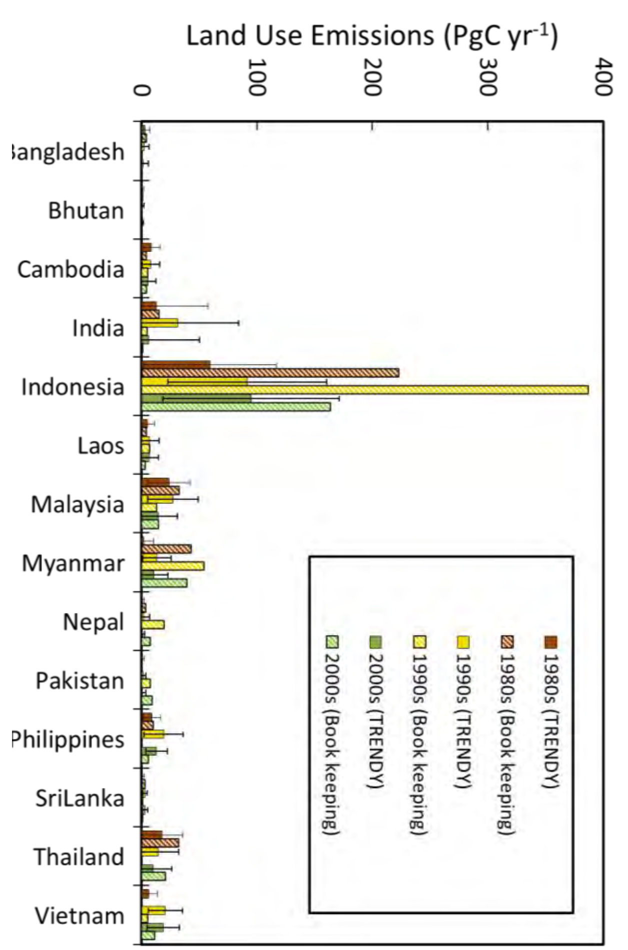


Figure 24: Decadal carbon emissions due to land cover and land use change for the countries of SSEA during the 1980s, 1990s, and 2000s estimated by the average of the DGVM models (solid) and the book keeping method (hashed). Error bars represent the 1σ of the DGVM models.

3.2.3. NBP

Figures 26 and 27 show the 2000-2013 estimates of NBP and its components, including NEP, carbon emissions from LCLUC, emissions due to non-LCLUC related fire, and emissions due to fossil fuel burning for SSEA and individual countries, respectively. The DGVM models estimated NBP for SSEA was 227 ± 279 TgC yr^{-1} (1-σ standard deviation of the 9 TRENDY models). The atmospheric inversion models estimated SSEA had an NBP of 24 ± 49 TgC yr^{-1}. The DGVM models average and atmospheric inversion models both suggest the terrestrial biosphere acted as a net sink for the period 2000-2013, but the sink estimated with the DGVM models is about seven times the estimate from the inverse model results. However, the atmospheric inversion estimate was within one standard deviation of the DGVM models. Possibly discrepancies between the two strategies may be the low resolution of the inversion models, and the lack of CO_2 observations in South Asia.

Our assessment of the terrestrial carbon budget and fossil fuel emissions for SSEA and its countries provides insight into the trends and fluxes of NBP, its components. Additionally, our use of fossil fuel emissions data allows us to make quantitative comparisons between the terrestrial net carbon flux (NBP) to the emission from fossil fuel burning. NBP of SSEA region

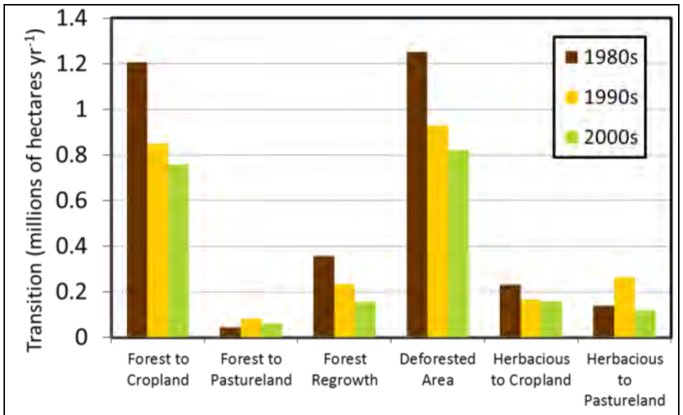


Figure 25: Decadal average rate of conversions of land in South and Southeast Asia (SSEA).

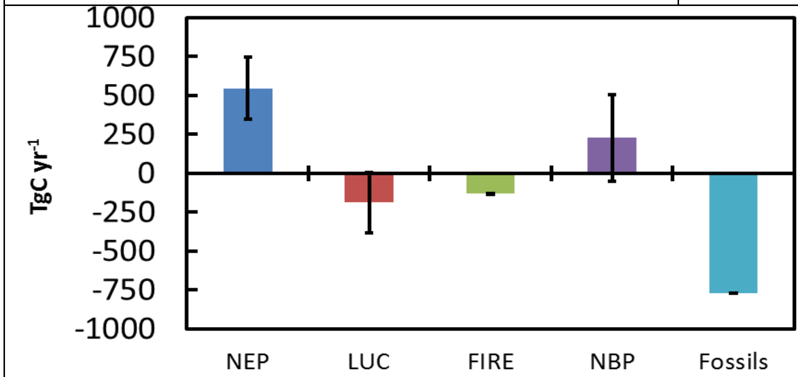


Figure 26: Mean carbon fluxes for the period 2000-2013. Error bars represent the first standard deviation of the model results. Fire emissions are from Global Fire Emissions Database version 4s (van der Werf et al., 2010) and fossil fuel emissions are from the Carbon Dioxide Information Analysis Center (CDIAC) database. NEP, LUC, and NBP are estimated from the DGVM models.

was a net sink of carbon in the 2000s. NBP, determined from the average of the nine DGVM models' estimates, was 227 TgC yr^{-1} and based on average of atmospheric inverse models is 24 TgC yr^{-1}. In comparison, fossil fuel emissions were 700 TgC yr^{-1}. Fossil fuel emissions grew at 27 TgC yr^{-2}, which is about three times faster than the growth of the NBP sink, 9 TgC yr^{-2}, indicating the net emissions between NBP and fossil fuels is growing.

The NBP sink is increasing steadily due to higher atmospheric CO_2 and its effect on plant growth (CO_2 fertilization effect), while atmospheric CO_2 source is increasing due to LULCC, forest fires and fossil fuel emissions. NEP, the largest component of the terrestrial carbon budget, had an average sink of 545 TgC yr^{-1} and grew at 12 TgC yr^{-2} in the 2000s. NEP increases due to CO_2 fertilization indicating the NEP sink increases in response to an increase in fossil fuel emissions. CO_2 is well mixed in the atmosphere and affects all countries regardless of its origin.

E_{LUC} emissions increased from the 1980s to 1990s then reversed the trend from the 1990s to the 2000s. The reversing of the trend is attributed to human and policy factors such as the afforestation efforts in India. E_{LUC} was 244 TgC yr^{-1} and decreased at 1.6 TgC yr^{-2} in the 2000s, with relatively low inter-annual variability suggesting the E_{LUC} is not influenced by environmental factors. Furthermore, nearly every country decreased E_{LUC} from the 1990s to the 2000s with the exception of Laos and Indonesia. Land use change practices in Indonesia have been well-documented and attributed to the expansion of palm oil plantations at the expense of tropical forests, and in Laos due to the expansion of agriculture, deforestation for timber, and expansion of cities.

Fire emissions due to non-LULCC fire activities, E_{FIRE} in SSEA are primarily from Indonesia and mainland Southeast Asia. In mainland Southeast Asia, there is a local maxima of lightening that triggers fires in vegetated areas, including forest fires.

Considering both NBP and fossil fuels, SSEA was a net source of 542 TgC yr^{-1} in the 2000s. Fossil fuel emissions increased at an exponential rate throughout the 2000s, simultaneously the

NBP sink increases linearly. If the trends continue the net land-to-atmosphere flux will further decrease, but many factors may complicate future projections. For example, increased temperatures due to increased greenhouse gas concentrations may further weakening the carbon sink in terms of NEP in the region. LULCC has been a source over the 2000s, but this source term is shrinking in magnitude since the 1990s and therefore is helping to increase the NBP sink.

Figures 26 and 27 show large uncertainties, represented here as the standard deviation of the model derived estimates, for the terrestrial carbon budget and its components. At the country level uncertainty may be introduced from the different spatial resolutions employed by the

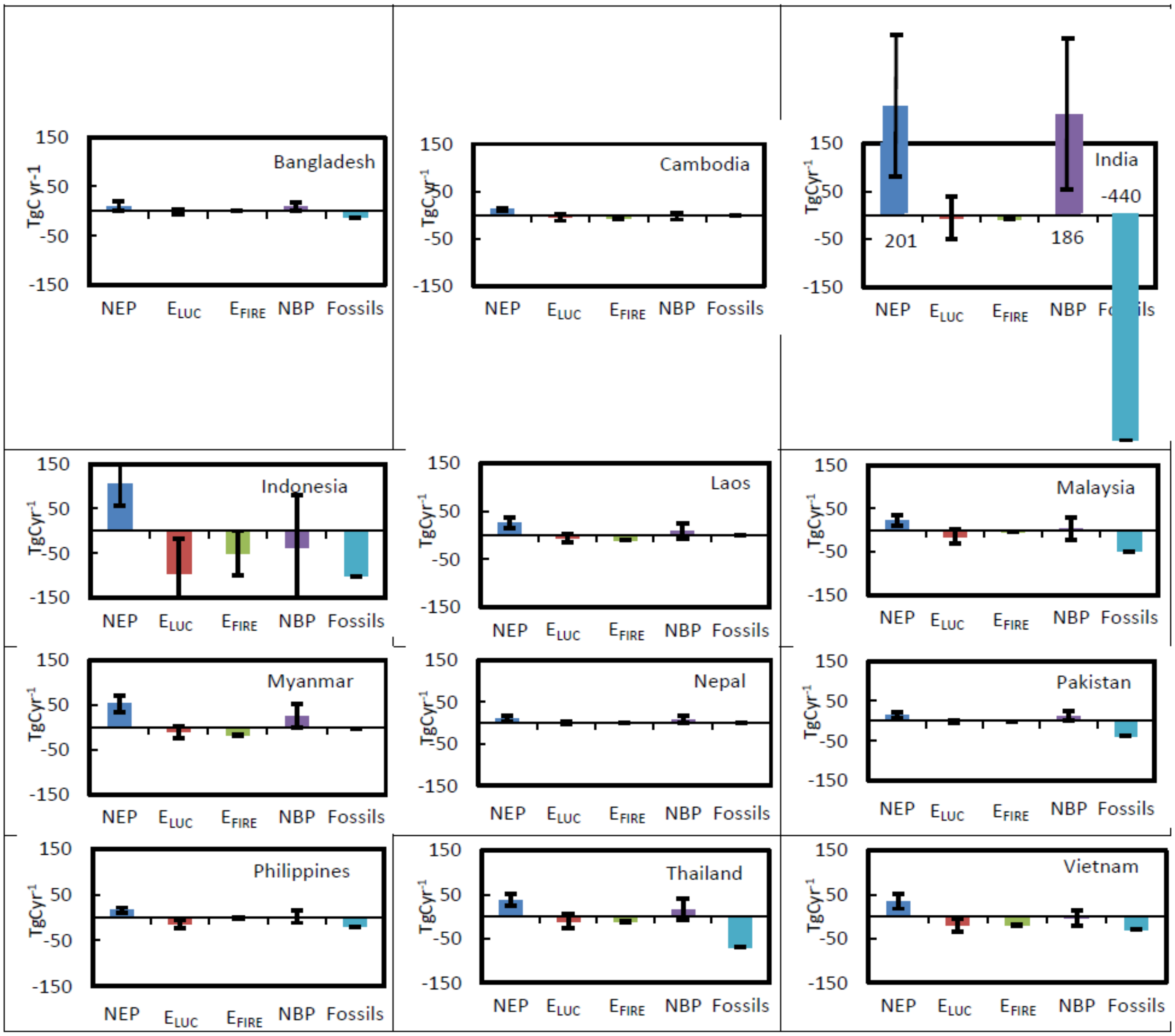


Figure 27: Mean carbon fluxes for the period 2000-2014 for select individual countries. Error bars represent the first standard deviation of the model results. Fire emissions are from Global Fire Emissions Database version 4 (van der Werf et al., 2010) and fossil fuel emissions are from La Quéré et al. (2015). Error bars represent the 1σ uncertainty.

DGVM models. For SSEA, differences may be because models apply different parameterizations for physical processes. DGVM models can be further refined by decreasing the spatial resolution of DGVMs in conjunction with a robust network of fluxnet tower data which are presently lacking in SSEA and the inclusion of more reliable remote sensing products to force the bottom up models.

4. Development of Cropping System Data for South and Southeast Asia

In collaboration with Co-I, Dr. Hanqin Tian, and his team members, we have developed a fine resolution (5’ × 5’) cropping system data for India based on Monfreda et al. (2008). We grouped the major crop types into 17 cropping systems in India. After grouping the major crop types into 17 cropping systems, we found that rice, wheat and millet were the dominant crop types in India (Figure 28). We are developing similar cropping system data for other countries in SSEA.

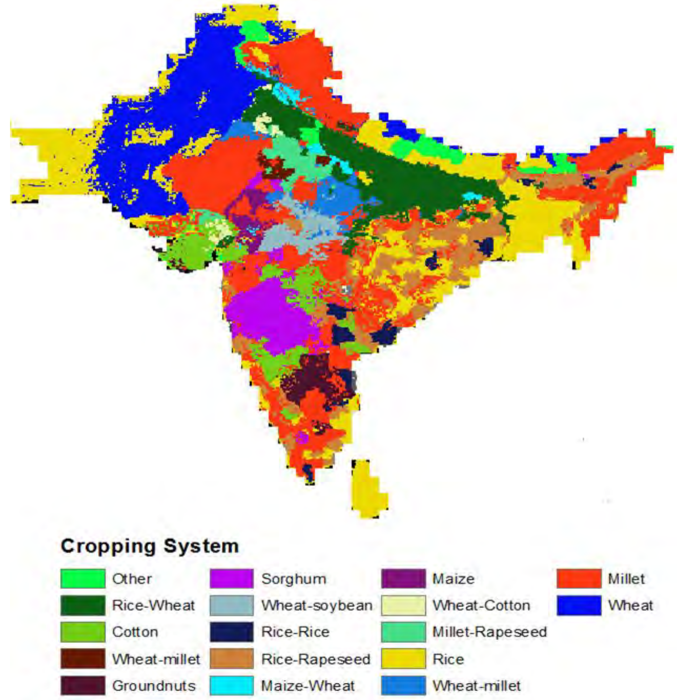


Figure 28: Cropping system (17) developed based on Monfreda et al. (2008) at 5’ × 5’ spatial resolution.

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