Research article

Mapping Land Use Shifts in Nepal's Protected Regions: Insights for Biodiversity and Resource Management

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Abstract This study investigated the temporal dynamics of Land Use and Land Cover (LULC) changes across 13 protected areas (PAs) (12 National Parks and 1 Wildlife Reserve) and their associated buffer zones from 1990 to 2021. Data from the National Land Cover Monitoring System (NLCMS) for the years 1990, 2000, and 2010 were acquired, while random forest modeling using Landsat 7 images at the Google Earth Engine (GEE) platform was utilized for the year 2021. The data were analyzed using the Land Change Modeler (LCM) within the TerraSet IDRISI software. Total forest cover for the core areas of the 13 PAs exhibited resilience, declining from 4,731.89 km² (1990) to 4,554.87 km² (2000) before recovering to 5,021.95 km² (2021), marking a net gain of 290.06 km². Total shrubland area fluctuated, peaking at 298.24 km² (2010) but declining to 252.47 km² (2021). Total grassland area experienced dramatic shifts, plummeting to 1,723.04 km² (2010) before rebounding to 3,088.57 km² (2021). Total agricultural land area peaked at 207.62 km² (2010) but sharply contracted to 82.33 km² (2021). Total barren land area expanded by 65% (1990–2000) but stabilized at 2,203.70 km² (2021). Total built-up areas surged 179-fold (0.19 to 34.08 km²), reflecting anthropogenic encroachment pressures. Total snow/glacier cover recovered from a low of 2,276.57 km² (2000) to 2,997.39 km² (2021). Buffer zones exhibited contrasting trends: total agricultural land area expanded steadily (1,322.24 to 1,407.36 km²), total shrubland area doubled (92.75 to 211.90 km²), and total barren land area plummeted 90% (488.07 to 46.40 km²). Total built-up areas grew tenfold (3.87 to 32.54 km²), highlighting urbanization pressures. Total grassland area rebounded from x (1990) to 941.19 km² (2021). Total snow/glacier coverage was halved post-2010 (419.83 to 244.61 km²). In summary, the core areas demonstrated biodiversity recovery, demonstrated by forest regeneration and reduced agriculture, while buffer zones faced intensified land use from agricultural and urbanization uses and climate impacts. These findings highlight the delicate balance between conservation and development pressures in Nepal's protected areas. They offer valuable insights for planning and policy, stressing the need for targeted interventions to address human impacts while preserving ecological connectivity. Given Nepal's diverse landscapes, from tropical lowlands to Himalayan ranges, these insights can guide sustainable management both locally and globally.

Keywords Land Use Land Cover (LULC), protected areas, conservation, Nepal, remote sensing, buffer zones, ecological monitoring, biodiversity

INTRODUCTION

Land use and land cover (LULC) changes in protected areas play a crucial role in impacting the conservation and ecological integrity of these environments. Protected areas such as national parks (NPs), animal reserves and nature sanctuaries, and conservation areas are established to safeguard biodiversity, protect endangered species (Zhou et al., 2025), and maintain ecological equilibrium by providing a sanctuary for a wide variety of animals, including rare and endangered species. These areas contribute to sustaining essential ecosystem activities, including water purification, carbon sequestration, soil stabilization, and climate regulation. Nonetheless, they are susceptible to the impact of human activities, including local development and ecotourism (Ramaano, 2024). The repercussions of LULC modifications can be far-reaching, encompassing habitat alteration, loss of biodiversity, and changes in ecosystem services. Effective monitoring of LULC in protected areas is imperative for biodiversity conservation, the preservation of ecological services, and sustainable resource management (Wade et al., 2003).

Human activities, notably unsustainable tourism, have a significant impact on LULC changes in protected areas, with potentially far-reaching environmental consequences. The development of tourism infrastructure, such as hotels, resorts, roads, and recreational facilities, often necessitates extensive land alteration and deforestation, resulting in habitat loss and fragmentation (Gössling, 2002). These transformations not only diminish biodiversity but also affect the natural landscape and ecological services. Both natural processes and human activities influence the LULC dynamics in these areas, emphasizing the necessity of understanding these changes for designing effective conservation programs. Habitat fragmentation, deforestation, and land degradation can all adversely affect plant and animal life, resulting in species extinction and genetic diversity loss. Conservationists can identify critical areas requiring protection and restoration efforts by continuously monitoring LULC changes (Pickering and Hill, 2007).

Protected area ecosystems offer a wide range of crucial services, including soil stabilization, carbon sequestration, water purification, and climate management. The extent of land cover directly influences these services. For example, wetlands and forests are essential for maintaining natural carbon sinks and hydrological cycles. Protected areas, by trapping carbon, are also pivotal in attempts to mitigate climate change. Alterations to LULC can disrupt these services, leading to adverse effects on the environment and society. Routine monitoring allows for early detection of such changes, enabling swift action to safeguard these vital ecological functions. Tracking changes in LULC helps in evaluating carbon sequestration capacity and devising strategies to enhance it. Understanding LULC dynamics also aids in identifying vulnerable areas and developing management strategies to increase resilience, contributing to climate adaptation efforts (Roy et al., 2022).

Resources within protected areas are pivotal for the livelihoods of residents, particularly in developing and the least developed countries, offering nature-based tourism (ecotourism) and biodiversity conservation. Effective monitoring of LULC can assist in developing sustainable land management methods that strike a balance between conservation efforts and the needs of local communities. By providing data on the prevalence of human activities like farming, grazing, and tourism, LULC monitoring enables the design of solutions that address community needs with minimal negative environmental consequences. Its primary goal is to preserve the ecological integrity of protected areas while ensuring sustainable resource extraction. Detailed and accurate LULC information supports the development of successful conservation initiatives, land use planning, and regulatory frameworks. This valuable LULC information can be harnessed by policymakers to implement measures aimed at reducing negative impacts and fostering long-term growth (Marion and Leung, 2001).

In Nepal, there are 20 protected areas including 12 National Parks (NPs), 6 conservation areas, 1 wildlife reserve,1 hunting reserve, and 13 buffer zones, extending from lowland Terai to high mountains, which covers 23.39% of the country's total land area and contributes to in-situ conservation of ecosystems and biodiversity across the country (DNPWC, 2024). This study is particularly important due to the country's exceptional geographic and ecological diversity. Nepal has a wide range of ecosystems, from tropical forests in the lowlands to alpine meadows in the high Himalayas, creating a global biodiversity hotspot. Preserving the country's protected areas is crucial for conserving its unique biodiversity, including numerous endemic and endangered species such as the snow leopard, the red panda, and the Bengal tiger. Despite its enormous tourism potential, Nepal faces challenges such as a lack of recreational centers, insufficient transportation and communication, a shortage of skilled labor, pollution management issues, inadequate advertising, poor tourist destinations, low-quality lodging, and security concerns (Badal and Kharel, 2019). Furthermore, these regions are experiencing growing pressures from human activities, climate change, and natural disasters such as landslides and floods. Monitoring LULC changes in Nepal's protected regions can aid in recognizing and addressing these dangers, thus guaranteeing the ongoing preservation of its distinct wildlife and ecosystems.

Furthermore, the economy of Nepal and the livelihoods of numerous rural communities are intricately connected to natural resources and ecosystem services. The effective monitoring of LULC can play a vital role in the development of sustainable land management practices that strike a balance between conservation endeavors and the requirements of local populations. This is imperative for attaining long-term ecological sustainability and socio-economic advancement in Nepal. Moreover, Nepal faces significant vulnerability to the effects of climate change, with its glaciers and snowpacks serving as critical sources of water for millions of people. Understanding LULC dynamics holds the utmost importance for climate adaptation strategies, facilitating improved water resource management and mitigation of disaster risks from glacial and snowpack melt.

OBJECTIVES

The objectives of this study were to quantify the observed changes of LULC in protected areas of Nepal every ten years from 1990 to 2021, and to identify their impacts on conservation. The analysis sought to answer how the conservation strategies can be evaluated and how to measure their impact on biodiversity, ecosystem services, and sustainable resource management, thereby providing pivotal data to inform policy decisions and effective conservation strategies.

METHODOLOGY

Study Area: The research focused on 13 protected areas with established buffer zones, which are designated areas within protected regions with specific resource use restrictions to enhance conservation (Table 1 and Fig.1). Pandit et al. (2018) defined a buffer zone as an area within the protected area that has restrictions on resource use and specific measures to enhance its conservation value.

Table 1 Selected National Parks, Wildlife Reserve, and Buffer Zones

	National parks with their buffer zone	Year established	Abbreviation used
1	Chitwan NP and Buffer Zone	1990	CNP
2	Lamtnag NP and Buffer Zone	2000	LNP
3	Sagarmatha NP and Buffer Zone	2010	SNP
4	Bardiya NP and Buffer Zone	2000	BNP
5	Shey-Phoksundo NP and Buffer Zone	2000	SPNP
6	Makalu Barun NP and Buffer Zone	2000	MBNP
7	Shuklaphanta NP and Buffer Zone	2010	SUNP
8	Parsa NP and Buffer Zone	2010	PNP
9	Rara NP and Buffer Zone	1990	RNP
10	KoshiTappu Wildlife Reserve and Buffer Zone	1990	KTWR
11	Khaptad NP and Buffer Zone	2010	KNP
12	Banke NP and Buffer Zone	2020	BKNP
13	ShivaPuri NP and Buffer Zone	2020	SNNP

Source: DNPWC 20024

Nepal's geographical setting spans between 26°-31°N and 80°-89°E, bordered by China and India, with elevations ranging from 60 m above sea level in the Terai to 8,848.86 m at Mount Everest's peak. This topographical diversity creates distinct ecological zones, from the subtropical Terai lowlands to the alpine Himalayas, all influenced by the South Asian monsoon (June-September). The country's ecoregions support rich biodiversity: the Terai features tropical forests housing Bengal tigers and rhinoceros; the mid-hills contain temperate forests with red pandas and Himalayan black bears; and the alpine zones provide habitat for snow leopards and Himalayan tahr. The country as a whole received 91.2% of the typical annual precipitation of 1570.4 mm. The average maximum temperature of Nepal was 27.9°C (0.6°C above the normal annual maximum temperature) and the average minimum temperature was 15.6°C (0.5°C above the normal annual minimum temperature) in 2023 (DHM, 2023), supporting over 6,000 flowering plant species, 800 bird species, and 180 mammal species.

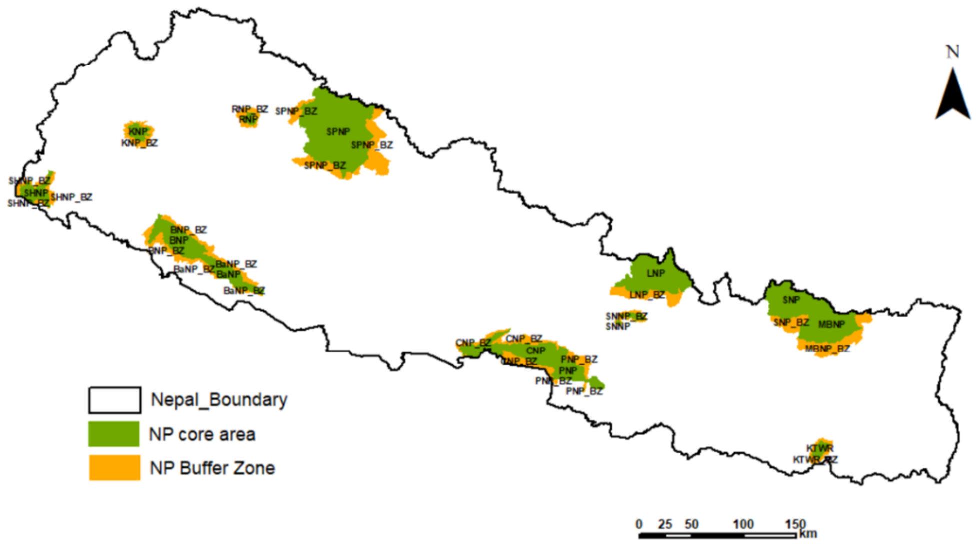


Fig. 1 Shapefile showing the selected protected areas of Nepal

Data Acquisition and Processing

The study utilized secondary data, which was generated through the National Land Cover Monitoring System (NLCMS) for Nepal, developed by the Forest Research and Training Centre (FRTC) under the Ministry of Forests and Environment, Government of Nepal (FRTC, 2024). The system utilizes readily accessible remote-sensing data from the Landsat 7 satellite and operates on a cloud-based machine learning architecture within the Google Earth Engine (GEE) platform. It facilitates the generation of annual land cover maps employing a standardized classification system, ensuring uniformity and reliability, which can be used for land management initiatives in Nepal. We used NLCMS data for 2000, 2010, and 2019 (FRCT, 20022). For 1990, we received maps from the UN Food and Agriculture Organization in Nepal (FAO-Nepal), which they also acquired from the International Centre for Integrated Mountain Development (ICIMOD). Data and maps for 2021 were generated using GEE, where we utilized the former generated maps as a training sample supplemented by using Google Earth images using a random forest supervised classification method in GEE. The accuracy of the map for 2021 was over 80 % kappa coefficient.

Land Change Modeler

The Land Change Modeler (LCM), integrated within the TerraSet IDRISI software platform (Clark Labs, 2020), offers a robust framework for quantifying transitions between land cover categories. This tool enabled us to analyze and visualize changes in land use over time, facilitating the identification of areas undergoing transitions from one land cover class to another. By employing a variety of analytical techniques, such as Markov chains and cellular automata, LCM allowed for the comparison of land cover losses, gains, and net persistent areas across different time periods. The user-friendly interface and comprehensive analytical capabilities made this a valuable tool for our study.

RESULTS AND DISCUSSION

Overview of Land Use Land Cover Change within the Study Areas

The assessment of LULC changes in the 12 NPs and one wildlife reserve between 1990 and 2021 demonstrated substantial temporal dynamics (Table 2. Between 1990 and 2021, land use patterns exhibited significant shifts. Forest area initially declined from 7,467.59 km² (1990) to 7,133.85 km² (2000) before recovering to 7,654.86 km² (2021). The shrubland area showed a steady increase from 338.34 km² to 464.37 km² over the same period. Grassland area experienced a decline, reaching 2,317.25 km² (2010), but rebounded sharply to 4,029.76 km² (2021). In contrast, agricultural land area peaked at 1,598.67 km² (2010) before declining to 1,489.69 km² (2021). Barren land area surged to 3,041.22 km² (2000) but later decreased to 2,250.10 km² (2021), while water body area steadily diminished from 170.43 km² to 150.23 km². Snow/glacier coverage fluctuated throughout the period, settling at 3,242.00 km² (2021). Built-up areas exhibited exponential growth, expanding from 4.06 km² to 66.63 km². Meanwhile, unclassified areas saw a sharp decline from 46.65 km² to 1.60 km², reflecting advancements in classification accuracy.

Table 2 Land use land cover area over the study period

Land use/Years	1990	2000	2010	2021
Forest	7467.59	7133.85	7169.29	7654.86
Shrubland	338.34	392.41	410.61	464.37
Grassland	3469.97	3109.28	2317.25	4029.76
Agriculture area	1508.33	1534.10	1598.67	1489.69
Barren area	1903.22	3041.22	2906.26	2250.10
Water body	170.43	159.07	161.00	150.23
Snow/glacier	3075.95	2562.15	3362.67	3242.00
Built-up area	4.06	4.74	10.46	66.63
Unclassified	46.65	47.64	48.33	1.60

Note: Area in km²

Changes Occurred in the Land Cover Classes

A total of 54 transitions from one land use to another were identified. However, less than 3 km² were excluded for further analysis between the studied years (1990 and 2021), revealing complex patterns of land use change. The priority classes where the transition occurred are within forest, grasslands, shrublands, agriculture, waterbodies, builtups, and snow/glaciers.

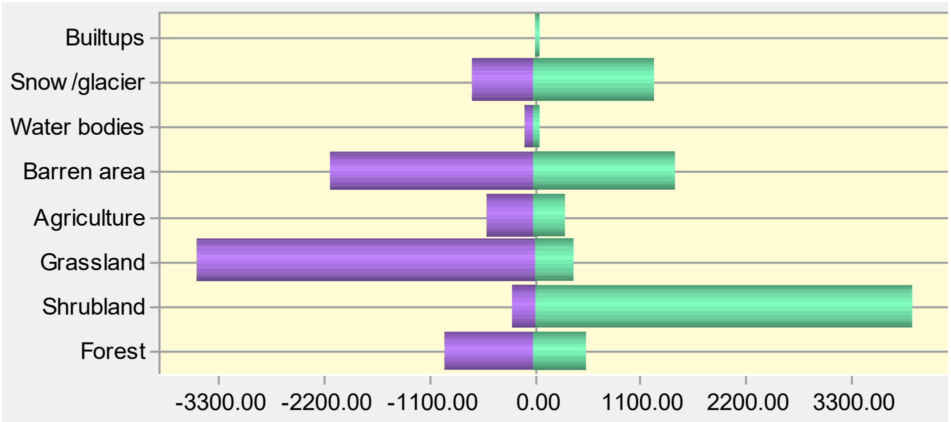
The results were also interpreted using loss, gain, net change, and net persistence (Figs. 3 and 4), which were generated from using the LCM tool. Forest area exhibited a net gain of +364.29 km², indicating expansion, while Shrubland and Grassland showed gains of +83.80 km² and +775.29 km² (the largest net increase), respectively. Agriculture remained stable with a marginal net gain of +6.29 km². In contrast, the Barren area experienced the most substantial net loss (−569.03 km²), followed by Water body (−10.90 km²) and Unclassified areas (−45.95 km²), the latter nearly reduced. Snow/glacier expanded significantly (+698.47 km²), a notable deviation from global glacial retreat patterns, and Built-up areas surged by +62.52 km², reflecting rapid urbanization.

The study reveals significant transitions in land cover patterns during the period of study. The most significant change was from forest to shrubland, affecting 470.86 km² of area. The reverse transition from shrubland to forest occurred over 80.0145 km². Forest to grassland conversion was substantial at 310.38 km², with grassland to forest reclamation observed across 158.6835 km². Agricultural transitions were noteworthy, with 117.55 km² of forest converted to agriculture and a larger area of 246.2985 km² transitioned from agriculture back to forest. Barren areas saw bidirectional changes, with 27.30 km² of forest becoming barren and 55.8045 km² of barren land reverting to forest. Minor transitions included forest to water bodies and water bodies to forest.

Shrublands experienced both gains and losses across various categories, with the largest conversion being from grassland to shrubland, covering 1,675.44 km². Other major transitions included grassland to barren areas, snow/glacier, and forest. Smaller transitions occurred with agriculture, water bodies, snow/glacier areas, and built-up zones. Overall, the data suggests a net loss in grassland area, with the most significant transformations occurring in grasslands and barren areas.

Water bodies experienced both gains and losses across various categories, with the largest conversion from water bodies to shrubland. Snow/glacier areas underwent significant transitions across various land cover types, with some areas gaining snow/glacier coverage while others lost it, indicating potential impacts of climate or land use changes on glacial environments.

The data indicates a significant expansion of built-up areas across various land cover types, with agriculture and barren areas experiencing the most substantial transitions to built-up land. Grasslands also saw notable conversions, with 13.84 km² transitioning to built-up.



Change in km²

Fig. 3 Loss and gain in each class type from 1990-2021 for the selected PAs

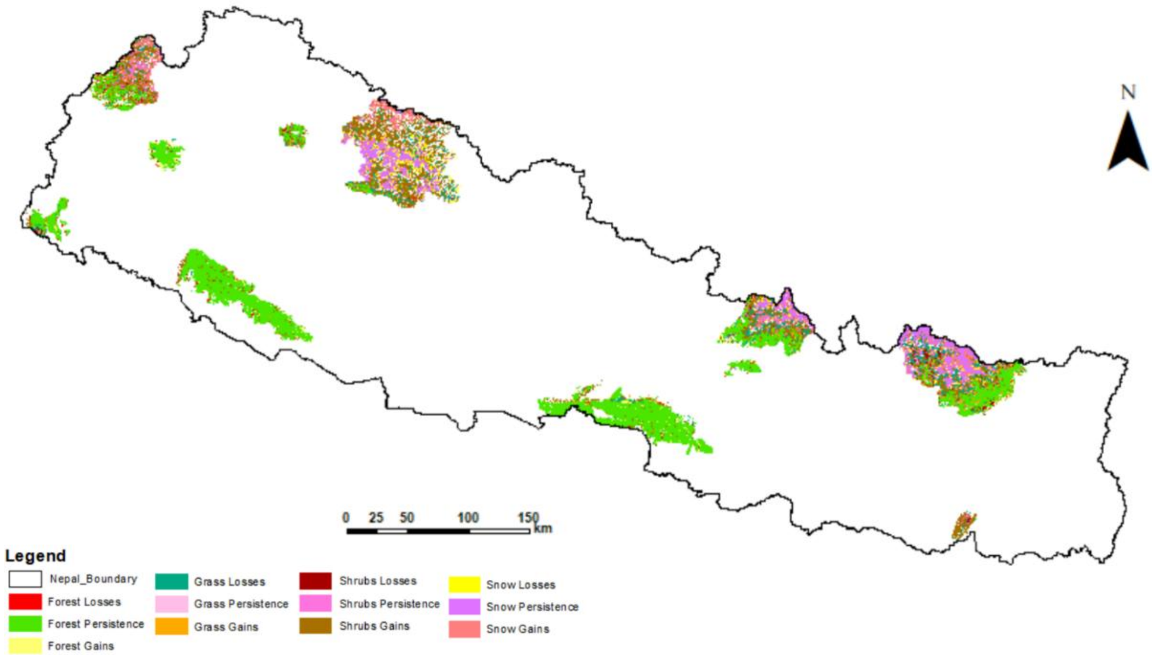


Fig. 4 Spatial map showing loss and gain

Forest, shrub, grass and snow/glacier from 1990-2021 for the selected PAs

Results for Individual National Parks

The clipped tool used in the ArcGIS pro for the individual NP results (Fig. 5) interpreted that, between 1990 and 2021, forest cover remained the dominant land type across all national parks, with slight increases in CNP (1369.29 to 1449.05 km²) and BarNP (1186.19 to 1263.80 km²), while remaining stable in SNP and MBNP. Shrubland expanded notably in SNP (18.22 to 209.30 km²) and BarNP (22.10 to 73.14 km²), suggesting vegetation regeneration or land use changes.

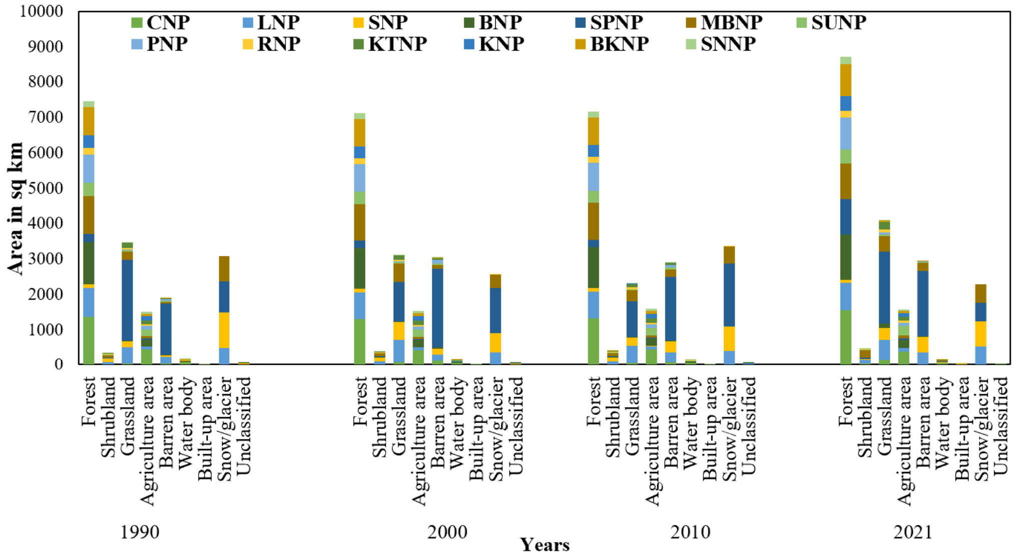


Fig. 5 Loss, persistence, and gain observed in the four main class types

Grassland declined significantly in SNP (115.78 to 45.81 km²) and CNP (88.60 to 66.26 km²), likely due to land conversion. Agricultural areas decreased across most parks, particularly in SNP (115.78 to 67.41 km²), indicating reduced cultivation. Barren land increased in SNP (64.94 to 166.52 km²) and SPNP (25.70 to 91.91 km²), possibly due to glacial retreat or land degradation. Water bodies and built-up areas showed minimal change. Snow/glacier cover became more distinct from 2000, particularly in SNP and MBNP, reflecting improved classification and potential climate influences. Unclassified areas declined sharply, highlighting enhanced mapping accuracy. Overall, SNP and BarNP exhibited dynamic shifts in shrubland and barren land, while CNP and MBNP remained forest-dominated with moderate variations.

Table 3 LULC categories in the core area for the study periods

	LULC	1990	2000	2010	2021	Trend
1	Forest	4731.89	4554.87	4583.08	5021.95	
2	Shrubland	245.59	287.82	298.24	252.47	
3	Grassland	2604.20	2388.70	1723.04	3088.57	
4	Agriculture area	186.09	161.17	207.62	82.33	
5	Barren area	1415.15	2331.06	2243.04	2203.70	
6	Water body	115.77	106.47	108.35	111.60	
7	Snow/glacier	2808.99	2276.57	2942.84	2997.39	
8	Built-up area	0.19	0.24	0.52	34.08	
9	Unclassified	37.23	38.13	38.41	0.96	

Overall Trend Changes in the Core Areas

Between 1990 and 2021, the 13 NPs showed dynamic land-cover transitions (Table 3). Forest cover experienced a net increase—from 4731.89 km² in 1990 to 5021.95 km² in 2021—even though it receded to 4554.87 km² around 2000 before recovering. Shrubland and agricultural areas both fluctuated: shrubland grew from 245.59 km² in 1990 to 298.24 km² by 2010 and then declined to 252.47 km² by 2021, while agricultural land peaked at 207.62 km² in 2010 (after falling to 161.17 km² in 2000) and then shrank sharply to 82.33 km² by 2021. Grassland area fell steeply from 2604.20 km² in 1990 to 1723.04 km² in 2010 before rebounding dramatically to 3088.57 km² by 2021. Barren land expanded markedly between 1990 and 2000 (from 1415.15 km² to 2331.06 km²) and then declined slightly to 2203.70 km² by 2021. Snow and glacier cover declined from 2808.99 km² in 1990 to 2276.57 km² in 2000 but increased in the following decades (reaching 2997.39 km² by 2021). Built-up area grew dramatically (from 0.19 km² in 1990 to 34.08 km² in 2021). Water bodies remained relatively stable (115.77 km² in 1990 vs. 111.60 km² in 2021), and unclassified land remained minor and roughly constant (around 37–38 km² through 2010, nearly zero by 2021). Overall, these trends indicate notable gains in forest and built-up areas and a complex pattern of gains and losses in other land cover types over the 31 years.

Overall Trend Changes in the Buffer Zone Areas of the Study Sites

The analysis of LULC changes in the buffer zone areas of 13 selected PAs in Nepal between 1990 and 2021 highlights notable transformations distinct from those observed in the core protected areas. Forest cover exhibited an overall increase from 2735.70 km² in 1990 to 2632.91 km² in 2021, despite an initial decline observed in 2000. Shrubland expanded markedly, more than doubling from 92.75 km² in 1990 to 211.90 km² by 2021. Grassland cover showed a decreasing trend until 2010 but later rebounded, ultimately reaching 941.19 km² in 2021, surpassing its 1990 extent. Agricultural land steadily increased across the decades, rising from 1322.24 km² in 1990 to 1407.36 km² in 2021, indicating continued cultivation pressure in buffer zones. In contrast, barren areas witnessed a dramatic decline from 488.07 km² in 1990 to just 46.40 km² in 2021, possibly due to land rehabilitation or conversion to vegetated cover. Water bodies showed a marginal decline, while snow/glacier coverage initially increased, peaking at 419.83 km² in 2010, but subsequently decreased to 244.61 km². Built-up areas experienced substantial growth—from 3.87 km² in 1990 to 32.54 km² in 2021—highlighting rapid infrastructure development in the peripheries of protected areas. Unclassified land declined sharply, reflecting improved categorization or land use stabilization. Collectively, these patterns indicate dynamic land transformations in buffer zones, with efforts for conservation, land management, and human-wildlife interactions in Nepal's protected area network.

Table 4 LULC categories in the buffer zone area for the study periods

	LULC	1990	2000	2010	2021	Trend
1	Forest	2735.70	2578.98	2586.22	2632.91	
2	Shrubland	92.75	104.59	112.37	211.90	
3	Grassland	865.76	720.57	594.22	941.19	
4	Agriculture area	1322.24	1372.93	1391.05	1407.36	
5	Barren area	488.07	710.16	663.23	46.40	
6	Water body	54.66	52.60	52.65	38.63	
7	Snow/glacier	266.96	285.58	419.83	244.61	
8	Built-up area	3.87	4.50	9.94	32.54	
9	Unclassified	9.42	9.51	9.92	0.64	

DISCUSSION

The overall transition analysis of land cover classes between 1990 and 2021 across the 13 PAs (whole areas) in Nepal reveals dynamic and multidirectional land transformations, indicative of both ecological processes and anthropogenic interventions. Forest areas were predominantly converted into shrubland and grassland, with notable transitions also occurring toward agriculture, barren land, and, to a lesser extent, built-up areas and snow/glacier. Shrubland exhibited a high degree of conversion into forest, grassland, barren land, and agriculture, suggesting its transitional nature within the landscape mosaic.

Grassland experienced substantial shifts, primarily transitioning into shrubland, barren land, and snow/glacier, indicating potential ecological succession or climatic influences. Agricultural land was largely transformed into forest, shrubland, and barren areas, while some of it also transitioned to built-up areas, highlighting pressures from land abandonment or urban expansion. Barren areas were converted into shrubland, snow/glacier, and to a lesser extent, forest and agriculture, pointing to potential re-vegetation or geomorphological changes.

Snow/glacier areas underwent notable transitions to barren land, shrubland, and grassland, while also gaining area from forest and grassland, likely reflecting climate-induced cryospheric dynamics (Thapa et al., 2021). Water bodies experienced conversions to and from various classes, including forest, barren land, and shrubland, suggesting seasonal or long-term hydrological alterations. Built-up areas expanded at the expense of forest, shrubland, and agriculture, underscoring developmental pressures within protected landscapes. These patterns collectively reflect the complexity of land system dynamics within Nepal's protected areas, driven by natural succession, climatic variability, and socio-economic change.

The change analysis in the core areas for the studied period indicates considerable ecological dynamics. Core forest cover showed a net gain over the period, reflecting positive conservation outcomes, despite a dip in 2000. This success has played a highly significant role as a result of community management. For instance, Nepal’s community forests span roughly 2.3 million hectares and are managed by more than 22,000 user groups that include 3 million households—nearly 57% of the nation’s population (Pandey and Pokhrel, 2021). The Government of Nepal is focusing more on transferring the national forest management to community-led forest management in the future.

In contrast, the grassland area declined significantly until 2010 but rebounded sharply by 2021, possibly due to active habitat restoration and management practices (Budhathoki et al., 2024). Likewise, shrubland areas experienced overall decline, suggesting reduced human activity within the core zones. Barren areas expanded in the early years, followed by a slight contraction, while built-up areas increased rapidly, although they remain relatively limited in total area. Snow and glacier coverage exhibited moderate variability, increasing in recent years. These trends emphasize ongoing ecological transitions in core zones and highlight the impact of conservation policies and climate-related factors on land cover dynamics.

Additionally, between 1990 and 2021, land use and land cover (LULC) changes in the buffer zones surrounding twelve national parks and one wildlife reserve indicate intensified human–landscape interactions. The buffer zone Forest area fluctuated but generally increased, suggesting reforestation or natural regeneration efforts. Notably, shrubland and agricultural areas expanded substantially, indicating persistent livelihood dependence on land resources. Grasslands, after an initial decline, recovered to exceed 1990 levels, potentially due to local management initiatives. A dramatic reduction in barren land points to successful land reclamation or conversion to productive uses. Built-up areas rose sharply, reflecting increasing settlement and infrastructure development. Snow and glacier coverage varied, while water bodies showed a slight decline. These transformations underscore the growing pressure on buffer zones and the urgent need for integrated conservation and development approaches to sustainably manage these transitional landscapes.

The study suggests implementing integrated conservation approaches that combine strict protection measures with community-based management, sustainable tourism development, and climate change adaptation strategies.

CONCLUSIONS

This research highlights several major findings with significant implications for protected area management in Nepal. First, while forest conservation efforts have shown success, the substantial loss of grasslands and expansion of shrublands indicate a need for ecosystem-specific management approaches. Second, the rapid increase in built-up areas demonstrates the growing pressure of development on protected areas, requiring stronger regulation and sustainable tourism planning. Third, the changes in snow/glacier coverage and water bodies suggest vulnerability to climate change impacts, necessitating adaptive management strategies. The study recommends implementing integrated conservation approaches that combine strict protection measures with community-based management, sustainable tourism development, and climate change adaptation strategies. Priority should be given to grassland ecosystem restoration, controlling infrastructure development in sensitive areas, and strengthening buffer zone management policies. Future conservation success will depend on balancing ecological preservation with local community needs while adapting to climate change impacts. These findings can inform conservation policies not only in Nepal but also in other regions facing similar protected area management challenges.

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