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Forest restoration and support for sustainable ecosystems in the Gandaki Basin, Nepal

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Abstract Restoring degraded forest is essential if we are to reduce human pressure on natural ecosystems and their biodiversity. Forests were nationalized in 1957 in Nepal and as a consequence, forest cover declined from 45% in 1964 to just 29% in 1994. However, as its response, sectoral plans and policies, particularly introduction of community-based forest management programs since the 1980s and conservation activities resulted in large scale forest cover restoration. Here, we examined the forest cover change in the Gandaki River Basin (GRB), the catchment with the largest altitudinal variation (ranging from ± 93 to 8167 m) and environmental and ecological significance. To see how forests have changed since then, we analyzed snapshots of spatiotemporal, ecological and physiographic changes in forest cover, and forest type at decadal intervals from 1996 to 2016 using Landsat 5 and 8 satellite images. We observed an overall gain in forest cover of 207 km^2, from 7571 km^2 (34.4% of the total area) in 1996 to 7778 km^2 (35.3%) in 2016. Of the 21 forest cover types identified, the greatest forest coverage during 2016 was of Schima-Castanopsis forest (25.9%) and hill sal forests (16.4%). In terms of physiographic zones, land below 500 m (Tarai) where most people live, witnessed gradual declines in forest cover, in contrast to large increases

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in forests above 500 m. Historical examination of forest cover at ecological and physiographic scales helps to identify the elevation-wise distribution of forest resources, vegetation composition, ecosystem characteristics, anthropogenic pressure upon vegetation, and hence the overall influence of LULC upon the environment. These outputs will assist planners, policy makers, and researchers in their formulation of effective basin wide plans and policies to ensure the protection of basin level biodiversity and ecosystem function.

Keywords Forest cover change · Forest management and restoration · Physiography · Gandaki River Basin · Nepal

Introduction

Forests cover change has a pivotal role in global ecosystem services and environmental sustainability (Mori et al., 2017). Improved forest cover ensures the supply of terrestrial ecosystem services: provisioning, regulating, cultural and supportive services (Alfonso et al., 2017) as it delivers goods and services, sequesters carbon, improves habitat quality, and natural environment at local to global level (Paudyal et al., 2017a; Rijal et al., 2021). Meanwhile, it helps to mitigate the adverse impacts of climate change, while aiding the conservation of biodiversity with ensuring socioeconomic benefits and ecosystem services including food security (Borrelli et al., 2020). In sharp contrast, deforestation or forest degradation results in direct adverse effects, ranging from the supply of native food, fuel-wood, construction materials, loss of biodiversity as well as other indirect impacts such as the depletion of water resources and increased carbon emissions (Giam, 2017).

Change in forest cover is largely associated with several anthropogenic and natural factors (Sharma et al., 2020). Anthropogenic determinants of forest cover change include agriculturral land expansion (Solomon et al., 2018), urbanization (Browder, 2002; Nguyen et al., 2020), population pressure (Cueva Ortiz et al., 2019) deforestation, forest degradation, over grazing and forest fires (Chaudhary et al., 2016; Cueva Ortiz et al., 2019), mining (Tsai et al., 2019), government policies (Li et al., 2013) and natural factors including natural regeneration, landslides, soil erosion and flood events (Rickli & Graf, 2009) and other natural disaster (Rifat & Liu, 2020). Such factors have contributed to global forest cover decline in the recent decades: forests occupied 31.6% of Earth's terrestrial surface in 1990 which declining to 30.6% area by 2015 (FAO, 2018).

Regeneration and reforestation programs have become a top priority globally to help maintain a sustainable environment (Löf et al., 2019). The UN Environment's sixth Global Outlook lists 17 Sustainable Development Goals (SDG) which were developed to help sustain the planet (Flinzberger et al., 2020; Menton et al., 2020) with the 15th Goal including the sustainable management of forest resources (UN, 2015). Similarly, Forest Landscape Restoration (FLR) is widely recognized as a key goal of a range of programs including the Bonn Challenge 2011 (www.bonnchallenge.org), New York Declaration 2014 (Dave et al., 2018), REDD program (reducing emissions from deforestation and forest degradation), land degradation-neutral world (LDN), and UN decade 2021–2031 for ecosystem restoration (UN, 2019).

Despite an overall global decline in forest cover, Asia is witnessing a gradual increase in the recent decades. Regional forest increase was the highest for Asia (+1.2 million ha) compared to Africa (−3.9 million ha), Europe (+0.3 million ha), North America (−0.1 million ha), South America (−2.6 million ha), and Australia (+0.4 million ha) between 2010–2020 (FAO, 2020). Forest cover increase in Asia is an outcome of the collective efforts to conserve forest through various national plans and programs such as LDN and Bonn Challenge commitments upon where India, for example aims to restore 13 million ha of degraded land by 2020 and an additional 8 million ha by 2030 (Borah et al., 2018). Additionally,the reforestation initiatives of South Korea, Vietnam, and China (Choi et al., 2019); landscape restoration program of Indonesia (Van Oosten et al., 2014); Grain to Green Program (GTGP) launched in China (Feng et al., 2013); and the community forest management program in Nepal (Agrawal & Chhatre, 2006) have contributed considerably in forest restoration.

Historically, Nepal's forest were managed under- a state owned centralized system until the 1970s. However, the approach failed to sustainably manage forest resources (Wakiyama, 2004) resulting in widespread deforestation (Khatri et al., 2018).

Forests occupied 45% of total land cover in 1964 (MoPE, 2001) declining to 38% by 1978/1979 (Land Resources Mapping Project (LRMP)), 35.9% by 1984 (National Remote Sensing Center (NRSC)), and to 29% by 1994 (National Forest Inventory (NFI)) and 40.36 % in 2015 (DFRS, 2015). Hence, the government changed its forest policy (Agrawal & Chhatre, 2006) by introducing a community-based forest management program in the 1980s. Forest Act, 1993 (HMGN, 1993) and the Forest Regulation Act, 1995 (HMGN, 1995) were the legal documents to legitimize it. Since 1993, Nepal has gradually handed over portions of national forest to local communities (Paudel et al., 2018) and community-based forest management plans have been successfully restoring the forest resource. Deforestation rate, which was 1.31% during 1930–1975 under the centralized management approach decreased to 0.01% during 2005–2014, under community-based management (Reddy et al., 2018). Forest cover in Nepal plays an important role in mitigating the adverse impacts of climate change and offering diversified livelihood options (Bhattarai & Conway, 2021a). Combined the aforementioned strategies and plans have been remarkably successful in preserving and growing forest resources in recent decades with forest degradation rate dropping and a gradual regeneration being observed. Community forestry has proved successful particularly in the mid-hills (Baral et al., 2018b; Niraula et al., 2013; Tripathi et al., 2020) due to the collective conservation practices (Bhattarai & Conway, 2021a). However, in the case of Tarai, (the fertile lowland plains in the south), forest cover is under extreme pressure due to population concentration and urbanization (Rijal et al., 2020), illegal logging and smuggling of high valued timber and weaker management of community forest (Gautam et al., 2004). In the Tarai region of Nepal, the population was 8.62 million in 1991 (accounting 46.7% of the national population) increased to 13.31 million (50.3% of national population) by 2011 (CBS, 2014). Meanwhile, the urban area which was 71.36 km^2 during 1989 expanded within 327.26 km^2 by 2016 and expansion has mainly occurred in the outskirts of major city centers and adjacent to major road networks in western tarai of Nepal (Rimal et al., 2020a). In addition to these factors, shifting cultivation, overgrazing, poaching and rampant excavation of sand and gravel and subsequent soil erosion and landslide events have massively degraded the forest cover of Churia, the region with young and fragile topography (DSCWM, 2012).

Forest cover is the important natural resource of Nepal and comprises 112 forest ecosystem of the total 118 ecosystems in the country, of which 12 are centered in Tarai, 14 in Churia, and 53 in Middle Mountains and High Himal/ High Mountains 38 and one others (Kharal and Dhungana, 2018; DFRS, 2015). The forests of our study area—the Gandaki Province—are particularly remarkable in terms of touristic, environmental, ecological significance. Some form the habitats of various endangered animal and bird species are recognized as the important floristic regions where high valued herbs plants are found (PPC, 2019). The province includes major national tourist destinations globally recognized for their religious, cultural, adventurous and ecotourism significance (PPC, 2019). In Particular, the Panchase Conservation area, Annapurna Trekking route, Manaslu Circuit Trail and Dhorpatan Hunting reserve are well known destinations for forest-based ecotourism. The land cover variation of the basin ranges from the highest elevation glaciers and snow cover, grasslands, shrub and coniferous forest to sub-tropical broad-leaved forest in the Tarai region through steep slopes, rugged terrain and deep gorges in the mid-hills (Dandekhya et al., 2017). Since monitoring forest condition at different scales and forest types aids the government in improving its performance in national and international initiatives (Armenteras et al., 2017), exploring forest changes in a geographically complex and biodiversity-rich landscape (Goodin et al., 2015) is imperative.

The historical examination of forest cover at ecological and physiographic scales helps to identify the elevation-wise distribution of forest resource, vegetation composition, ecosystem characteristics, anthropogenic pressure upon vegetation and overall influence of LULC upon the environment (Gerhardt & Foster, 2002). Nepal is characterized by acomplex physiography extending from snowcapped high-mountain ranges in the north to Mahabharat Mountain range, Siwalik region to Tarai, the flat plain in the south (Bhattarai & Conway, 2021b). Several studies (Baral et al., 2018a; Oli & Shrestha, 2009; Paudyal et al., 2017b; Rimal et al., 2018) have assessed the forest cover change of some small areas within the study area and Bhattarai et al. (2009) investigated the forest cover change scenario of central Nepal during

1975–2000 using Landsat satellite data. However, wider assessment of forest resource over a longer time span at the Province level is lacking. Hence, we aim to analyze the spatiotemporal, physiographic level of changes in forest cover for the years 1996, 2006, and 2016 using Landsat time series images. We anticipate our outputs will be useful to the planners, policy makers and researchers in their formulation of effective plans and policies which can ensure the protection of basin-wide biodiversity and ecosystem function.

Methodology

Study area

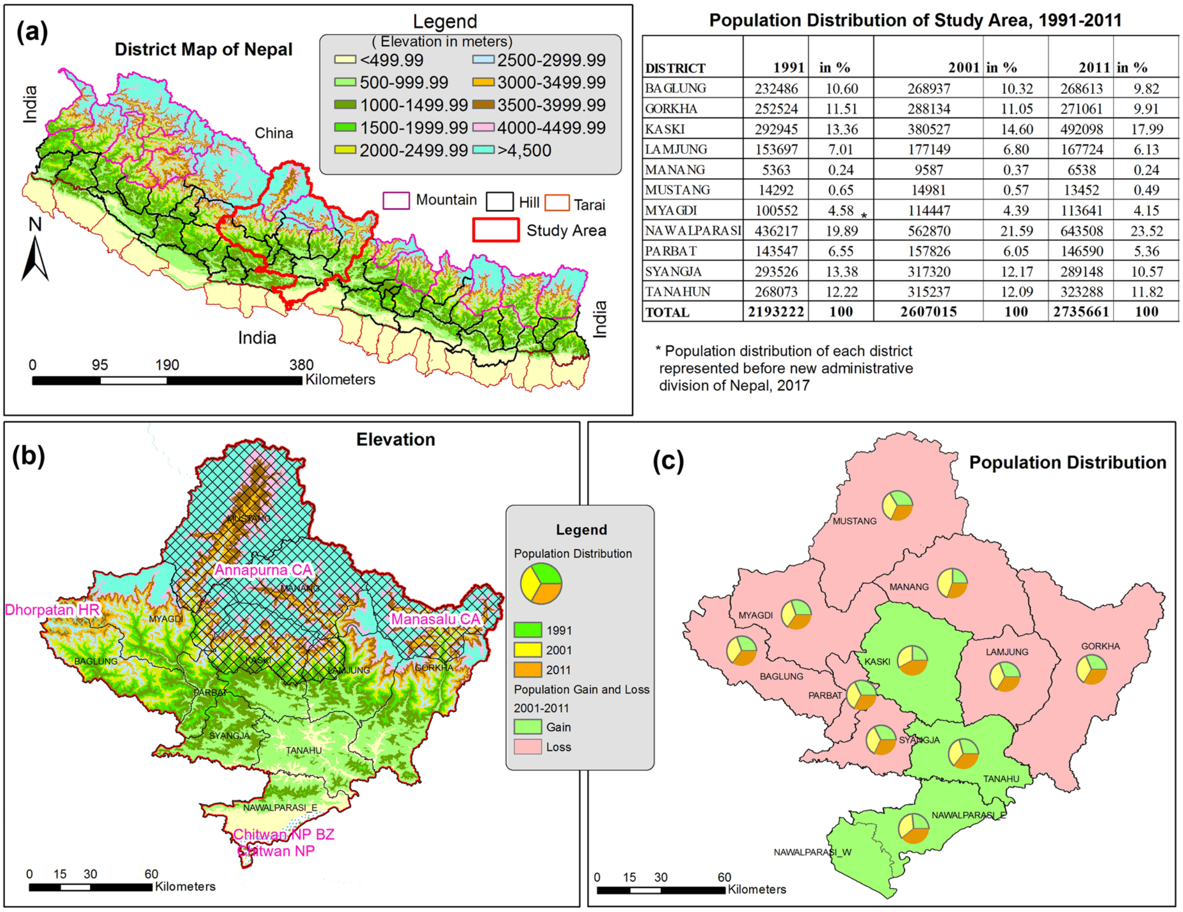
Nepal is physiographically divided into five classes on the base of land form (Bhuju et al., 2007).The study area, High-Mountain (more than 4500 m covering 24.9%), Mid-Mountain (2500–4500 m covering 28.3%), Mid-Hill (1000–2500 m covering 24.3%), Chure and Mahabharat (500–1000 m covering 15.2%), and Flat Plain (hereinafter Tarai) (less than 500 m covering 7.3% area of the Gandaki River Basin); physicographical division of the study area is done on the base of elevation.

The study area, the Gandaki River Basin is located in the Gandaki Province of Nepal, sharing its eastern boundary with Bagmati Province, western boundary with Lumbini Province and Karnali Province , northern boundary with Tibet autonomous region of China, and the southern boundary with Bardaghat Susta -East of Nawalpur and with India. Administratively, the study area integrates 11 districts (Myagdi, Mustang, Parbat, Baglung, Gorkha, Lamjung, Manang, Syangja, Kaski, Tanahun, and Nawalparasi East) (Fig. 1a, b), one (1) metropolitan city (Pokhara), 26 municipalities and 58 rural municipalities. The population of the basin was 2.19 million in 1991, 2.61 million in 2001 and 2.74 million in 2011 (Fig. 1c). Major population concentrations are in Nawalparasi (23.52% (including east and west), Kaski (17.99%), and Tanahun (11.82%) districts (CBS, 2014).

Geographically, the study area is enclosed between 27.441667 and 29.330556 N latitude to 82.878333″ to 85.201389 E longitude covering about 22,000 km^2 (approximately 15% area of the country) with complex topography extending from the Tarai ± 93 masl up to the High Mountain region with a maximum of 8167 masl. The basin is characterized by multiple land use features (Pant et al., 2020), variations of hydrogeochemistry and ecology (Pant et al., 2018). The northern part of the study area consists of the Annapurna mountain range integrating the snowcapped mountain peaks (Mahhapuchhre, Annapurna first, Annaapurna second, Dhaulagiri, Nilgiri, Manaslu, Himchuli, and Lamjung Himal). Ramsar listed lakes of Nepal (60,561 ha): study area includes (Phewa, Begnas, Rupa, Dipang, Khaste, Maidi, Nyureni, Kamalpokhari and Gunde (172.83 Km^2 area) as well as Tilicho—the highest lake in the world also located). Additonally, it has incorporated 96 km^2 core and 151 km^2 buffer area of Chitwan National Park, 501 km^2 of Dhorpatan Hunting Reserve, the entire area of Annapurna Conservation Area (7629 km^2), and Manaslu Conservation Area (1663 km^2) (PPC, 2019). Gandaki is the major river of the watershed with 368 small to large sub/watersheds. Regarding LULC, forest is the dominant land cover of the area and 29% of the forest cover is community managed with 3844 Community Forest Users Groups (CFUGs) , 1073 leasehold forests, 18 religious forests, one collaborative forest, one protected forest, (Panchase Conservation area), and 377 private forests (PPC, 2019).

Data

In this study, freely available terrain corrected (LIT) Landsat images (Landsat 5, hereinafter Thematic Mapper (TM); Landsat 8, hereafter Operational Land Image (OLI)) for the years 1996, 2006, and 2016 were used for the land cover analysis, and all images were collected from the United State Geological Survey (USGS) Web site https://earthexplorer.usgs.gov (USGS) (Table 1). The images were verified for accuracy. The FLAASH atmospheric model was used for image processing using ENVI environment and eight land cover classes were extracted from 93 to 8167 masl. A 30-m resolution digital elevation model (DEM) was acquired from Shuttle Radar Topographic Mission (SRTM). Furthermore, topographical data for the scale 1:25,000 and 1:50,000 were used from the Survey Department, Government of Nepal (GoN, 1998). High-resolution Google Earth images and land cover data 2010 (Uddin et al., 2015) were additional data sources.



Population Distribution of Study Area, 1991-2011

DISTRICT	1991	in %	2001	in %	2011	in %
BAGLUNG	232486	10.60	268937	10.32	268613	9.82
GORKHA	252524	11.51	288134	11.05	271061	9.91
KASKI	292945	13.36	380527	14.60	492098	17.99
LAMJUNG	153697	7.01	177149	6.80	167724	6.13
MANANG	5363	0.24	9587	0.37	6538	0.24
MUSTANG	14292	0.65	14981	0.57	13452	0.49
MYAGDI	100552	4.58 *	114447	4.39	113641	4.15
NAWALPARASI	436217	19.89	562870	21.59	643508	23.52
PARBAT	143547	6.55	157826	6.05	146590	5.36
SYANGJA	293526	13.38	317320	12.17	289148	10.57
TANAHUN	268073	12.22	315237	12.09	323288	11.82
TOTAL	**2193222**	**100**	**2607015**	**100**	**2735661**	**100**

* Population distribution of each district represented before new administrative division of Nepal, 2017

Fig. 1 Location of the study area

Extraction of LULC

There are multiple advanced parametric and non-parametric technologies available for land cover classification (Steiner, 1970) including parametric classifiers such as maximum likelihood (ML), minimum distance (MD), and Bayesian classifiers (BCs) and nonparametric classifiers such as support vector machine (SVM), artificial neural network (ANN), and decision tree. ML classifier, MD, BC, ANN, and fuzzy classification (FC) are further described by Campbell (Campbell & Wynne, 1996). Nonparametric approaches are considered to be most appropriate for LULC analysis (Rodriguez-Galiano et al., 2012). However, thorough-going training samples or region of interest (ROI) is essential to achieve high levels of accuracy in land cover classification (Campbell, 1981; Hixson & Fuhs, 1980; Scholz & Hixson, 1979). In this study, we used SVM algorithms to extract the major land cover categories in the study area using Landsat images. To extract the land cover data of the study area, topographical data developed by Survey Department and Google Earth images were used as reference data. SVM is supervised, nonlinear, nonparametric classification method which is widely applied for the extraction of land cover change of the study area as it has higher accuracy compared with ML (Kavzoglu &

Table 1 Dates of the Landsat time series 5 and 8 images

Path/row	1996 (Landsat 5 TM)	2006 (Landsat 5 TM)	2016 (Landsat 8 OLI)
141/040/041	18 Oct	30 Oct	25 Oct
142/041/42	10 Nov	5 Oct	22 Mar
143/040	17 Nov	2 March	23 Oct

Colkesen, 2009; Rimal et al. 2020b). SVM approaches was evaluated by Ortega Adarme et al. (Ortega Adarme et al., 2020) for deforestation mapping, and this approach was used for land cover change and urban monitoring (Karimi et al., 2019).

SVM approach is generally arranged into four major kernel function, such as polynominal, linear, radial function, and sigmode. In this study, the radial basic function (RBF) kernel was chosen as it usually provides better results compared with other kernels. The penalty parameter of the error 100 was assigned using ENVI software.

$$\begin{aligned}
&(i)\quad Linear: K(x_i, y_i) = x_i^T \cdot x_j,\\
&(ii)\quad Polynomial: K(x_i, y_i) = (g.x_i^T \cdot x_j + r)^d, g > 0,\\
&(iii)\quad Radial\ basis\ function: K(x_i, y_i) = e^{-g(x_i - x_j)^2}, g > 0,\\
&(iv)\quad Sigmoid: K(x_i, y_i) = \tanh(g.x_i^T \cdot x_j + r)
\end{aligned} \tag{1}$$

where x_i, y_i are training vectors, g, ^{d}, and r are user-controlled parameters of kernel function.

Land cover analyses for the years 1996, 2006, and 2016 were based on the classification scheme developed by Anderson (1976) and eight major LULC classes were identified: urban/built-up, agriculture, forest, shrub, grass land, barren land, water body, ice, and snow cover (Table 2).

Land cover change trajectories

A transition matrix of the land cover map of period 1 and period 2 was prepared using Land Change Modeller of IDRISI software (https://clarklabs.org/). The LULC transition statistics show the change of attributes from period 1 to period 2. This LULC change considers two paths (Yadav & Ghosh, 2019) and change analysis shows the pixel based change amount from one class to another during the study period.

Physiographic zone and forest type

First, elevation data was prepared using SRTM DEM (30 m resolution), and this data was used to prepare the elevation-wise physiography-level land cover change data for the year 1996, 2006, and 2016. Furthermore, forest cover within the study area was broadly categorized into 21 forest types. The forest type data (GIS vector data) of the study area was collected from ICIMOD (https://servir.icimod.org/datasets), and change for each forest type was assessed for the study period using modified data. We extracted the forest class of our classified images of different years (1996–2016) using collected forest type layer and analyzed the difference regarding the changes in forest type. Forest-related information at provincial, district, and local level were acquired from various non/governmental sources. In addition, various key government policies were evaluated.

Accuracy and uncertainty

The land cover classification accuracy assessment is significiant when land cover maps are prepared using satellite images (Feng et al., 2017; Jensen, 1996; Sexton et al., 2013). The confusion matrix method is widely used for the assessment of land cover classification (Foody, 2002) as is user's accuracy (UA), producer's accuracy (PA), and overall accuracy (OA).

Table 2 Land use/cover classification schemes

Land cover types	Description
Urban (built up)	Urban and rural settlements, commercial areas, industrial areas, construction areas, traffic, airports, public service areas (e.g., school, college, hospital)
Cultivated land	Wet and dry crop lands, orchards
Forest	Evergreen broad leaf forest, deciduous forest, temperate forest, scattered forest, low-density sparse forest, degraded forest, mix of trees, and other natural covers
Shrub	Mix of short trees and other natural covers
Barren land	Cliffs/small landslides, bare rocks, other unused land, sandy areas, river banks
Water	River, lake/pond, canal, reservoir, and swamp areas
Grass	Mainly grass fields (dense coverage grass, moderate coverage grass, and low coverage grass)
Snow cover	Perpetual/temporary snow cover, perpetual ice/glacier

Here, accuracy assessment was prepared based on the GPS points collected from field verification conducted on 2016 and 2018. Accuracy assessments were aided by the use of topographical maps developed by the Survey Department of 1998 (scale 1:25,000 and 1:50,000) (GoN, 1998), land cover maps of 1990 and 2013 (Rimal et al., 2015) of the Seti river watershed, and high-resolution Google Earth images (http://earth.google.com). For the accuracy assessment, a total of 2382 stratified random sample points for each year were developed in the already classified land cover maps for 1996, 2006 and 2016 and were further verified in high-resolution Google Earth images and land cover data 2010 (Uddin et al., 2015). The available Google Earth images were printed in A1 size for field verification. Additionally, hand GPS was used for further collection of the sample points. The acquired sample points were used for accuracy assessment. Classified images were overlaid in Google Earth and observed for verification.

At least 200 sample points for each LULC class were represented with many LULC that covered larger areas having many more sample points (see Table 6). Accuracy assessment was conducted on sample points using GPS during field verification conducted in 2016 and 2018. The confusion matrix was generated based on the existing ground truth reference data and classified images.

Producer's accruracy

$$N_{ii} + N_{+i} n \ 100\% \tag{2}$$

where N_{ii} = total number correct cells in a class and N_{+i} = sum of cell values in the column.

User's accruracy

$$N_{ii} + N_{i+} n \ 100\% \tag{3}$$

where N_{ii} = total number correct cells in a class and N_{i+} = sum of cell values in the row.

Overall accruracy

$$X/Nx \ 100\% \tag{4}$$

where X = total number correct cells as summed along the major diagonal and N = total number of cells in the error matrix.

Land cover classification accuracy can be determined by training sample points developed during the land cover classification process (Prestele et al., 2016). Various factors can play a role in this error. For the accuracy assessment, collection of high-resolution real-time data can be a major challenge (Bhattarai & Conway, 2021c). Sample size affects the magnitude of margin of error. The larger the sample, the smaller the margin of error. On the other hand, the low Producer's accuracy for urban areas can be one of the reasons for the increase margin of error in this class. We recognized that in this study, there are a few limitations. First, we limited our classification to only eight major LULC classes which limits the mapping of the major ecosystems of the basin. Second, lack of updated reference data and the very complex landscape also limits the classification accuracy. For example, in the northern part of the project area, there were some seasonal fluctuations between the areas of grass land, barren land and snow cover which we did not assess. Land cover classification were also impacted by regional weather and climate (Ge et al., 2019). Thirdly, we could not assess urban areas into sub-categories such as garden and urban forest due to the limited resolution of the Landsat images (Rimal et al., 2019).

In the current study, we performed stratified random sampling to determine the accuracy of classification. In this way, it is possible to estimate the area of the LULC classes by adjusting the area for the mapping error (Gallaun et al., 2015). Confidence intervals were extracted to assess the uncertainty of the accuracy measures and the area estimates of all classes. This unbiased estimator of the area proportion covers the area of map omission error and eliminates the area of commission error (Costa et al., 2018). Using the information directly provided by the error matrix and the Eqs. 5, 6, 7 and 8 (Olofsson et al., 2013), we adjusted the biased results.

$$\widehat{A}_j = A_{tot} \times \sum_i W_i \frac{n_{ij}}{n_{i+}} \tag{5}$$

where A_j is unbiased estimator of the total area, n_{ij} is the number of points of category j which mapped as category i, n_{i+} is the total number of points related to category i, W_i is the proportion of the area mapped as category i, and A_{tot} is the total mapped area. The estimated standard error of the estimated area proportion is:

$$\left(\widehat{P}_j\right) = \sqrt{\sum_{i=1}^{q} W_i^2 \frac{\frac{n_{ij}}{n_i}\left(1 - \frac{n_{ij}}{n_i}\right)}{n_{i+} - 1}} \tag{6}$$

The standard error of the error-adjusted estimated area is:

$$S(\widehat{A}_j) = A_{tot} \times S(\widehat{P}_j) \quad (7)$$

A 95% confidence interval for A_j is:

$$\widehat{A}_j \pm 1.96 \times S(\widehat{A}_j) \quad (8)$$

To assess the accuracy for the post classification change analysis of forest class, we overlaid two maps to produce the 1996–2016 forest change map. Accordingly, a stratified random sample was selected as the reference of land cover for forest class to assessing the accuracy using Google Earth images, TM, and Landsat images. Then, the abovementioned equations were applied to evaluate the error-adjusted area of deforestation.

Results

Accuracy and uncertainty assessment

An assessment of the accuracy measures and estimated areas suggests that the classification of most classes was highly accurate (Tables 3, 4, 5, 6, and 7). For example, the mapped area of forest class for years 1996, 2006, and 2016 km^2 is 7571, 7673 km^2, and 7778 km^2, respectively; whereas the stratified error-adjusted area estimate of forest area is only slightly less (i.e. 7404 km^2, 7581 km^2, and 7577 km^2) (Tables 3, 4, and 5). The confidence interval quantifies the uncertainty associated with the sample-based estimate of the area of different classes. Accordingly, the true area of forest for 2016 could be as low as 7410 km^2 or as high as 7744 km^2 at the 95% level of confidence (Tables 3, 4, 5, 6, and 7).

The accuracy assessment based on the stratified estimators showed that the forest area had an overall accuracy of 91%, 93%, and 96% and a user's accuracy of 96%, 97%, and 96% for years 1996, 2006, and 2016, respectively (Table 7). Also, the producer's accuracy is above 95% for forest class, except for 1996 which is 90%. So, the omission error of forest class does not have a strong influence on the estimated area of forest. Accordingly, map error is small and the area mapped of forest class is close to the true area. If the producer's accuracy was too low, it would have alerated to the problem of omission error associated with the forest category. Totally, the difference between the biased and unbiased overall accuracies was less than 0.03 in all years (Tables 6 and 7).

Table 3 The mapped and estimated adjusted areas with a margin of error (95% confidence interval) for 1996

Class	Mapped	Adjusted	Margin of error (95% CI)
Urban	53	160	±73.36
Cultivated	4346	4010	±212.3
Forest	7571	7404	±154.12
Shrub land	624	852	±125.32
Barren land	4130	4228	±190.32
Water body	177	170	±17.81
Grass land	2434	2691	±171.15
I&SC	2679	2498	±144.65

Table 4 The mapped and estimated adjusted areas with a margin of error (95% confidence interval) for 2006

Class	Mapped	Adjusted	Margin of error (95% CI)
Urban	83	152	±57.96
Cultivated	4293	4151	±189.06
Forest	7673	7581	±148.12
Shrub land	727	856	±108.52
Barren land	3941	3840	±153.61
Water body	219	209	±17.87
Grass land	2349	2476	±138.89
I&SC	2729	2749	±127.98

Table 5 The mapped and estimated adjusted areas with a margin of error (95% confidence interval) for 2016

Class	Mapped	Adjusted	Margin of error (95% CI)
Urban	141	215	±62.12
Cultivated	4077	3924	±180.37
Forest	7778	7577	±167.04
Shrub land	635	821	±120.94
Barren land	4233	4177	±153.51
Water body	196	207	±25.8
Grass land	2799	2870	±154.16
I&SC	2154	2222	±107.02

Table 6 Accuracy measures based on error matrix of sample counts for 1996, 2006, and 2016

	Urban	Cultivated	Forest	Shrub land	Barren land	Water body	Grass land	I&SC
1996								
User's	0.84	0.84	0.96	0.88	0.92	0.91	0.91	0.87
Producer's	0.93	0.86	0.96	0.88	0.83	0.96	0.85	0.93
Overall	0.90							
2006								
User's	0.88	0.89	0.97	0.87	0.92	0.91	0.92	0.93
Producer's	0.95	0.88	0.96	0.89	0.90	0.97	0.87	0.92
Overall	0.92							
2016								
User's	0.90	0.89	0.96	0.90	0.93	0.95	0.91	0.95
Producer's	0.95	0.89	0.96	0.91	0.90	0.97	0.89	0.94
Overall	0.92							

The obtained user's accuracy of the deforestation class through change detection procedure was about 84% which shows the forest change obtained by post classification is acceptable. Also, forest/non-forest maps were highly accurate with user's accuracy more than 90% (Table 8).

Details of LULC changes and the spatial distribution of LULC classes are presented in Table 9 and Fig. 2. Major changes observed during 1996–2016 include increases in urban/built-up, forest cover and barren land, sharp declines in cultivated land, and fluctuations for grassland, water bodies, barren land and shrub areas. Built-up land expanded in this period, increasing from 53 to 141 km^2. Grass land was converted into forest and forests increased by 207 km^2 over the 20-year period. Cultivated land faced intense pressure due to the rapid urbanization below 999.99 m elevation zone. However, forest area decreased in the < 500 m elevation zone. Forest encroachment was observed mainly in the city outskirts (Appendix Fig. 6).

During 1996–2006, forest cover increased by 102 km^2, from 7571 to 7673 km^2 with losses of 37 km^2 cultivated land, 19 km^2 shrub, 38 km^2 barren land, 11 km^2 water body, 142 km^2 grass land, and 16 km^2 snow/ice cover. Shrub area increased from 624 to 727 km^2 as 60 km^2 was converted from cultivated land and 89 km^2 from forest (Appendix Table 12). A transition map of the year 1996 and 2006 and 2006 and 2016 highlights these changes (Fig. 3a–c).

Table 7 Accuracy measures based on error matrix of estimated area proportions (with a 95% confidence interval) for 1996, 2006, and 2016

	Urban	Cultivated	Forest	Shrub land	Barren land	Water body	Grass land	I&SC
1996								
User's	0.84 ± 0.049	0.84 ± 0.037	0.96 ± 0.018	0.88 ± 0.044	0.92 ± 0.031	0.91 ± 0.039	0.91 ± 0.032	0.87 ± 0.043
Producer's	0.48 ± 0.13	0.91 ± 0.03	0.90 ± 0.009	0.64 ± 0.091	0.90 ± 0.029	0.94 ± 0.089	0.83 ± 0.046	0.93 ± 0.031
Overall	0.91 ± 0.013							
2006								
User's	0.88 ± 0.045	0.89 ± 0.032	0.97 ± 0.016	0.87 ± 0.045	0.92 ± 0.03	0.91 ± 0.039	0.92 ± 0.031	0.93 ± 0.031
Producer's	0.58 ± 0.18	0.92 ± 0.028	0.95 ± 0.01	0.74 ± 0.088	0.94 ± 0.023	0.96 ± 0.07	0.87 ± 0.041	0.93 ± 0.031
Overall	0.93 ± 0.011							
2016								
User's	0.90 ± 0.042	0.89 ± 0.032	0.96 ± 0.019	0.90 ± 0.04	0.93 ± 0.028	0.95 ± 0.03	0.91 ± 0.031	0.95 ± 0.027
Producer's	0.69 ± 0.167	0.92 ± 0.028	0.96 ± 0.009	0.69 ± 0.098	0.94 ± 0.021	0.88 ± 0.105	0.91 ± 0.039	0.92 ± 0.036
Overall	0.95 ± 0.012							

Table 8 Error matrix for the 1996–2016 change map of forest class. Accuracy measures are presented with a 95% confidence interval

Class	Deforestation	Stable forest	Stable non-forest	Total	W_i	User's	Producer's
Deforestation	98	14	7	119	0.003	0.84 ± 0.07	0.72 ± 0.24
Stable forest	8	461	37	506	0.352	0.91 ± 0.02	0.90 ± 0.03
Stable non-forest	0	38	647	685	0.645	0.94 ± 0.02	0.93 ± 0.01
Total	106	513	689	1310			

Based on the land use transition matrix grass land declined by 84 km^2 (from 2434 to 2349 km^2), mainly due to the conversions into cultivated land (21 km^2), forest (142 km^2), barren land (52 km^2), water body (25 km^2), and ice/snow cover (5 km^2). The land cover change matrix during 2006–2016 (Appendix Table 13) shows that forest area increased by 105 km^2 (from 7673 to 7778 km^2). Major factors contributing to the increase in forest cover are conversions from cultivated land (277 km^2), shrub (75 km^2), barren land (66 km^2), water body (15 km^2), grass (115 km^2), and snow/ice (19 km^2) into forest cover. Meanwhile, barren land increased by 292 km^2 (from 3941 to 4233 km^2) due to the conversions from snow/ice (628 km^2), grass (310 km^2), and forest (40 km^2) (Fig. 3a–c). Shrub area declined by 92 km^2 (from 727 to 635 km^2) due to the conversion of 60 km^2 shrub area into cultivated land, 75 km^2 into forest cover, and 42 km^2 into grass.

Table 9 Land use/land cover change of the study area during 1996–2016 (in km^2)

LULC	1996	2006	2016	Change 1996–2006	Change 2006–2016
Urban/built-up	53	83	141	30	58
Cultivated land	4346	4293	4077	−53	−216
Forest land	7571	7673	7778	102	105
Shrub land	624	727	635	103	−92
Barren land	4130	3941	4233	−189	292
Water body	177	219	196	42	−23
Grass land	2434	2349	2799	−84.41	450
Snow/ice cover	2679	2729	2154	50	−575

Forest cover change based on physiographic zone

The Tarai and the Mid-Hill zones are mostly cultivated and forest land. Forest, barren land, and grass are the dominant land uses in the mid-mountain zone and most of the high-mountain zone is covered by barren land and snow. Most importantly, extensive deforestation occurred during 1996–2006 which contributed in the decline of forest area from 625 to 558 km^2 and doubled the shrub area by 78 to 155 km^2 (Appendix Table 14) in Tarai < 500 meters. Forest encroachment and forest decline was observed mainly in areas where there was infrastructure development and urban development.

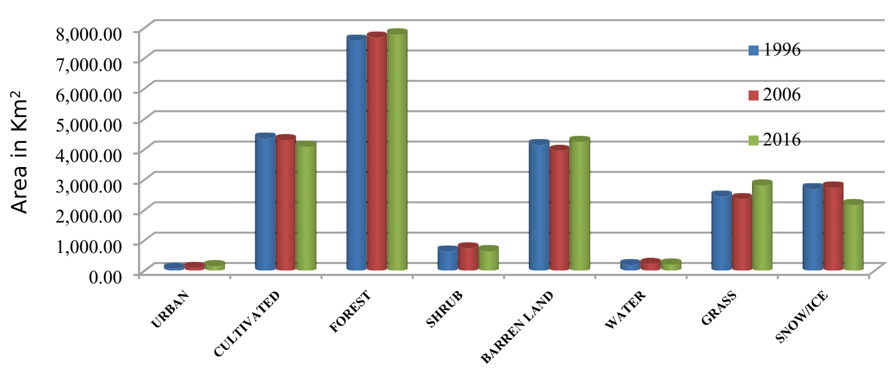


Fig. 2 Land use/land cover changes in the Gandaki Basin during 1996–2016

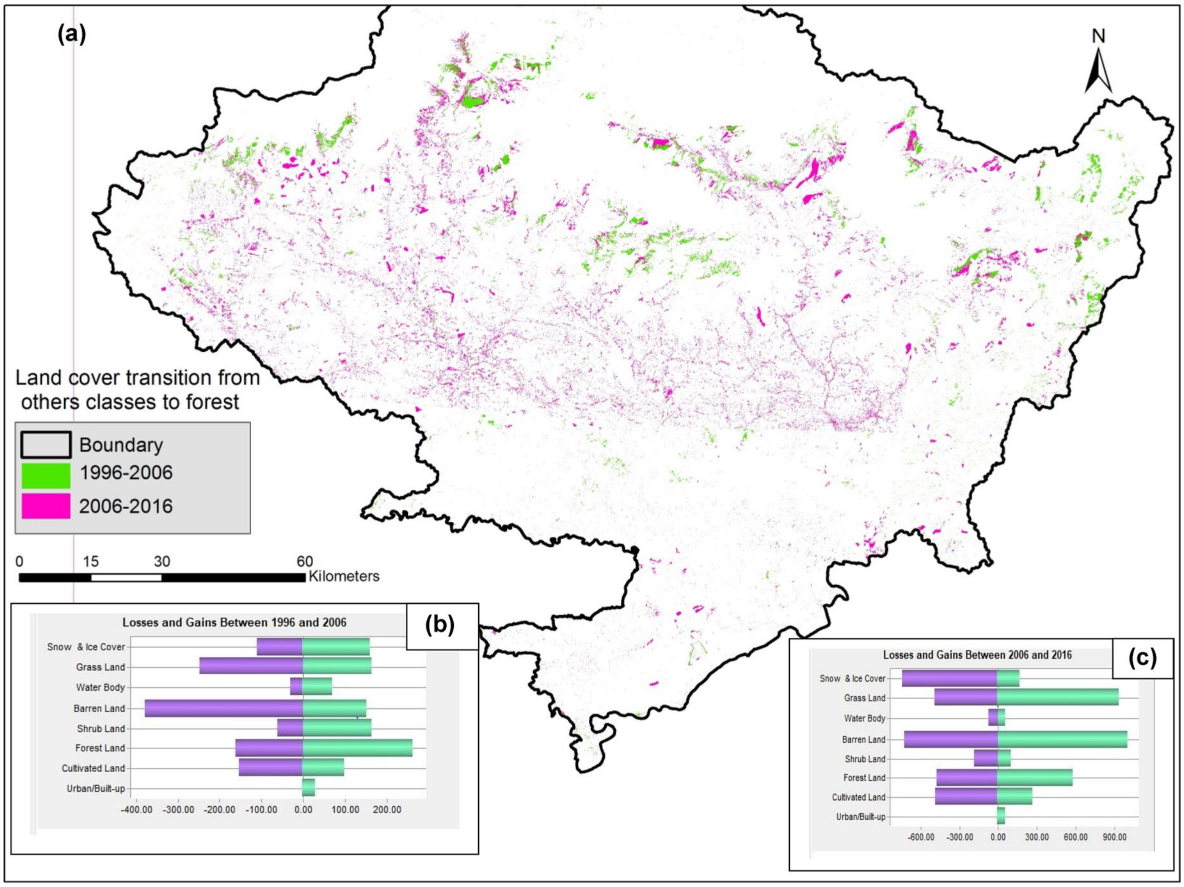


Fig. 3 Transition map. (**a**) Land cover transition from all land cover to forest cover 1996–2006 and 2006–2016. (**b**) Land cover change 1996–2006. (**c**) Land cover change 2006–2016

However, during 2006–2016, forest cover decline was limited to 1 km^2 because of the strong contribution of community-based forest management plans and Chure Conservation program of the Government of Nepal to combat deforestation and degradation.

In Chure and Mahabharat (Siwalik), increases in urban area and forest cover and decline in cultivated land area were the notable transformations during 1996–2016. Forest cover area increased by 1 km^2, from 1399 to 1400 km^2 during 1996–2006 and a further 49 km^2 during 2006–2016 (Table 10). We observed that the major changes were driven by the community forestry program and increases in private forest in abandoned cultivated land in the rural

Table 10 Physiographic distribution of forest cover change during 1996–2016 (in km^2 and percentage)

Physiographical zones	1996		2006		2016	
	km^2	%	km^2	%	km^2	%
< 499.99 (Tarai)	625	8.36	558	7.3	557	7.2
500–999.99 (Siwalik (Chure))	1399	18.5	1400	18.3	1451	18.7
1000–2499.99 (mid-hill)	3111	41.1	3125	40.7	3183	40.9
2500–4499.99 (mid-mountain)	2436	32.2	2590	33.8	2587	33.3
> 4500 (high mountain)	0	0	0	0	0	0

areas due to out-migration. Decline in cultivated land and increases in urban/built-up and forest area were the major changes for the Mid-Hill zone. Urban area increased in both time periods 1996–2006 and 2006–2016 (Appendix Table 14). Forest cover increased by 14 km^2 during 1996–2006 and 56 km^2 during 2006–2016 (Table 10, Fig. 4) in mid-hill. In the mid-mountain zone, the majority of the area is occupied by forest, barren land, and grass. According to our analysis, forest cover had occupied 2436 km^2 in 1996 which increased by 154 km^2 (2590 km^2)in 2006 but slightly dropped (−3 km^2) and totaled 2587 km^2 by 2016 (Fig. 5a–o). The High mountain zone is mainly occupied by barren land, snow cover and grass land. However, the northern-most part of the study area is mostly periodically covered by snow. Seasonal snowfall means that coverage of ice/snow, grass land, and barren land fluctuate.

The total forest area across all zones increased from 7571 km^2 in 1996 to 7673 in 2006 and 7778 km^2 in 2016 (Appendix Fig. 7 and Table 14). Most of these increases were in the Siwalik, mid-hill, and mid-mountain zones, but forest cover declined in the Tarai region from 8.36% in 1996 to 7.2% to 2016 (Table 10).

Fig. 5 Physiographic distribution of forest cover and other ▸ land uses in the Gandaki basin during 1996–2016 (Tarai (**a**–**c**); Chure and Mahabharat (**d**–**f**); mid-hill (**g**–**i**); high-hill (**j**–**l**); and high-mountain (**m**–**o**))

Ecological distribution of forest resource

We identified 21 different forest types in the study area (Appendix Fig. 8) which Schima-Castanopsis and hill sal forest were the two most widespread. During 1996–2006, there were notable increases in some of the forest classes including birch-fir-blue pine-cypress, birch-rhododendron forest, Schima-Castanopsis, temperate mountain oak, trans-Himalayan forest, fir forest, and upper temperate blue pine forest. In northern part, birch-fir-blue pine-cypress increased from 332 km^2 in 1996 to 395 km^2 in 2006. Similarly, trans-Himalayan forest expanded by 40 km^2, from 51 to 91 km^2, and birch-rhododendron expanded by 15 km^2, from 245 to 260 km^2. Schima-Castanopsis, which had occupied 1949 km^2 which expanded by 16 km^2 and temperate mountain oak forest increased from 1006 km^2 to 1017 km^2 by 2006 (Table 11). In contrast, there were declines for hill sal forests, lower tropical sal, and mixed broad leaved forest, Khair Sisoo riverine, mixed blue pine oak forests. Hill sal forest declined

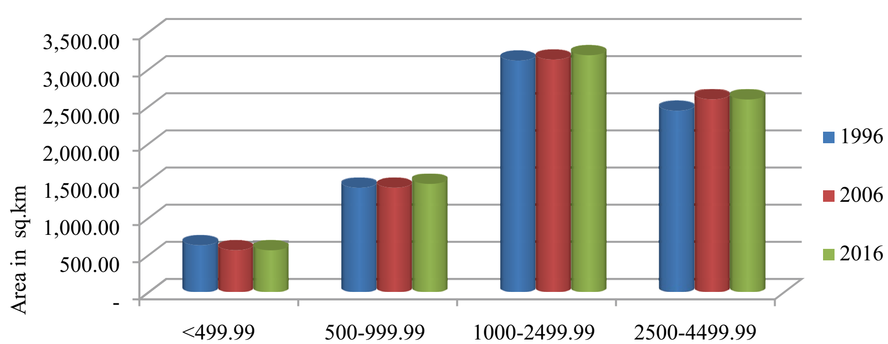


Fig. 4 Physiographic distribution of forest cover area in the study area during 1996–2016

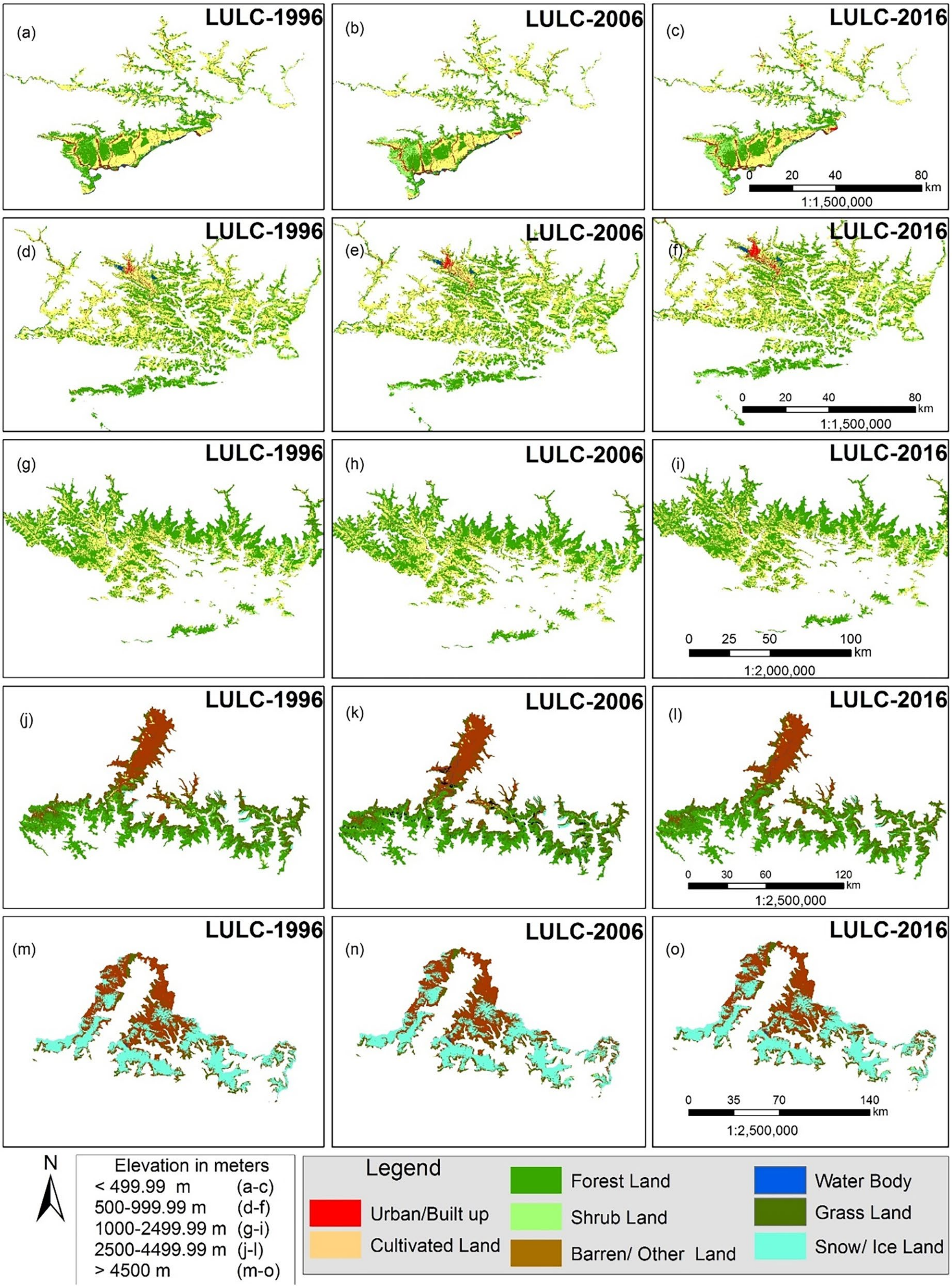

LULC-1996
LULC-2006
LULC-2016
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
(n)
(o)
0 20 40 80 km
1:1,500,000
0 25 50 100 km
1:2,000,000
0 30 60 120 km
1:2,500,000
0 35 70 140 km
1:2,500,000
N
Elevation in meters
< 499.99 m (a-c)
500-999.99 m (d-f)
1000-2499.99 m (g-i)
2500-4499.99 m (j-l)
> 4500 m (m-o)
Legend
Urban/Built up
Cultivated Land
Forest Land
Shrub Land
Barren/ Other Land
Water Body
Grass Land
Snow/ Ice Land

Table 11 Changes in areas of different forest types during 1996–2016 (in km^2)

SN	Forest type	1996	2006	2016	Change 1996–2006	Change 2006–2016	Net change 1996–2016
1	Alder forest deciduous walnut-maple-alder forest (AF)	117	118	132	1	14	15
2	Birch-fir-blue pine-cypress forest (BPB)	332	395	385	63	-10	53
3	Birch-rhododendron forest (FBR)	245	260	251	15	-9	6
4	Blue pine-spruce forest (BPS)	42	44	47	2	3	5
5	Chir pine forest (CPF)	87	89	93	2	4	6
6	Chir pine-broad leaved forest (CPB)	66	66	72	0	6	6
7	East Himalayan oak-laurel forest (OLF)	651	654	662	3	8	11
8	Fir forest (FF)	491	500	496	9	-4	5
9	Hill sal forest (HSF)	1299	1246	1276	−53	30	-23
10	Juniper forest (JF)	71	75	77	4	2	6
11	Larch forest (LF)	17	17	17	0	0	0
12	Lower temperate oak forest (LTO)	644	646	646	2	0	2
13	Lower tropical sal and mixed broad-leaved forest (LTS)	162	148	146	−14	−2	−16
14	Khair-Sissoo riverine forest (KSR)	28	23	23	−5	0	5
15	Mixed blue pine-oak forest (MBPO)	79	77	80	−2	3	1
16	Rhododendron Hemlock oak forest (RHO)	52	53	56	1	3	4
17	Schima-Castanopsis forest (SCF)	1949	1966	2014	16	49	65
18	Temperate mountain oak forest (TMO)	1006	1017	1021	11	4	15
19	Trans-Himalayan zone (THZ)	51	91	85	40	− 6	34
20	Upper temperate blue pine forest (UTB)	147	156	167	9	11	20
21	Other (O)	34	32	32	−3	0	−2

Source of forest types: TISC (2002) and https://rds.icimod.org/Home/Data?any=ecology&Category=datasets

from 1299 km^2 in 1996 to 1246 km^2 by 2006. Similarly, lower tropical sal and mixed broad leaved forest declined by 14 km^2 from 162 to 148 km^2 and continued to decline from 2006 to 2016 but the rate of decline was low. On the other hand, alder forest and lower temperate oak forest remained almost constant.

During 2006–2016, alder forest, hill sal forest, Schima-Castanopsis, and upper temperate blue pine witnessed increase whereas trans-Himalayan zone, fir forest, birch-fir-blue pine-cypress forest experienced some declines.

Alder forest increased from 118 to 132 km^2 whereas hill sal forest increased from 1246 to 1276 km^2. Schima-Castanopsis increased by 49 from 1966 km^2 to 2014 km^2. Upper temperate blue pine increased from 156 to 167 km^2. Trans-Himalayan forest decreased by 6 km^2, from 91 to 85 km^2. Birch-rhododendron declined from 260 to 251 km^2. Fir forest declined from 500 to 496 km^2 while birch-fir-blue pine-cypress had decreased by 10 km^2 during 2006 to 2016.

Discussion and conclusion

Many factors could have contributed to the increase in forest cover change in the hill and mountain regions, and these include (a) improved institutional mechanisms (Ministry of forests, departments, regional forest offices and district forest offices); (b) sectoral plans and policies; (c) community, leasehold, and collaborative forestry programs (at least 3,844 CFUG); and (d) other factors such as abandonment of agricultural land, partnership with donor agencies, and collaborative actions with conservation partners such as IUCN, UNDP, WWF, and ICIMOD (Ghimire et al., 2018). REDD+program to reduce deforestation and forest degradation, sustainably managing forests resource while conserving and enhancing forest-based carbon stocks (MoFSC, 2015). Furthermore, the Government of Nepal introduced a forestry decade (2014–2024) with the motto of “one house one tree, one village one forest, one city several gardens” targeting in particular the restoration and planting of at least 26,000 hectares of forest in the Tarai, Siwalik, and Hill regions. Consequently, a scientific forest management program was created aiming the protected forest area by around 0.2 million hectares (DFRS, 2016). Similar successful forest restoration programs were observed in India (Borah et al., 2018), China, South Korea, Vietnam (Choi et al., 2019), Indonesia (Van Oosten et al., 2014), and Africa (Goffner et al., 2019).

In this study, we have explored the spatiotemporal, physiographic and ecological changes in forest within the Gandaki river basin during 1996–2016 and identified the increases in forest cover in all the regions except Tarai (< 500 m). A common trend in Nepal as previous reported by Bhattarai and Conway (2021d), in the study area, is the out-migration in the mid-hill and mountain regions,has resulted in previously cultivated lands being left fallow and turning into other forms of vegetation cover (Bhattarai & Conway, 2021e).

The trend in increasing also seen in the national level from 38% in 1978/1979 (LRMP) to 40.36% in 2015 (DFRS, 2015). Furthermore, this trend is also replicated in some smaller clusters within the study area such as Kaski district (Bhandari et al., 2019), Tanahun district (Oli & Shrestha, 2009; Shrestha, 2015), CHAL region (Subedi, 2018), and Phewa watershed (Paudyal et al., 2017b). In Phewa lake watershed, forest cover has increased by 12% since the 1970s mainly due to the community-based forest management and regeneration programs (Besseau et al., 2018). Subedi et al. (2018) found an increase in forest cover by 57.2 km^2 in the 12 districts of Chitwan Annapurna Landscape (CHAL) (Baglung, Dhading, Gorkha, Gulmi, Kaski, Lamjung, Manang, Mustang, Myagdi, Parbat, Syangja, and Tanahu districts) during 2000–2010.

The National Biodiversity Strategy and Action Plan provides the strategic roadmap for biodiversity conservation of Nepal (Rai et al., 2016). National level plans prioritize preservation of forest, control of forest fire and invasive species, community-based integrated forest management for water, wildlife, conservation of endangered species, wetland and riverine forest conservation and agroforestry (MoFSC, 2015).

In addition, there has been reduced risks of environmental degradation and watershed destruction and improved landscape regeneration (Paudyal et al., 2017b). Much of this is because of controls on illegal logging, encroachment and forest fires (Pokharel & Nurse, 2004), dissuading farmers from open grazing, reduced pressure upon the community forests (Upreti, 2001), and preservation-oriented forest operational plans (Kimengsi et al., 2019).

Emigration to the Tarai and peri/urban areas due to personal insecurity aroused by political conflict (1996–2006) and people's quest for better quality of life, economic opportunities, and public service accessibility has resulted in abandoned cultivated land in hill and mountain region of Nepal (Adhikari et al., 2019; Jaquet et al., 2016, 2019; Khanal & Watanabe, 2006; Rai et al., 2019). Of the total cultivated land, 24% was abandoned in the study area where private forest cover developed (PPC, 2019).

Shifts to alternative sources such as liquefied petroleum gas (LPG) and electricity (Paudyal et al., 2019) for cooking has reduced people's dependency upon forest aiding the increase in forest cover. The consumption of LPG gas was increased and imported 77,594 ton in 2004/2005 and 258,299 ton in 2014/2015 from India (Bhandari & Pandit, 2018).

The national-level plantation program of rehabilitation and conservation in degraded and denuded areas is still ongoing with trained and motivated NGOs and community-based organizations (CBOs) contributing. Funding has come through a number of bilateral and multilateral institutional arrangements including DFID/USAID, GIZ, and ADB. UK-funded DFID has largely contributed to the restoration of 1.56 million ha in the denuded hills and degraded forests through the Plantation and Forest Management Research and Extension Program (Tamrakar & Mohans,2013; DFRS, 1999). New plantations have been developed in 204.28 ha in the barren land in the study area during 2019 (PPC, 2019).

Protecting primary forests is essential as they maintain ecological functions, carbon storage, and environmental equilibrium. The increasing forest cover observed for the study area go a long way to help meet to the national and global agenda of reforestation along with SDG 15. However, utilization of the forest ecosystem for poverty alleviation and local livelihood enhancement still remains as a challenge. For this, forest management, forest-based ecotourism and other enterprises map provide new opportunities.

Despite widely reported global forest losses and degradation, other evidence of forest restoration at the global, regional, and national levels indicates that the historical momentum is moving toward balanced ecosystems and the natural environment (Jacobs et al., 2015). The novelty of our study lies in the fact that we have used regional LULC data and forest cover data on ecological and physiographic zones to provide the details of changes in a mountain to lowland watershed, and we suggest it can be replicated to provide a scenario analysis of forest restoration elsewhere in the world at regional and local levels.

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Data availability The datasets generated and analyzed in the study can be made available on special reasonable request.

Declarations

Conflict of Interest The authors declare no conflict of interest.

Appendix

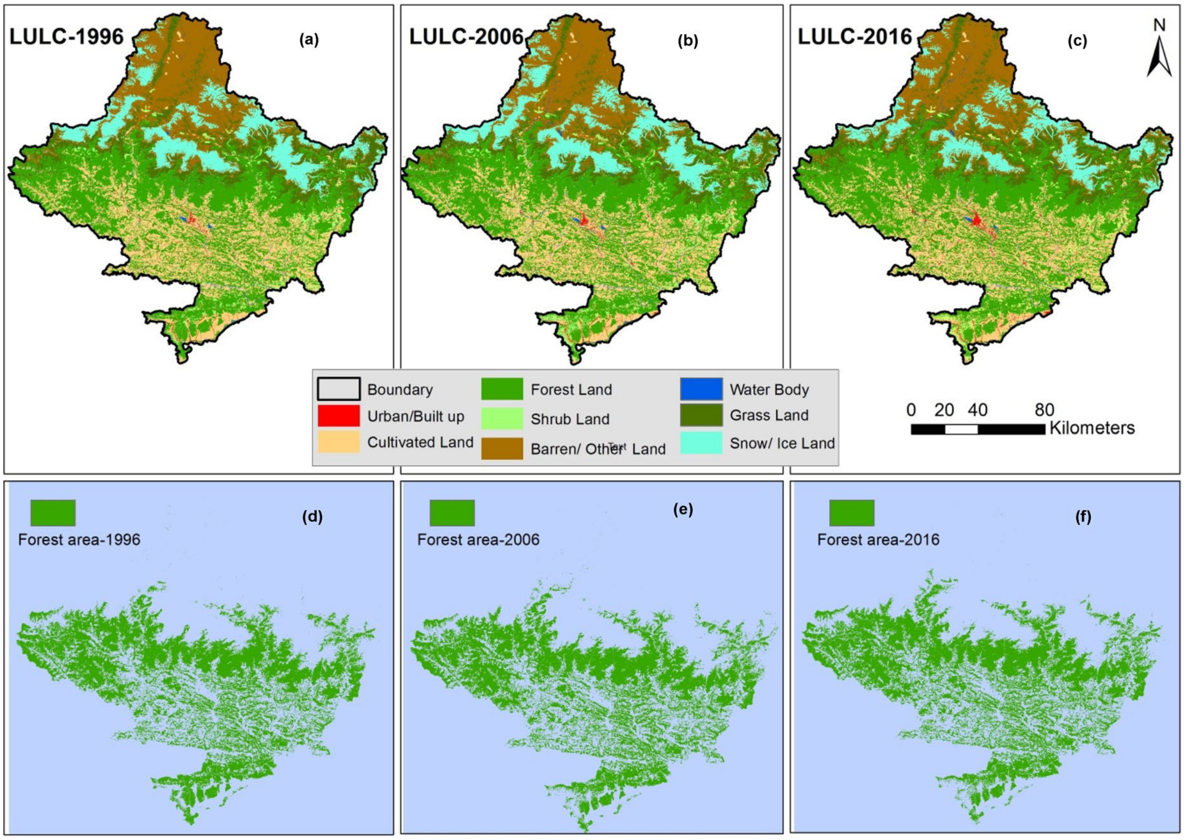

Fig. 6 Land use/cover map of the study area during (**a**) 1996, (**b**) 2006, and (**c**) 2016; (**d**) forest cover 1996; (**e**) forest cover 2006; (**f**) forest cover 2016

Table 12 Land use transfer matrix between 1996 and 2006 (area in km^2)

Year	2006									
	LULC	Urban	Cultivated	Forest	Shrub	Barren	Water	Grass	Snow/ice cover	Total
1996	Urban/built-up	53.3	0.000	0	0.000	0	0.007	0	0	53.3
	Cultivated land	26.3	4192.5	37.1	59.8	19.1	5.1	5.9	0.0	4345.8
	Forest land	1.0	34.6	7410.0	89.0	13.3	10.3	9.2	3.6	7571.0
	Shrub land	0.4	34.4	18.7	563.2	2.5	1.7	3.1	0	623.9
	Barren land	1.1	8.2	37.7	9.4	3758.3	29.9	134.4	151.0	4129.9
	Water body	0.2	2.4	10.7	1.6	12.9	147.2	1.1	1.5	177.5
	Grass land	0.4	20.7	142.5	3.7	51.6	24.6	2185.0	5.3	2433.6
	Snow/ice cover	0.0	0.0	16.2	0.3	83.6	0.6	10.6	2567.4	2678.6
	Total	82.6	4292.7	7672.8	727.0	3941.2	219.4	2349.2	2728.8	

Table 13 Land use transfer matrix between 2006 and 2016 (area in km^2)

Year	2016									
	LULC	Urban	Cultivated	Forest	Shrub	BL	WB	Grass	Snow/ice cover	Total
2006	Urban/built-up	80.99	1.1		0.3	0.2	0.1	0.0	0.0	82.6
	Cultivated land	50.06	3806.1	277.5	41.0	9.7	6.1	102.1	0.3	4292.8
	Forest land	3.1	170.5	7210.8	18.3	39.6	0.3	218.6	11.6	7672.8
	Shrub land	0.59	59.9	74.7	539.5	8.9	1.1	42.3	0.0	727.0
	Barren land	4.21	20.0	66.2	6.7	3209.4	24.7	473.1	136.9	3941.2
	Water body	1.1	6.4	14.8	1.4	27.5	158.0	9.6	0.6	219.3
	Grass land	1.02	12.9	115.4	28.3	310.4	3.7	1855.6	22.0	2349.2
	Snow/ice cover		0.0	18.8	0.0	627.8	2.4	97.4	1982.5	2728.8
	Total	141.06	4076.9	7778.2	635.4	4233.4	196.3	2798.7	2153.7	22,013.6

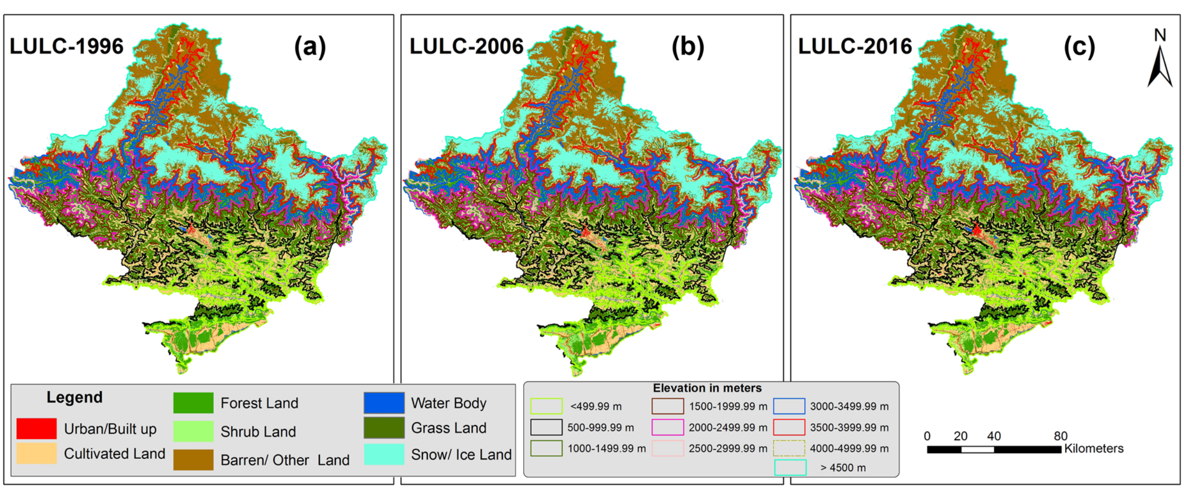

Fig. 7 Land use/land cover classes for 1996–2016 by elevation

Table 14 Forest distribution in the study area based on elevation (area in km^2)

Elevation in meters		1996	2006	2016	Change in % (1996–2016)
	Urban/built-up	8	15	27	237.50
< 499.99	Cultivated land	731	698	690	-5.61
	Forest land	625	558	557	-10.88
	Shrub land	78	155	169	116.67
	Barren land	77	87	86	11.69
	Water body	73	75	64	-12.33
	Grass land	4	8	3	-25.00
	Snow and ice land	0	0	0	
500–999.99	Urban/built-up	30	46	74	146.67
	Cultivated land	1656	1633	1567	-5.37
	Forest land	1399	1400	1449	3.57
	Shrub land	132	144	137	3.79
	Barren land	53	33	29	-45.28
	Water body	47	60	46	-2.13
	Grass land	26	26	41	57.69
	Snow and ice land	0	0	0	
1000–1499.99	Urban/built-up	9	15	27	189.62
	Cultivated land	1133	1120	1060	-6.45
	Forest land	1026	1037	1082	5.47
	Shrub land	80	81	67	-15.84
	Barren land	27	17	12	-54.27
	Water body	15	19	16	5.43
	Grass land	27	27	52	92.49
	Snow and ice land	0	0	0	
1500–1999.99	Urban/built-up	4	5	10	152.75
	Cultivated land	529	525	499	-5.65
	Forest land	916	921	927	1.23
	Shrub land	70	71	55	-22.10
	Barren land	10	7	5	-46.20
	Water body	6	7	5	-11.60
	Grass land	28	26	62	122.18
	Snow and ice land	0	0	0	
2000–2499.99	Urban/built-up	1	1	1	63.61
	Cultivated land	191	190	175	-8.39
	Forest land	1169	1170	1176	0.60
	Shrub land	55	57	41	-24.59
	Barren land	7	6	4	-50.41
	Water body	4	6	4	16.34
	Grass land	35	32	61	76.77
	Snow and ice land			0	

Table 14 (continued)

Elevation in meters		1996	2006	2016	Change in % (1996–2016)
2500–2999.99	Urban/built-up	1	1	1	51.65
	Cultivated land	61	67	44	-27.77
	Forest land	1159	1171	1177	1.50
	Shrub land	49	46	34	-29.35
	Barren land	68	72	59	-12.80
	Water body	6	14	13	123.58
	Grass land	79	51	94	19.30
	Snow and ice land				
3000–3499.99	Urban/built-up	0	0	1	288.89
	Cultivated land	18	27	13	-27.55
	Forest land	844	898	902	6.81
	Shrub land	78	64	38	-51.05
	Barren land	223	216	195	-12.55
	Water body	4	9	14	226.19
	Grass land	251	204	256	1.91
	Snow and ice land	4	4	3	-21.49
3500–3999.99	Urban/built-up	0		1	
	Cultivated land	21	25	20	-7.85
	Forest land	338	386	389	15.18
	Shrub land	55	50	37	-32.35
	Barren land	545	525	466	-14.44
	Water body	5	7	10	88.21
	Grass land	628	599	681	8.54
	Snow and ice land	28	27	16	-42.88
4000–4499.99	Urban/built-up	0	0	1	
	Cultivated land	6	6	4	-28.10
	Forest land	94	135	120	27.58
	Shrub land	11	13	15	42.33
	Barren land	714	695	603	-15.59
	Water body	5	6	7	31.68
	Grass land	804	791	943	17.22
	Snow and ice land	134	124	76	-43.74
> 4500	Urban/built-up	0	0	0	
	Cultivated land	0	0	0	
	Forest land	0	0	0	
	Shrub land	16	44	44	175.00
	Barren land	2403	2277	2771	15.31
	Water body	9	12	13	44.44
	Grass land	551	584	604	9.62
	Snow and Ice land	2507	2570	2055	-18.03

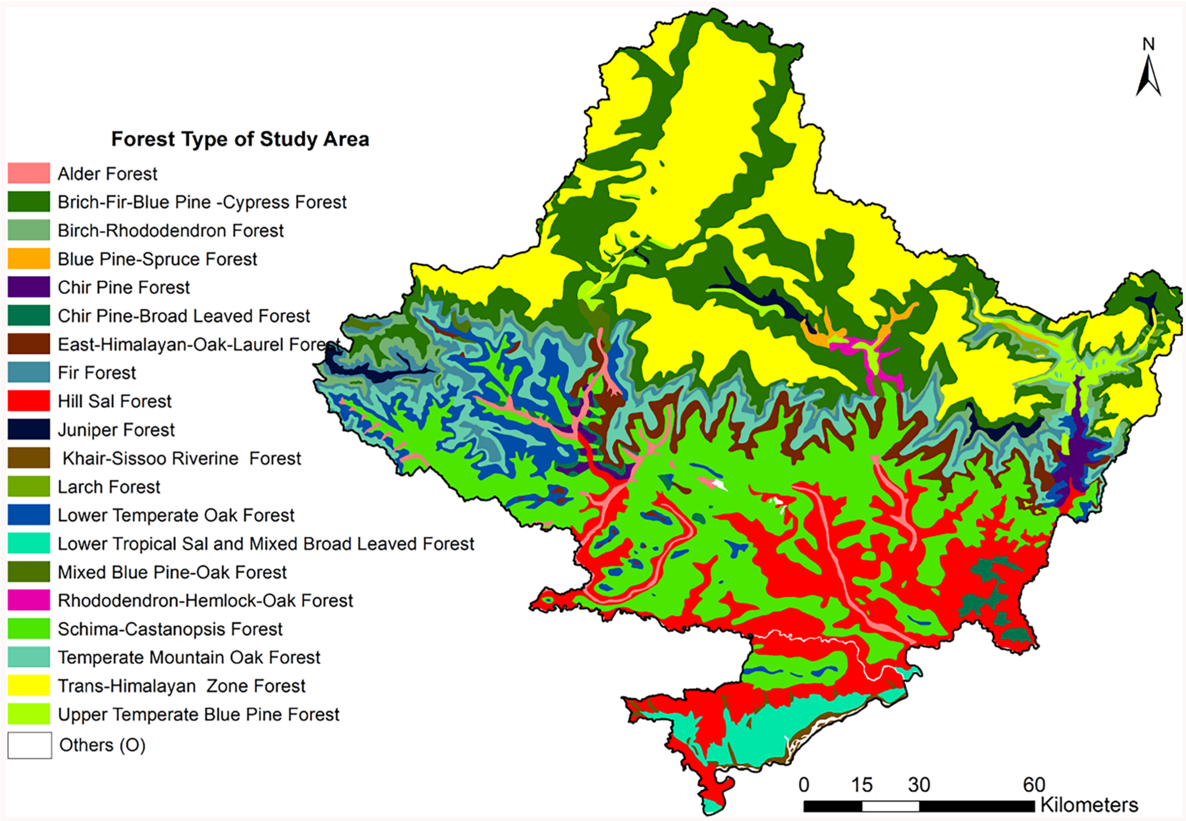

Fig. 8 Ecological distribution of forest types in the study area

References

Adhikari, S., Baral, H., Sudhir Chitale, V., & Nitschke, C. R. (2019). Perceived changes in ecosystem services in the Panchase Mountain ecological region Nepal. *Resources, 8*(1), 4.

Agrawal, A., & Chhatre, A. (2006). Explaining success on the commons: Community forest governance in the Indian Himalaya. *World Development, 34*(1), 149–166.

Alfonso, A., Zorondo-Rodríguez, F., & Simonetti, J. A. (2017). Perceived changes in environmental degradation and loss of ecosystem services, and their implications in human well-being. *International Journal of Sustainable Development & World Ecology, 24*(6), 561–574. https://doi.org/10.1080/13504509.2016.1255674

Anderson, J. R. (1976). *A land use and land cover classification system for use with remote sensor data* (Vol. 964). US Government Printing Office. https://doi.org/10.3133/pp964

Armenteras, D., Espelta, J. M., Rodríguez, N., & Retana, J. (2017). Deforestation dynamics and drivers in different forest types in Latin America: Three decades of studies (1980–2010). *Global Environmental Change, 46*, 139–147. https://doi.org/10.1016/j.gloenvcha.2017.09.002

Baral, P., Wen, Y., & Urriola, N. N. (2018a). Forest cover changes and trajectories in a typical middle mountain watershed of western nepal. *Land, 7*(2), 72. https://doi.org/10.3390/land7020072

Besseau, P., Graham, S., & Christophersen, T. (2018). Restoring forests and landscapes: the key to a sustainable future. *Global Partnership on Forest and Landscape Restoration, Vienna, Austria. ISBN,(978–3)*, 902762–97.

Bhandari, P. K., Bhusal, P., Paudel, G., Upadhyaya, C. P., & Khanal Chhetri, B. B. (2019). Importance of community forestry funds for rural development in Nepal. *Resources, 8*(2), 85.

Bhandari, R., & Pandit, S. (2018). Electricity as a cooking means in nepal—a modelling tool approach. *Sustainability, 10*(8), 2841.

Bhattarai, K., Conway, D., & Yousef, M. (2009). Determinant of deforestation in the central development region of Nepal: 1973–2000. *Journal of Environmental Management, 91*, 471–488.

Bhattarai, K., & Conway, D. (2021). Contemporary environmental problems in Nepal-Geographic perspective: Forestry and environment (Chapter 8). In Nusser, M. (Eds.) *Advances in Asian Human Environmental Research,* (1st ed., pp. 663–754). Springer Nature, Switzerland. *ISSN:* 1879–7199. https://doi.org/10.1007/978-3-030-50168-6

Bhattarai K. and Conway D. (2021). Contemporary environmental problems in Nepal-Geographic perspective: Introduction (Chapter 1). In Nusser, M (Eds.), Advances in Asian Human Environmental Research, (1st ed., pp. 1–36). Springer Nature, Switzerland. ISSN: 1879–7199. https://doi.org/10.1007/978-3-030-50168-6

Bhattarai, K., & Conway D. (2021). Contemporary Environmental Problems in Nepal-Geographic Perspective: Urban Growth (Chapter 4). In Nusser, M (Eds.), Advances in Asian Human Environmental Research, (1st ed., pp. 201–334). Springer Nature, Switzerland. ISSN: 1879–7199. https://doi.org/10.1007/978-3-030-50168-6

Bhattarai, K., & Conway, D. (2021). Contemporary environmental problems in Nepal-Geographic perspective: Demography, Caste/ethnicity, Federalism and Socio-economic Conditions in Relation to Contemporary Environment (Chapter 2). In Nusser, M (Eds.), Advances in Asian Human Environmental Research, (1st ed., pp. 37–114). Springer Nature, Switzerland. ISSN: 1879–7199. https://doi.org/10.1007/978-3-030-50168-6

Bhattarai, K., & Conway, D. (2021). Contemporary environmental problems in Nepal-Geographic perspective: The environment (Chapter 3). In Nusser, M (Eds.), Advances in Asian Human Environmental Research, (1st ed., pp. 115–199). Springer Nature, Switzerland. ISSN: 1879–7199. https://doi.org/10.1007/978-3-030-50168-6

Bhuju, D. R., Yonjan, P. B., & Baidya, B. M. (2007). Landuse pattern and its change in the eastern Churiya hills of Nepal Himalaya. *Ecoprint: An International Journal of Ecology*, *14*, 65–71. https://doi.org/10.3126/eco.v14i0.4827

Borah, B., Bhattacharjee, A., & Ishwar, N. M. (2018). Bonn challenge and India: Progress on restoration efforts across states and landscapes. *New Delhi, India: IUCN and MoEFCC, Government of India*. https://doi.org/10.2305/IUCN.CH.2018.12.en

Borrelli, P., Panagos, P., & Wüpper, D. J. (2020). Positive cascading effect of restoring forests. *International Soil and Water Conservation Research, 8*(1), 102. https://doi.org/10.1016/j.iswcr.2019.12.002

Browder, J. O. (2002). The urban-rural interface: Urbanization and tropical forest cover change. *Urban Ecosystems, 6*(1), 21–41. https://doi.org/10.1023/A:1025962512653

Campbell, J. B. (1981). Spatial correlation effects upon accuracy of supervised classification of land cover. *Photogrammetric Engineering and Remote Sensing, 47*(3), 355–363.

Campbell, J. B., & Wynne, R. H. (1996). *Introduction to remote sensing*.

CBS (2014) Populaation Monograph. Central Bureau of Statistics, National Planning Commission, Government of Nepal, Kathmandu, Nepal

Chaudhary, R. P., Uprety, Y., & Rimal, S. K. (2016). Deforestation in Nepal: Causes consequences and responses. *Biological and Environmental hazards risks and disasters*, 335–372.

Choi, G., Jeong, Y., & Kim, S. I. (2019). Success factors of national-scale forest restorations in South Korea, Vietnam, and China. *Sustainability, 11*(12), 3488.

Costa, H., Almeida, D., Vala, F., Marcelino, F., & Caetano, M. (2018). Land cover mapping from remotely sensed and auxiliary data for harmonized official statistics. *ISPRS International Journal of Geo-Information, 7*(4), 157. https://doi.org/10.3390/ijgi7040157

Cueva Ortiz, J., Espinosa, C. I., Quiroz Dahik, C., Aguirre Mendoza, Z., Cueva Ortiz, E., Gusmán, E., & Hildebrandt, P. (2019). Influence of anthropogenic factors on the diversity and structure of a dry forest in the Central Part of the Tumbesian Region (Ecuador–Perú). *Forests, 10*(1), 31.

Dandekhya, S., England, M., Ghate, R., Goodrich, C. G., Nepal, S., Prakash, A., & Udas, P. B. (2017). The Gandaki basin: Maintaining livelihoods in the face of landslides, floods, and drought. *HI-AWARE Working Paper*, *9*. https://doi.org/10.13140/RG.2.2.17756.28802

Dave, R., Saint-Laurent, C., Murray, L., Antunes Daldegan, G., Brouwer, R., de Mattos Scaramuzza, C. A., & Pearson, T. (2018). Second Bonn challenge progress report. *Application of the Barometer in*, *2019*.

DFRS (1999). Forest Resources of Nepal. Department of Forest Research and Survey, Kathmandu, Nepal.

DFRS (2015) State of Nepal's Forests. Forest Resource Assessment (FRA) Nepal, Government of Nepal, Ministry of Forests and Soil Conservation, Department of Forest Research and Survey (DFRS). Kathmandu, Nepal

DFRS (2016) Forestry Decade Program, 2014–2024. Government of Nepal, Ministry of Forests and Soil Conservation,Department of Forest Research and Survey (DFRS). Kathmandu, Nepal

DSCWM (2012) Sustainable management of Chure: efforts, challenges and potential

Earth explorer, Landsat data Archive, https://earthexplorer.usgs.gov/

FAO (2018) FAO. 2018. The State of the World's Forests 2018 - Forest pathways to sustainable development. Food and Agriculture Organization of the United Nations, Rome. Licence: CC BY-NC-SA 3.0 IGO

FAO. (2020). Global Forest Resources Assessment 2020. *Key Findings*. Food and Agriculture Organization of the United Nations (FAO), Rome https://doi.org/10.4060/ca8753en

Feng, X., Fu, B., Lu, N., Zeng, Y., & Wu, B. (2013). How ecological restoration alters ecosystem services: An analysis of carbon sequestration in China's Loess Plateau. *Scientific Reports, 3*(1), 1–5. https://doi.org/10.1038/srep02846

Feng, Y., Lu, D., Moran, E. F., Dutra, L. V., Calvi, M. F., & De Oliveira, M. A. F. (2017). Examining spatial distribution and dynamic change of urban land covers in the Brazilian Amazon using multitemporal multisensor high spatial resolution satellite imagery. *Remote Sensing, 9*(4), 381.

Flinzberger, L., Zinngrebe, Y., & Plieninger, T. (2020). Labelling in Mediterranean agroforestry landscapes: A Delphi study on relevant sustainability indicators. *Sustainability Science, 15*(5), 1369–1382. https://doi.org/10.1007/s11625-020-00800-2

Foody, G. M. (2002). Status of land cover classification accuracy assessment. *Remote Sensing of Environment, 80*(1), 185–201. https://doi.org/10.1016/S0034-4257(01)00295-4

Gallaun, H., Steinegger, M., Wack, R., Schardt, M., Kornberger, B., & Schmitt, U. (2015). Remote sensing based two-stage sampling for accuracy assessment and area estimation of land cover changes. *Remote Sensing, 7*(9), 11992–12008. https://doi.org/10.3390/rs70911992

Gautam, A. P., Shivakoti, G. P., & Webb, E. L. (2004). A review of forest policies, institutions, and changes in the resource condition in Nepal. *International Forestry Review, 6*(2), 136–148. https://doi.org/10.1505/ifor.6.2.136.38397

Ge, J., Pitman, A. J., Guo, W., Wang, S., & Fu, C. (2019). Do uncertainties in the reconstruction of land cover affect the simulation of air temperature and rainfall in the CORDEX region of East Asia? *Journal of Geophysical Research: Atmospheres, 124*(7), 3647–3670. https://doi.org/10.1029/2018JD029945

Gerhardt, F., & Foster, D. R. (2002). Physiographical and historical effects on forest vegetation in central New England, USA. *Journal of Biogeography, 29*(10–11), 1421–1437. https://doi.org/10.1046/j.1365-2699.2002.00763.x

Ghimire, P., Kafle, G., & Bhatta, B. (2018). Carbon stocks in Shorea robusta and Pinus roxburghii forests in Makawanpur district of Nepal. *Journal of AFU, 2*, 241–248.

Giam, X. (2017). Global biodiversity loss from tropical deforestation. *Proceedings of the National Academy of Sciences, 114*(23), 5775–5777. https://doi.org/10.1073/pnas.1706264114

Goffner, D., Sinare, H., & Gordon, L. J. (2019). The Great Green Wall for the Sahara and the Sahel Initiative as an opportunity to enhance resilience in Sahelian landscapes and livelihoods. *Regional Environmental Change, 19*(5), 1417–1428. https://doi.org/10.1007/s10113-019-01481-z

GoN. (1998). *Topographical map*. Government of Nepal , Survey Department,Min Bhawan, Kathmandu

Goodin, D. G., Anibas, K. L., & Bezymennyi, M. (2015). Mapping land cover and land use from object-based classification: An example from a complex agricultural landscape. *International Journal of Remote Sensing, 36*(18), 4702–4723. https://doi.org/10.1080/01431161.2015.1088674

Hixson, M. S., & Fuhs, N. (1980). Evaluation of several schemes for classification of remotely sensed data. *Photogrammetric Engineering and Remote Sensing, 46*, 1547–1553.

HMGN. (1993). *Forest Act 1993*. His Majesty's Government of Nepal.

HMGN. (1995). *Forest regulation 1995*. His Majesty's Government of Nepal.

Jacobs, D. F., Oliet, J. A., Aronson, J., Bolte, A., Bullock, J. M., Donoso, P. J., & Weber, J. C. (2015). Restoring forests: What constitutes success in the twenty-first century? *New Forests, 46*, 601–614. https://doi.org/10.1007/s11056-015-9513-5

Jaquet, S., Kohler, T., & Schwilch, G. (2019). Labour migration in the middle hills of Nepal: Consequences on land management strategies. *Sustainability, 11*(5), 1349.

Jaquet, S., Shrestha, G., Kohler, T., & Schwilch, G. (2016). The effects of migration on livelihoods, land management, and vulnerability to natural disasters in the Harpan watershed in western Nepal. *Mountain Research and Development, 36*(4), 494–505. https://doi.org/10.1659/MRD-JOURNAL-D-16-00034.1

Jensen, J. R. (1996). *Introductory digital image processing: a remote sensing perspective* (No. Ed. 2). Prentice-Hall Inc..

Karimi, F., Sultana, S., Babakan, A. S., & Suthaharan, S. (2019). An enhanced support vector machine model for urban expansion prediction. *Computers, Environment and Urban Systems, 75*, 61–75. https://doi.org/10.1016/j.compenvurbsys.2019.01.001

Kavzoglu, T., & Colkesen, I. (2009). A kernel functions analysis for support vector machines for land cover classification. *International Journal of Applied Earth Observation and Geoinformation, 11*(5), 352–359. https://doi.org/10.1016/j.jag.2009.06.002

Khanal, N. R., & Watanabe, T. (2006). Abandonment of agricultural land and its consequences. *Mountain Research and Development, 26*(1), 32–40. https://doi.org/10.1659/0276-4741(2006)026[0032:AOALAI]2.0.CO;2

Khatri D, Maskey G, Adhikari B (2018) REDD+ and Community Forestry in Nepal: Strengthening or Paralysing Decentralised Governance?. *Journal of Forest and Livelihood, 16*(1):35-55. https://doi.org/10.3126/jfl.v16i1.22881

Kharal,DK and Dhungana (2018) FOREST COVERAGE AND BIODIVERSITY IN NEPAL, Government of Nepal Ministry of Forests and Environment Singha Durbar, Kathmandu

Kimengsi, J. N., Bhusal, P., Aryal, A., Fernandez, M. V. B. C., Owusu, R., Chaudhary, A., & Nielsen, W. (2019). What (de) motivates forest users' participation in co-management? Evidence from Nepal. *Forests, 10*(6), 512.

Li, Y., Viña, A., Yang, W., Chen, X., Zhang, J., Ouyang, Z., & Liu, J. (2013). Effects of conservation policies on forest cover change in giant panda habitat regions, China. *Land Use Policy, 33*, 42–53. https://doi.org/10.1016/j.landusepol.2012.12.003

Löf, M., Madsen, P., Metslaid, M., Witzell, J., & Jacobs, D. F. (2019). Restoring forests: Regeneration and ecosystem function for the future. *New Forests, 50*(2), 139–151. https://doi.org/10.1007/s11056-019-09713-0

Menton, M., Larrea, C., Latorre, S., Martinez-Alier, J., Peck, M., Temper, L., & Walter, M. (2020). Environmental justice and the SDGs: From synergies to gaps and contradictions. *Sustainability Science, 15*(6), 1621–1636. https://doi.org/10.1007/s11625-020-00789-8

MoFSC. (2015). Nepal REDD+ Strategy Part 1: Operational summary.

MoPE. (2001). Nepal's State of the Environment (Agriculture and Forests). Ministry of Population and Environment/ESS, Kathmandu.

Mori, A. S., Lertzman, K. P., & Gustafsson, L. (2017). Biodiversity and ecosystem services in forest ecosystems: A research agenda for applied forest ecology. *Journal of Applied Ecology, 54*(1), 12–27. https://doi.org/10.1111/1365-2664.12669

Nguyen, T. T., Barber, P., Harper, R., Linh, T. V. K., & Dell, B. (2020). Vegetation trends associated with urban development: The role of golf courses. *PloS One, 15*(2), e0228090. https://doi.org/10.1371/journal.pone.0228090

Niraula, R. R., Gilani, H., Pokharel, B. K., & Qamer, F. M. (2013). Measuring impacts of community forestry program through repeat photography and satellite remote sensing in the Dolakha district of Nepal. *Journal of Environmental Management, 126*, 20–29. https://doi.org/10.1016/j.jenvman.2013.04.006

Oli, B. N., & Shrestha, K. (2009). Carbon status in forests of Nepal: An overview. *Journal of Forest and Livelihood, 8*(1), 62–66.

Olofsson, P., Foody, G. M., Stehman, S. V., & Woodcock, C. E. (2013). Making better use of accuracy data in land change studies: Estimating accuracy and area and quantifying uncertainty using stratified estimation. *Remote Sensing of Environment, 129*, 122–131. https://doi.org/10.1016/j.rse.2012.10.031

Ortega Adarme, M., Queiroz Feitosa, R., Nigri Happ, P., Aparecido De Almeida, C., & Rodrigues Gomes, A. (2020). Evaluation of deep learning techniques for deforestation detection in the Brazilian Amazon and cerrado biomes from remote sensing imagery. *Remote Sensing, 12*(6), 910.

Pant, R. R., Zhang, F., Rehman, F. U., Koirala, M., Rijal, K., & Maskey, R. (2020). Spatiotemporal characterization of dissolved trace elements in the Gandaki River, Central Himalaya Nepal. *Journal of Hazardous Materials, 389*, 121913. https://doi.org/10.1016/j.jhazmat.2019.121913

Pant, R. R., Zhang, F., Rehman, F. U., Wang, G., Ye, M., Zeng, C., & Tang, H. (2018). Spatiotemporal variations of hydrogeochemistry and its controlling factors in the Gandaki River Basin, Central Himalaya Nepal. *Science of the Total Environment, 622*, 770–782. https://doi.org/10.1016/j.scitotenv.2017.12.063

Paudel, N. S., Adhikary, A., Mbairamadji, J., & Nguyen, T. Q. (2018). Small-scale forest enterprise development in Nepal: overview, issues and challenges. *FAO Rome*, *84*.

Paudyal, K., Baral, H., Bhandari, S. P., Bhandari, A., & Keenan, R. J. (2019). Spatial assessment of the impact of land use and land cover change on supply of ecosystem services in Phewa watershed Nepal. *Ecosystem Services, 36*, 100895. https://doi.org/10.1016/j.ecoser.2019.100895

Paudyal, K., Baral, H., Lowell, K., & Keenan, R. J. (2017a). Ecosystem services from community-based forestry in Nepal: Realising local and global benefits. *Land Use Policy, 63*, 342–355. https://doi.org/10.1016/j.landusepol.2017.01.046

Paudyal, K., Baral, H., Putzel, L., Bhandari, S., & Keenan, R. J. (2017b). Change in land use and ecosystem services delivery from community-based forest landscape restoration in the Phewa Lake watershed Nepal. *International Forestry Review, 19*(4), 88–101. https://doi.org/10.1505/146554817822295966

Pokharel, B. K., & Nurse, M. (2004). Forests and people's livelihood: Benefiting the poor from community forestry. *Journal of Forest and Livelihood, 4*(1), 19–29.

PPC. (2019). *Status Paper of Gandaki Province Provincial Policy and Planning Commission (PPC)*. Provincial Governments of Nepal.

Prestele, R., Alexander, P., Rounsevell, M. D., Arneth, A., Calvin, K., Doelman, J., & Verburg, P. H. (2016). Hotspots of uncertainty in land-use and land-cover change projections: A global-scale model comparison. *Global Change Biology, 22*(12), 3967–3983. https://doi.org/10.1111/gcb.13337

Rai, R., Neupane, P., & Dhakal, A. (2016). Is the contribution of community forest users financially efficient? A household level benefit-cost analysis of community forest management in Nepal. *International Journal of the Commons*, *10*(1). https://doi.org/10.18352/ijc.594

Rai, R., Zhang, Y., Paudel, B., & Khanal, N. R. (2019). Status of farmland abandonment and its determinants in the transboundary gandaki river basin. *Sustainability, 11*(19), 5267. https://doi.org/10.3390/su11195267

Reddy, C. S., Pasha, S. V., Satish, K. V., Saranya, K. R. L., Jha, C. S., & Murthy, Y. K. (2018). Quantifying nationwide land cover and historical changes in forests of Nepal (1930–2014): Implications on forest fragmentation. *Biodiversity and Conservation, 27*(1), 91–107. https://doi.org/10.1007/s10531-017-1423-8

Rickli, C., & Graf, F. (2009). Effects of forests on shallow landslides–case studies in Switzerland. *Forest Snow and Landscape Research, 82*(1), 33–44.

Rifat, S. A. A., & Liu, W. (2020). Measuring community disaster resilience in the conterminous coastal United States. *ISPRS International Journal of Geo-Information, 9*(8), 469. https://doi.org/10.3390/ijgi9080469

Rijal, S., Rimal, B., Stork, N., & Sharma, H. P. (2020). Quantifying the drivers of urban expansion in Nepal. *Environmental Monitoring and Assessment, 192*(10), 1–17. https://doi.org/10.1007/s10661-020-08544-3

Rijal, S., Techato, K., Gyawali, S., Stork, N., Dangal, M. R., & Sinutok, S. (2021). Forest Cover Change and Ecosystem Services: A Case Study of Community Forest in Mechinagar and Buddhashanti Landscape (MBL) Nepal. *Environmental Management, 67*(5), 963–973. https://doi.org/10.1007/s00267-021-01430-9

Rimal, B., Baral, H., Stork, N. E., Paudyal, K., & Rijal, S. (2015). Growing city and rapid land use transition: Assessing multiple hazards and risks in the Pokhara Valley Nepal. *Land, 4*(4), 957–978. https://doi.org/10.3390/land4040957

Rimal, B., Rijal, S., & Kunwar, R. (2020b). Comparing support vector machines and maximum likelihood classifiers for mapping of urbanization. *Journal of the Indian Society of Remote Sensing, 48*(1), 71–79. https://doi.org/10.1007/s12524-019-01056-9

Rimal, B., Sharma, R., Kunwar, R., Keshtkar, H., Stork, N. E., Rijal, S., & Baral, H. (2019). Effects of land use and land cover change on ecosystem services in the Koshi River Basin Eastern Nepal. *Ecosystem Services, 38*, 100963. https://doi.org/10.1016/j.ecoser.2019.100963

Rimal, B., Zhang, L., Keshtkar, H., Sun, X., & Rijal, S. (2018). Quantifying the spatiotemporal pattern of urban expansion and hazard and risk area identification in the Kaski District of Nepal. *Land, 7*(1), 37.

Rimal, B., Sloan, S., Keshtkar, H., Sharma, R., Rijal, S., & Shrestha, U. B. (2020a). Patterns of historical and future urban expansion in Nepal. *Remote Sensing, 12*(4), 628. https://doi.org/10.3390/rs12040628

Rodriguez-Galiano, V. F., Ghimire, B., Rogan, J., Chica-Olmo, M., & Rigol-Sanchez, J. P. (2012). An assessment of the effectiveness of a random forest classifier for land-cover classification. *ISPRS Journal of Photogrammetry and Remote Sensing, 67*, 93–104.

Scholz DF, N.; Hixson, M. (1979) An evaluation of several different classification schemes, their parameters, and performance. Paper presented at the In Proceedings, Thirteenth International Symposium on the Remote Sensing of the Environment, Ann Arbor: University of Michigan,

Sexton, J. O., Song, X. P., Huang, C., Channan, S., Baker, M. E., & Townshend, J. R. (2013). Urban growth of the Washington, DC–Baltimore, MD metropolitan region from 1984 to 2010 by annual, Landsat-based estimates of impervious cover. *Remote Sensing of Environment, 129*, 42–53. https://doi.org/10.1016/j.rse.2012.10.025

Sharma, P., Thapa, R. B., & Matin, M. A. (2020). Examining forest cover change and deforestation drivers in Taunggyi District, Shan State, Myanmar. *Environment, Development and Sustainability, 22*(6), 5521–5538. https://doi.org/10.1007/s10668-019-00436-y

Shrestha B.P (2015) Faunal (mammal) diversity and human wildlife conflict in community forests (A case study from Tanahun and Kavrepalanchok districts, Nepal). Community Forestry in Nepal,51.

Solomon, N., Hishe, H., Annang, T., Pabi, O., Asante, I. K., & Birhane, E. (2018). Forest cover change, key drivers and community perception in Wujig Mahgo Waren forest of northern Ethiopia. *Land, 7*(1), 32.

Steiner, D. (1970). Automation in photo interpretation. *Geoforum, 1*(2), 75–88.

Subedi, B., et al. (2018). *Forest Carbon Assessment in Chitwan-Annapurna Landscape Nepal*.

Tamrakar, P.R., Mohans, B. (2013), *Forest Restoration at Landscape Level in Nepal*. Asia Pacific Forestry Commission.

TISC (2002) Forest and vegetation types of Nepal. Tree Improvement and Silviculture Component (TISC) Forest and vegetation types of Nepal. Kathmandu: Natural Resource Management Sector Assistance Programme. (TISC) Document Series No. 104

Tripathi, S., Subedi, R., & Adhikari, H. (2020). Forest cover change pattern after the intervention of community forestry management system in the mid-hill of Nepal: A case study. *Remote Sensing, 12*(17), 2756.

Tsai, Y. H., Stow, D. A., López-Carr, D., Weeks, J. R., Clarke, K. C., & Mensah, F. (2019). Monitoring forest cover change within different reserve types in southern Ghana. *Environmental Monitoring and Assessment, 191*, 281. https://doi.org/10.1007/s10661-019-7450-z

Uddin, K., Shrestha, H. L., Murthy, M. S. R., Bajracharya, B., Shrestha, B., Gilani, H., & Dangol, B. (2015). Development of 2010 national land cover database for the Nepal. *Journal of Environmental Management, 148*, 82–90.

UN. (2015). *The 2030 Agenda for Sustainable Development-SDGs 15*. United Nation.

UN. (2019). *United Nations Decade on Ecosystem Restoration (2021–2030)*. United Nations General Assembly

Upreti, B. (2001). Beyond rhetorical success: Advancing the potential for the community forestry programme in Nepal to address equity concerns. *Social learning in community forests*, 189–209.

Van Oosten, C., Gunarso, P., Koesoetjahjo, I., & Wiersum, F. (2014). Governing forest landscape restoration: Cases from Indonesia. *Forests, 5*(6), 1143–1162.

Wakiyama, T. (2004). Community forestry in Nepal: A comparison of management systems between indigenous forestry and modern community forestry. *Policy Trend Report*, 1–20.

Yadav, V., &Ghosh, S. K. (2019). Assessment and prediction of urban growth for a mega-cityusing CA-Markov model.*Geocarto International*, 1-33. https://doi.org/10.1080/10106049.2019.1690054