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Carbon Dynamics in Response to Land Use and Land Cover Change in Dir Kohistan, Hindu Kush Himalaya Ranges, Pakistan (1992–2018)

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Abstract: Monitoring carbon dynamics in relation to land use and land cover change (LULCC) is critical for effective global carbon management and climate change mitigation. This study assesses the carbon dynamics associated with LULCC in the Dir Kohistan region of the Hindu Kush Himalaya Ranges in Pakistan, using both field inventory data and remote sensing (RS) techniques. The results reveal an annual reduction rate of 0.17% in forest land (FL) and 0.44% in rangeland (RL), while agricultural land (AL) and barren land (BL) expanded at rates of 0.25% and 2.04%, respectively. The total ecosystem carbon stock in FL ranged from $122.17 \mathrm{Mg\,C\,ha^{-1}}$ in Oak-Geordiana (OG) forests to $423.51 \mathrm{Mg\,C\,ha^{-1}}$ in Deodar (CD) forests. In contrast, the carbon stock in AL and RL was considerably lower, at $31.54\ \mathrm{Mg\,C\,ha^{-1}}$ and $37.27 \mathrm{Mg\,C\,ha^{-1}}$, respectively. The conversion of AL to RL led to an 18.16% loss in ecosystem carbon, while the transition from FL to AL resulted in a significant 668.92% reduction in ecosystem carbon. Within the FL-to-AL transition, the lowest carbon loss of 287.36% was observed in the conversion from OG forest to AL, while the greatest loss of 1242.79% occurred in the conversion from CD forest to AL . These findings highlight the substantial carbon losses resulting from land transitions from natural ecosystems to built environments, driven by agricultural and settlement expansion, rapid urbanization, illegal logging, inadequate law enforcement, and heavy dependence on natural resources. Therefore, restoration and rehabilitation efforts, along with improved land management strategies, are urgently needed in these mountainous regions to conserve carbon stocks and meet global emission reduction targets under the Kyoto Protocol.

Keywords: Land conversion; Carbon loss; Carbon management; Conservation

1 Introduction

In the terrestrial ecosystem, forests act as one of the largest carbon sinks and have stored huge amounts of carbon [1, 2]. It has been estimated that approximately 308 gigatons of carbon are stored in the aboveground biomass of global forests, with an annual sequestration of about 8 gigatons of carbon from the atmosphere [3–5]. Although forests play a crucial role in the global carbon cycle, conversion of forests to other land uses (LUs), such as AL and settlement, releases about 1.2 Pg C to 3 Pg C each year [6–8]. Along with fossil fuel burning, LULCC is considered to be equally responsible for climate change and global warming [4, 5]. The conversion of forest to other LUs through deforestation contributes about 12% to 23% of the total global emissions [1, 8, 9]. Besides forests, grassland conversion to other LUs also results in a reduction in carbon stock.

Deforestation and forest degradation are the major drivers of forest carbon loss [5]. The anthropogenic interventions associated with rapid urbanization, agriculture and settlement expansion have largely affected forests and grassland on a global, regional, national and local scale [10, 11]. The regional and national pattern of carbon emissions with LULCC and their major drivers are uncertain because of the complex nature of direct and indirect drivers [2]. LULCC, particularly forest conversion, has both natural causes (forest fire, floods, and diseases) and human causes such as illegal cutting, agriculture and settlement expansion [6, 9, 10]. Though human causes can be linked mainly to population growth, underlying causes, such as management regimes, social and political culture and governmental policies, are now considered to be also the major drivers [12, 13]. Although conversion of natural ecosystems, such as forests and grasslands to other LUs, is a major contributor to climate change, forest conversion through plantation and controlling of deforestation is also considered to be a potential climate change mitigation option [7]. During 2001 and 2011, alone in the tropical region, a reduction of 0.9 Pg C per year from LULCC emissions was estimated through avoiding deforestation [7, 14].

LULCC at the regional level affects interregional LU dynamics, which can ultimately affect the global environment. Therefore, understanding of these drivers and related emissions is crucial for curbing the emissions and avoiding environmental consequences [15]. The international community, under the umbrella of the United Nations Framework Convention on Climate Change (UNFCCC), stresses the monitoring of LULCC-induced emissions at global, regional and national levels [16]. The ecological changes in the vegetation of land can be best judged by assessing the LU patterns and changes and the global LULCC monitoring and assessment are critical parts of ecological management and restoration [17, 18]. Both RS and field inventory are used to monitor the status of LULCC and its impacts on the carbon stock. RS is considered to be very effective for the change detection in the land area as well as in the status of vegetation [19–21]. It has been proven to be a cost-effective way to provide accurate information on the LULCC dynamics [22, 23]. The use of RS to assess the regional, interregional and global LULCCC has contributed profuse benefits to the scientific community [24]. The use of RS techniques is attaching greater importance globally in measuring the status and change of the aboveground biomass carbon [5]. However, apart from the aboveground biomass carbon, in a forest ecosystem there are other important carbon pools such as soil carbon, belowground biomass carbon, litter deadwood biomass carbon and forest floor vegetation biomass carbon. In order to measure the accurate status of carbon dynamics with LULCC, field inventory is also crucial. The use of field inventory for the measurement of carbon dynamics in all carbon pools and the application of RS to judge the LULCC are considered to be the most effective way for this [25–27].

As per the obligation of the UNFCCC and the UN Sustainable Development Goal (SDG) No. 13 "climate action," each member country is responsible for the monitoring of emissions by source and reduction by sink. Pakistan is a member country of the UNFCCC and is required to document its accurate emissions and reductions. The country is experiencing a forest deficit, with approximately 5% of its total land area covered by forests [9]. In the Himalaya Ranges of Pakistan, the status of carbon stock in different forests, such as subtropical broadleaved forests, sub-tropical Chir forests, and moist temperate forests, has been evaluated [25–27]. Similarly, a number of studies have also evaluated carbon dynamics with LULCC in these ranges [26–28]. In the Hindu Kush Ranges of Pakistan, some studies have evaluated the status of carbon either in a particular site or for particular carbon pools like the aboveground biomass carbon [29, 30]. Similarly, some studies have assessed the status of LULCC and found their impacts on carbon for particular sites [9, 31, 32]. However, most of the available studies were based on the working plan information [9]. Working plans only provided information on managed forests and did not account for unmanaged forests such as Oak scrub forests and *Pinus gerardiana*. In addition, the working plan data did not consider trees less than 16 cm in enumeration. Therefore, using the working plans data might underestimate the carbon stock of the area. Furthermore, in Pakistan, no study has been conducted on the effect of grassland conversion to other LUs and its impact on carbon dynamics. Hence, the available information is not sufficient on LULCC-related carbon changes. Therefore, it is required to bridge the above gaps to accurately document the carbon dynamics with LULCC. In this study, both field inventory and RS data were used to assess the carbon dynamics with LULCC. RS data was used to measure the LULCC dynamics while field inventory was carried out to measure the carbon stock in all carbon pools. This study can help policymakers to develop ecological management strategies and provide baselines for future studies. This study aims to:

(a) Assess LULCC and the major drivers in the region;
(b) Assess carbon dynamics with LULCC in the area;
(c) Study carbon loss associated with LULCC.

2 Methodology

2.1 Study Area

The study area is located in the Hindu Kush Himalaya Ranges of Pakistan, with geographic coordinates ranging from $35°9'\mathrm{N}$ to $35°47'\mathrm{N}$ and $71°52'\mathrm{E}$ to $72°22'\mathrm{E}$ [23]. The mean annual rainfall in the area ranges from 1000 mm to 1600 mm and temperature varies between $0.7°\mathrm{C}$ and $30°\mathrm{C}$. The elevation of the area ranges from 1000 m to $5500\ \mathrm{m.AL,FL}$ and RL are the major LUs. The major forest types in the area include OG forest, CD forest, Deodar-Kail (DK) forest and mix conifer forest (MCF). The dominant tree species in the area include *Quercus baloot, Pinus georgiana, Cedrus deodara, Pinus wallichiana, Picea smithiana*, and *Abies pindrow*.

2.2 LULCC Assessment

For the LULCC assessment, Geographic Information System (GIS) images for the years of 1992 and 2018 were downloaded from the website of the United States Geological Survey Department. The downloaded images were processed with software. Using the topographic sheet of the area and ground control points, the geometric correction of the image was performed using ENVI. The radiometric and atmospheric correction was made through FLAASH and calibration tools of ENVI. In order to classify the area into different classes, pre-pixel signatures were assigned. Then different colors were assigned to each class and supervised classification was performed using the maximum likelihood algorithm. The accuracy of the classified images was assessed using the confusion matrix. In order to check the accuracy of the images, Kappa statistics were applied.

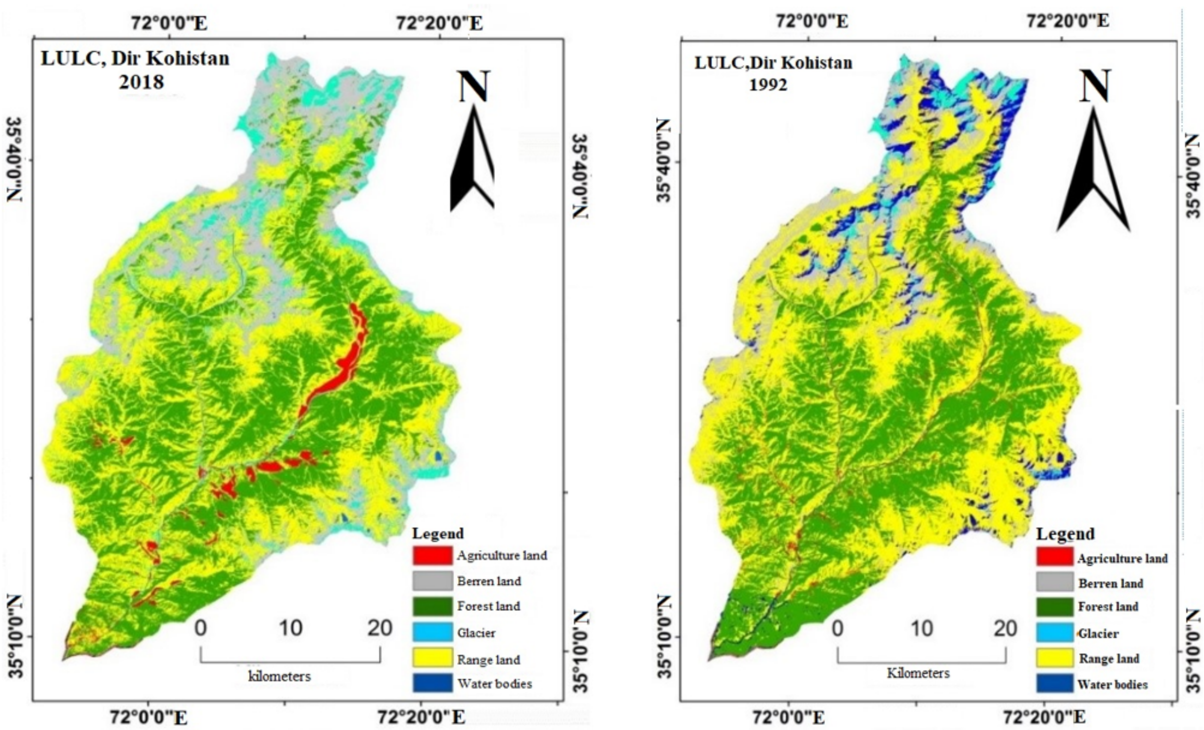
2.3 Growing Stock, Biomass and Carbon Inventory

For the assessment of carbon in stock in forests, inventory data available in the working plans were used. However, the working plan only covers managed protected forests, excluding unmanaged OG forests. Furthermore, in the available working plan, trees less than 16 cm and more than 150 cm in diameter are not enumerated. In order to assess the carbon value of the communal forests and trees below 16 cm and above 150 cm in diameter, 30 sample plots in each forest were laid out with a size of 33 m2 each. In each sample plot, the dendrometric variables of trees, such as tree diameter and height, were measured using a caliper and Haga altimeter. Tree volume was subsequently calculated by applying a volume factor derived from the product of tree diameter and height [33]. From the product of assessed growing stock and basic wood density of the respective tree species, stem biomass (STBM) was calculated [34]. The total tree biomass (TTBM) was calculated from STBM and biomass expansion factor (BEF) of the respective tree species [34, 35]. For the assessment of forest floor carbon, subplots of size 1 m2 were laid out in the respective forests. In each subplot, forest floor vegetation and deadwood litter were collected and their fresh weights were measured in the field. Similarly, in RL, vegetation was collected from 1 m2 and the fresh weight was calculated. Samples of 1 kg from respective forests, and RL were brought to the laboratory and were oven-dried at 72°C for 48 hours to measure their biomass as dry weight [25]. The carbon stock of each LU was measured from the biomass and conversion factor (0.5). This conversion factor has been widely used in Pakistan for the estimation of carbon.

For the assessment of soil carbon in each LU, soil carbon at the depth of 0-20 cm was collected. The collected samples were brought to laboratory and were oven-dried. Soil samples were sieved and the bulk density of each soil sample was measured [9, 25]. Carbon concentration in each sample was assessed [36]. The soil carbon (Mg C ha-1) in each LU was measured from soil bulk density, carbon concentration and soil depth [37].

3 Results

3.1 LULCC Dynamics



(a) (b)

Figure 1. LU map of Dir Kohistan in (a) 1992 and (b) 2018

The LU dynamics results showed (Table 1 and Figure 1) that FL, RL, AL, water bodies (WB), BL and glacier and snow (GS) are the major LUs. In 1992, FL in the area covered an area of 69,765 ha, while it was 66,406 ha in 2018. In 1992, RL and AL consisted of 82,615 ha and 3,391 ha, respectively, while they were 72,362 ha and 3,619 ha in 2018, respectively. The land use change (LUC) dynamics showed that over the period (1990-2018), the area of FL decreased from 36.82% to 35.07%. Similarly, RL decreased from 43.61% to 38.21%, whereas AL expanded from 1.79% to 1.91% during the period. The amount of BL in the area also expanded from 10.95% to 17.24% from 1992 to 2018. In summary, over the entire period, the area of FL and RL decreased by 3,359 ha and 10,253 ha, respectively, while the area of AL and BL expanded by 288 ha and 11,896 ha, respectively.

Table 1. LULCC

LUs	**1992ha**	**1992%**	**2018ha**	**2018%**	**Change During $1992-2018$**	**% Change During $1992-2018$**	**Annual Change During $1992-2018$**
FL	69765	36.82	66406	35.07	-3359	-4.81474	-0.17195
RL	82615	43.61	72362	38.21	-10253	-12.4106	-0.44323
AL	3391	1.79	3619	1.91	228	6.72368	0.240131
WB	9078	4.79	866	0.46	-8212	-90.4605	-3.23073
BL	20748	10.95	32644	17.24	11896	57.33565	2.047702
GS	3863	2.04	13481	7.12	9618	248.9775	8.892053

3.2 Growing Stock and Biomass

The results in Table 2 show that stem density in respective forests varied between 250 trees ha^{-1} in FirSpruce (FS) forest to $563\mathrm{ha}^{-1}$ in OG forest. The average stem density in the FL was recorded at $333\mathrm{ha}^{-1}$. The average growing stock volume of the entire forest was found at $452.81\ \mathrm{m}^3\mathrm{ha}^{-1}$. The maximum growing stock volume was recorded from CD forest, while it was minimum for OG forest. The average STBM and TTBM of the entire forest were estimated at 204.05 and $345.39\mathrm{Mgha}^{-1}$, respectively. Among the different forests, higher STBM and TTBM were recorded for CD forest. Forest floor biomass (FFBM), including forest floor vegetation and deadwood litter in the respective forest, was found higher in FS forest and it was lower in OG forest. The mean FFBM in the forest ecosystem of the area was $17.93\mathrm{Mgha}^{-1}$. The total ecosySTBM (TEBM) was estimated at $363.31\mathrm{Mgha}^{-1}$.

Table 2. Growing stock and biomass in respective forest types

Forest Type	**Density ha^{-1}**	**Volume $\mathrm{m}^3\,\mathrm{ha}^{-1}$**	**STBM $\mathrm{Mg\ ha}^{-1}$**	**TTBM $\mathrm{Mg\ ha}^{-1}$**	**FFBM $\mathrm{Mg\ ha}^{-1}$**	**TEBM $\mathrm{Mg\ ha}^{-1}$**
OG forest	563	162.41	92.60	140.64	7.71	148.35
CD forest	240	882.98	406.17	694.55	15.02	709.57
DK forest	238	374.75	179.69	307.27	24.07	331.34
MCF	373	448.02	192.54	329.24	17.36	346.60
FS forest	250	395.90	149.25	255.22	25.48	280.70
Mean	333	452.81	204.05	345.39	17.93	363.31

3.3 Carbon Dynamics

The results of the carbon stock in the respective pools are presented in Table 3. The results show that among the LUs, the highest vegetation biomass carbon was found in FL, followed by RL, while AL had the lowest. Soil carbon was also found maximum in FL, followed by RL, and it was minimum for AL. Among the different forests, CD forest exhibited the highest tree carbon, followed by MCF. Soil carbon was found maximum in FS forest, followed by CD forest. Forest floor carbon was found higher in FS forest, followed by DK forest. Overall among the different forests, the highest ecosystem carbon was recorded for CD forest, followed by DK forest, while a minimum ecosystem carbon was recorded in OG forest. The results show that among the different LUs in study area, AL holds a total of 31.45 $\mathrm{Mg\,C\,ha}^{-1}$, while RL and FL hold $37.27\,\mathrm{Mg\,C\,ha}^{-1}$ and $242.52\,\mathrm{Mg\,ha}^{-1}$.

The conversion of FL and RL to AL resulted in a significant amount of carbon loss in the area (Table 4). The conversion of RL to AL resulted in an 18.16% loss in the ecosystem carbon. Similarly, the conversion of FL into AL resulted in a loss of about a 668.92% loss of carbon. With respect to the conversion of different forests in to AL, the results in Table 4 show that the conversion of OG forest to AL resulted in a reduction of 287.38% carbon. Similarly, the conversion of CD forest, DK forest, MCF and FS forest to AL resulted in a loss of 1242.79%, 625.73%, 619.59% and 569.28% carbon, respectively.

Table 3. Carbon dynamics in each LU

LUs	TT/VBMC Mg C ha^{-1}	SOC Mg C ha^{-1}	FFBMC Mg C ha^{-1}	TEC Mg C ha^{-1}
AL	1.45	30.09	0	31.54
RL	4.57	32.7	0	37.27
OG forest	82.96	37.37	1.85	122.17
CD forest	347.27	68.73	7.51	423.51
DK forest	153.63	63.23	12.03	228.89
MCF	164.61	53.66	8.68	226.95
FS forest	127.61	70.74	12.74	211.09

Note: T/VBMC= Total tree/vegetation biomass carbon, SOC= Soil organic carbon, FFBMC= Forest floor biomass carbon, TEC= Total ecosystem carbon

Table 4. Change in carbon dynamics with land conversion

LU Conversion	% Ecosystem Carbon Reduction
From RL to AL	-18.16
From FL to AL	-668.92
From OG forest to AL	-287.36
From CD forest to AL	-1242.79
From DK forest to AL	-625.73
From MCF to AL	-619.59
From FS forest to AL	-569.28

4 Discussion

4.1 LULCC and the Major Drivers

nderstanding LULCC and the major drivers is important for improved policy and mitigation options for the conservation of natural ecosystems such as FL and RL. The LUC dynamics in Table 1 show that from 1992 to 2018, the annual FL conversion was found at 0.17%. This current annual rate of deforestation is similar to the reported value of 0.16% from Kumrat Valley of the Hindu Kush Ranges [9]. However, the estimate of annual deforestation in this study is much lower than the annual rate of deforestation reported from the Hindu Kush and Karakorum Ranges of Pakistan and is slightly lower than that of the Kashmir Himalaya [11, 28, 31, 32]. Similarly, the annual rate of deforestation in the area was found to be slightly higher than the national deforestation rate [38]. Compare to FL conversion to other LUs, RL conversion into other LUs was found much higher in the area. In Table 1, it can be seen that the annual reduction rate of RL in the area is 0.44%. This reduction rate was found lower than the annual reduction rate of 0.57% [39]. The difference in the rate of LUC clearly depicts the importance of regional-level studies on LUC.

Various drivers, such as commercial and subsistence agriculture, illegal cutting, settlement expansion, heavy dependency on natural resources, absence of alternative sources of income and existing management regimes, are to be blamed for natural land conversion to other LUs. Agricultural expansion is considered to be one of the major direct drivers of natural land conversion [7–10]. In the study area, agriculture is one of the major livelihood sources. With population increase, demands for substances and commercial agriculture have been increasing in the area and the local community is converting FL and RL into AL. Increasing population also causes a migration of lowland people to uplands, causing settlement expansion at the cost of RL and FL [9]. The mountain communities are heavily dependent on forests for fuel wood, timber, and fodder. Furthermore, about 16% of people are dependent on forests for their livelihoods [11]. In the absence of alternatives, the increasing population is putting more pressure on the FL, resulting in a decline in the forest area. Apart from the direct drivers, the cultural attitude of the local community towards the FL and RL, weak law enforcement and existing management regimes can also be blamed for the conversion of natural landscape to built landscape [9, 28, 32]. Forests and the RL in the area are declared to be protected, which are owned and managed by the government, while local communities hold different rights such as grazing, fuel wood, timber and fodder collection [9, 28]. However, as for the ownership rights, there are continuous conflicts between the government and local communities because the local communities consider the nature of the rights as unstable and insecure [28, 32]. This insecurity is the result of illegal cutting and encroachment of the RL and FL. Furthermore, the weak law enforcement in the area and the absence of a land management authority result in encroachment and rapid, unplanned expansion in the settlements for domestic and commercial purposes. Apart from this, the logging ban policy in 1992 is also considered to be a driver of LULCC. Before the ban, most of the demands for timber and fuel wood were met from the managed forests, while unmanaged forests were mostly used for fodder. However, following the ban, pressure on communal forests has increased, leading to unsustainable harvesting of timber and fuel wood. This shift in resource extraction practices has consequently contributed to deforestation within these communal forests [31].

4.2 Carbon Dynamics

LUC is considered to be one of the major sources of anthropogenic carbon emissions [7, 40] and the conversion of natural land to other LUs causes greater declines in the carbon value. The forest ecosystem has the ability to store 20 to 100 times more carbon compared to AL [1]. In the present study, CD forest holds about 15 times more carbon than AL (Table 3). Land conversion, particularly the conversion of FL into AL, causes changes in carbon value [41]. The results of this study clearly show that the overall conversion of FL into AL can reduce ecosystem carbon by 688.92% (Table 4). However, the conversion of different forest types to AL can reduce their carbon stock differently depending on their stock potential. The highest carbon loss can occur upon the conversion of CD forest into AL, followed by CD and DK forests, as these forests hold more carbon (Table 3 and Table 4). The long life and woody nature of the tree make forests a potential carbon sink [42]. Furthermore, compared to AL, forests receive fewer management interventions and disturbances, such as in terms of site preparation, cultivation and irrigation [43]. The conversion of forests not only reduces the biomass carbon by removing trees but also causes greater reduction in the soil carbon upon soil disturbances with agriculture practices [9, 43, 44]. Similarly, grassland conversion to AL also causes a reduction in the carbon, particularly in soil carbon (Table 4). Compared to AL, grassland bears continuous vegetation and nitrogen-fixing species and receives minimum management interventions, thus having more carbon than AL.

Agricultural expansion and associated carbon loss with the conversion of FL and RL are attributed to increasing population [7]. In order to fulfill food requirements, expansion of AL is occurring at the cost of FL and RL in the area. Furthermore, settlement expansion with increasing population also causes LUC and related carbon emissions. Avoiding deforestation can be a potential option for ecological conservation and climate change mitigation as it can potentially reduce carbon emissions and boost sequestration [7, 14]. Similarly, increasing forest area through plantation campaigns can also achieve the dual goal of carbon and diversity management. However, in the present scenario, plantation on the already established AL can create social and economic conflicts because agriculture in the mountains is the major livelihood source and provides fodder, fuel wood and grains to the community [9, 11, 32]. Therefore, agriculture incentives can increase the production of the AL agroforestry. Agroforestry can reduce pressure on FL and RL for fodder, fuel wood and timber. The introduction of smart farming, application of resource conservation technologies, mechanized agriculture and use of high-quality breeds can increase agricultural production and stop deforestation. The area bears excellent potential for tourism and the development of ecotourism can be an alternative source of income. This can reduce biotic pressure on FL and RL and boost carbon and diversity. Small-scale industries like poultry and the development of non-timber forest products can also be potential livelihood options that can ultimately reduce the dependency of locals on FL and RL. The area is home to important trophy animals such as Markhor and Ibex. The conservation of these animals and increasing their population are not only a potential ecological conservation but also a means of social and economic security. The implementation of the above strategies is necessary to reduce pressures on natural resources and to secure food provision, carbon and ecological conservation.

The introduction of the silviculture management system can also be a potential option for ecological and socio-economic security. Historically, the forests were managed under a selection system, where dead, diseased, and overmature trees, as well as those that were dried, were removed. However, following the 1992 ban on the felling of green trees, the removal of only dead, dried, and diseased trees is now permitted. This ban on green felling resulted in social conflicts and economic sacrifices and ecological sacrifices. Local communities in these forests have shares in the economic returns from the forests. The ban on green felling reduces the economic return from forests that are leading to social and economic insecurity among the local people, resulting in conflicts between locals and the government. The ban and associated conflicts triggered illegal cutting and encroachment, causing natural land degradation and reducing carbon stock. Therefore, management is crucial for socio-economic and carbon and ecological conservation.

Apart from variation in carbon value with different LUs, a greater variation in carbon stock among the forests was found. The highest tree carbon stock was recorded in CD forest, which is the result of larger and older trees. Old-age trees regulate biomass carbon because of time-dependent accumulation of carbon [30, 41]. In the study area, CD stand mostly consists of larger and old-age trees, possessing more biomass carbon. CD forests were mostly found at higher elevations with difficult topography, making them less prone to management and human intervention [30]. A minimum biomass carbon was recorded in OG forest. Compared to other forests, OG forest consists of small trees and is located at a lower elevation and in close proximity to the local community. Therefore, OG forest receives more human interventions and removal of trees for fuel wood and timber, thus resulting in lower biomass carbon.

Compared to CD forest, DK forest holds a lower value of biomass carbon. DK forest in the region was mostly found at lower elevations and is located on the gentle topography and near to the local community, thereby receiving more management and human interventions from the forest department and the local community. The forest in the region bears different communal rights, such as the right to timber, fuel wood, and livestock grazing [9, 28, 32]. The easy access of DK forest makes it a first-choice option for the local community to meet their need, resulting in lower biomass carbon. Compared to DK and FS forests, MCF holds higher biomass carbon, which is the result of more species diversity. The MCF contains a variety of species, including conifers such as *Cedrus deodara*, *Pinus wallichiana*, *Abies pindrow*, and *Picea smithiana*, as well as broad-leaved species like *Populus ciliata*. The increased species diversity contributes to higher biomass carbon, as diverse stands support both shade-tolerant and light-demanding species, which together can more efficiently utilize available resources [45].

Soil carbon is the integral component of a forest ecosystem, and variation in soil carbon among the forests can also be noted. Larger soil carbon was found in FS forest. Soil carbon depends on the organic matter received from the top in the form of litter and deadwood and the vegetation present on the forest floor [44]. Soil carbon also depends on the scale of human and management interventions, and those forests which receive more forest management and human interventions may result in the removal of deadwood and litter and lower carbon [9, 44]. It is clear from Table 3 that, among the forest types, the highest forest floor carbon was found in FS forest, which is the result of more litter and deadwood accumulation and more forest floor vegetation. Furthermore, FS forest is located at higher elevation and receives less disturbance from humans and grazing animals, resulting in less soil disturbance and bearing more carbon. Among the forest, the minimum soil carbon was found in OG forest. Due to more communal intervention with respect to wood harvesting and collection and heavy livestock grazing, soil disturbance and erosion result in lower soil carbon.

Overall, the present results show that forests in the area store and sequester a larger amount of carbon that mitigates significant climate change. The presence of old-age trees in CD forest and species diversity in MCF are important findings with respect to carbon and diversity management and conservation. Larger trees regulate biomass carbon by storing exceptional amounts of carbon. However, their presence also compromises future regeneration and carbon sequestration potential. Thus, the removal of larger trees under a selection system is required to ensure future regeneration and carbon sequestration [46]. The higher carbon associated with diverse stand also bears important management and ecological implications. As species diversity can increase productivity, species enrichment in CD, DK and FS forests can be a significant option for climate change mitigation and biodiversity conservation.

5 Conclusion

Using RS and GIS, this study evaluated carbon dynamics with LULCC in the Hindu Kush Ranges of Pakistan. The results highlight that natural land, such as FL and RL in the area, is reducing and AL and other LUs are expanding. With a population increase, biotic pressures, such as illegal cutting and logging, demands for substances and commercial agriculture, fuel wood and fodder collection, are increasing, causing FL and RL conversion. Furthermore, the migration of lowland communities, the absence of alternative sources of income, weak law enforcement, monitoring and ineffective land management authority are equally responsible factors. The conversion of FL and RL in the area is resulting in a greater loss in the carbon value of the area. In particular, conversion of FL into AL can result in a huge reduction in carbon. In order to conserve the carbon, rehabilitation and restoration of the already degraded FL and RL are required. These rehabilitation and restoration strategies include increasing forest cover through artificial regeneration, afforestation campaign increases, reseeding of grazing, growing of fodder species along with agricultural crops and protected area expansion. The introduction of agroforestry, increasing the production of AL through smart farming, the use of high-quality breeds and resource conservation technologies can reduce deforestation and RL degradation. The reintroduction of the silviculture management system is also required, as it can secure local rights, regeneration and carbon. Furthermore, alternative sources of income, such as promotion of tourism, trophy hunting and small-scale industries, should be promoted to reduce the pressure on natural resources and to promote carbon conservation.

Author Contributions

Conceptualization, investigation, methodology, formal analysis, writing original draft, software and images analysis, A.A.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Conflicts of Interest

The author declares that they have no conflicts of interest.

References

[1] R. A. Houghton, “Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000,” *Tellus B*, vol. 55, no. 2, pp. 378–390, 2003. https://doi.org/10.3402/tellusb.v55i2.16764

[2] R. A. Houghton, “How well do we know the flux of CO2 from landuse change?” *Tellus B*, vol. 62, no. 5, p. 337, 2010. https://doi.org/10.1111/j.1600-0889.2010.00473.x

[3] S. A. Spawn, C. C. Sullivan, T. J. Lark, and H. K. Gibbs, “Harmonized global maps of above and belowground biomass carbon density in the year 2010,” *Sci. Data*, vol. 7, no. 1, p. 112, 2020.

[4] M. Santoro, O. Cartus, N. Carvalhais, D. M. A. Rozendaal, V. Avitabile, and et al., “The global forest above-ground biomass pool for 2010 estimated from high-resolution satellite observations,” *Earth Syst. Sci. Data*, vol. 13, no. 8, pp. 3927–3950, 2021. https://doi.org/10.5194/essd-13-3927-2021

[5] L. Duncanson, M. Liang, V. Leitold, J. Armston, S. M. Krishna Moorthy, R. Dubayah, S. Costedoat, B. J. Enquist, L. Fatoyinbo, S. J. Goetz, M. Gonzalez-Roglich, C. Merow, P. R. Roehrdanz, T. K., and A. Zvoleff, “The effectiveness of global protected areas for climate change mitigation,” *Nature Commu.*, vol. 14, no. 1, p. 2908, 2023.

[6] J. Puhlick, C. Woodall, and A. Weiskittel, “Implications of land-use change on forest carbon stocks in the eastern United States,” *Environ. Res. Lett.*, vol. 12, no. 2, p. 024011, 2017. https://doi.org/10.1088/1748-9326/aa597f

[7] A. A. Barati, M. Zhoolideh, H. Azadi, J. Lee, and J. Scheffran, “Interactions of land-use cover and climate change at global level: How to mitigate the environmental risks and warming effects,” *Ecolo. Indic.*, vol. 146, p. 109829, 2023. https://doi.org/10.1016/j.ecolind.2022.109829

[8] P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, and et al., “Global warming of 1.5 C,” 2018. https://www.ipcc.ch/sr15/

[9] A. Ahmad, Q. Liu, S. M. Nizami, A. Mannan, and S. Saeed, “Carbon emission from deforestation, forest degradation and wood harvest in the temperate region of Hindukush Himalaya, Pakistan between 1994 and 2016,” *Land Use Poli.*, vol. 78, pp. 781–790, 2018. https://doi.org/10.1016/j.landusepol.2018.07.009

[10] A. Arneth, S. Sitch, J. Pongratz, B. D. Stocker, P. Ciais, and et al., “Historical carbon dioxide emissions caused by land-use changes are possibly larger than assumed,” *Nat. Geosci.*, vol. 10, pp. 79–84, 2017.

[11] A. Ahmad, S. Ahmad, G. Nabi, A. Zeb, M. N. Rajpar, S. Ullah, F. Khalid, M. Rahman, Q. Liu, K. Zu, X. Guo, and K. Wanghe, “Carbon emissions with forest cover change and wood harvest in the dry temperate region of Pakistan between 1908 and 2015,” *Front. Environ. Sci.*, vol. 10, 2022. https://doi.org/10.3389/fenvs.2022.876225

[12] “Global Forest Resources Assessment.” 2015. https://www.fao.org/forest-resources-assessment/past-assessments/fra-2015/en/

[13] R. J. Keenan, G. A. Reams, F. Achard, J. V. de Freitas, A. Grainger, and E. Lindquist, “Dynamics of global forest area: Results from the FAO global forest resources assessment 2015,” *For. Ecol. Manage.*, vol. 352, pp. 9–20, 2015. https://doi.org/10.1016/j.foreco.2015.06.014

[14] P. Friedlingstein, M. O’sullivan, M. W. Jones, R. M. Andrew, J. Hauck, and et al., “Global carbon budget 2020,” *Earth Syst. Sci. Data Discu.*, vol. 2020, pp. 1–3, 2020.

[15] M. G. Ghebrezgabher, T. Yang, and X. Yang, “Longterm trend of climate change and drought assessment in the Horn of Africa,” *Adv. Meteor.*, vol. 2016, no. 1, p. 8057641, 2016. https://doi.org/10.1155/2016/8057641

[16] S. S. Hasan, L. Zhen, M. G. Miah, T. Ahamed, and A. Samie, “Impact of land use change on ecosystem services: A review,” *Enviro. Develo.*, vol. 34, p. 100527, 2020. https://doi.org/10.1016/j.envdev.2020.100527

[17] R. D. Bansod and U. M. Dandekar, “valuation of Morna river catchment with RS and GIS techniques,” *J. Pharm. Phytochem.*, vol. 7, no. 1, pp. 1945–1948, 2018.

[18] G. F. Akomolafe and R. Rosazlina, “Land use and land cover changes influence the land surface temperature and vegetation in Penang Island, Peninsular Malaysia,” *Sci. Reports*, vol. 12, no. 1, p. 21250, 2022.

[19] A. Cavalli, S. Francini, G. Cecili, C. Cocozza, L. Congedo, and et al., “Afforestation monitoring through automatic analysis of 36-years Landsat Best Available Composites,” *iForest-Biogeosci. Fore.*, vol. 15, no. 4, p. 220, 2022.

[20] S. U. Ullah, M. Zeb, A. Ahmad, S. Ullah, F. Khan, and A. Islam, “Monitoring the billion trees afforestation project in Khyber Pakhtunkhwa, Pakistan through remote sensing,” *Acadlore Trans. Geosci.*, vol. 3, no. 2, pp. 89–97, 2024. https://doi.org/10.56578/atg030203

[21] M. Khan, M. Qasim, A. Ahmad, A. A. Tahir, and A. Farooqi, "Predicting land use dynamics, surface temperature and urban thermal field variance index in mild cold climate urban area of Pakistan," *Heliyon*, vol. 10, no. 19, 2024. https://doi.org/10.1016/j.heliyon.2024.e38787

[22] B. Bufebo and E. Elias, "Land use/land cover change and its driving forces in Shenkolla watershed, south Central Ethiopia," *Sci. World J.*, vol. 2021, no. 1, p. 9470918, 2021.

[23] M. J. Mashala, T. Dube, B. T. Mudereri, K. K. Ayisi, and M. R. Ramudzuli, "A systematic review on advancements in remote sensing for assessing and monitoring land use and land cover changes impacts on surface water resources in semi-arid tropical environments," *Remote Sens.*, vol. 15, no. 16, p. 3926, 2023.

[24] A. H. Chughtai, H. Abbasi, and I. R. Karas, "A review on change detection method and accuracy assessment for land use land cover," *Remote Sen. Appli.*, vol. 22, p. 100482, 2021. https://doi.org/10.1016/j.rsase.2021.100482

[25] M. Amir, X. Liu, A. Ahmad, S. Saeed, A. Mannan, and M. A. Muneer, "Patterns of biomass and carbon allocation across Chronosequence of Chir pine (Pinus Roxburghii) forest in Pakistan: Inventory-based estimate," *Adv. Meteorology*, vol. 2018, pp. 1–8, 2018. https://doi.org/10.1155/2018/3095891

[26] A. Mannan, Z. Feng, A. Ahmad, J. Liu, S. Saeed, and B. Mukete, "Carbon dynamic shifts with land use change in Margallah Hills National Park, Islamabad (Pakistan) from 1990 to 2017," *Appl. Ecol. Env. Res.*, vol. 16, no. 3, pp. 3197–3214, 2018. https://doi.org/10.15666/AEER/1603_31973214

[27] A. Mannan, J. Liu, Z. Feng, T. U. Khan, S. Saeed, B. Mukete, C. Y. Shen, Y. Fan, A. Ahmad, M. Amir, S. Ahmad, and S. Shah, "Application of land-use/land cover changes in monitoring and projecting forest biomass carbon loss in Pakistan," *Global Ecolo. Conser.*, vol. 17, p. e00535, 2019. https://doi.org/10.1016/j.gecco.2019.e00535

[28] T. Baig, S. Ali, and A. Shah, "Mountain studies: Understanding and managing mountains for people and nature," *Karakoram International University, Gilgit Pakistan*, 2022.

[29] R. Uddin, L. Ansari, A. Ahmad, S. Ullah, M. Munir, and K. Sher, "Soil analysis, species composition and carbon dynamics of abies pindrow forest of dir kohistan, Pakistan," *Appl. Ecol. Environ. Res.*, vol. 17, pp. 8049–8058, 2019.

[30] A. Ahmad, "Tree distribution pattern, growing stock characteristics and carbon mitigation potential of different forests ecosystems in Kumrat, Hindukush region of Northern Pakistan," *Pak. J. Bot.*, vol. 51, no. 6, pp. 2185–2194, 2019. https://doi.org/10.30848/pjb2019-6

[31] A. Zeb, "Spatial and temporal trends of forest cover as a response to policy interventions in the district Chitral, Pakistan," *Appl. Geogr.*, vol. 102, pp. 39–46, 2019. https://doi.org/10.1016/j.apgeog.2018.12.002

[32] A. Ahmad, S. Ahmad, G. Nabi, Q. Liu, N. Islam, and X. Luan, "Trends in deforestation as a response to management regimes and policy intervention in the Hindu Kush Himalaya of Pakistan," *Front. Environ. Sci.*, vol. 10, 2022. https://doi.org/10.3389/fenvs.2022.810806

[33] M. S. Philip, "Measuring Trees and Forests. CAB International," 1994. https://www.cambridge.org/core/services/aop-cambridge

[34] "Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas," 2006. https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

[35] G. S. Haripriya, "Estimates of biomass in Indian forests," *Biomass Bioene.*, vol. 19, no. 4, pp. 245–258, 2000. https://doi.org/10.1016/s0961-9534(00)00040-4

[36] A. Walkley and I. A. Black, "An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method," *Soil Sci.*, vol. 37, pp. 29–38, 1934.

[37] D. Zhou, S. Liu, J. Oeding, and S. Zhao, "Forest cutting and impacts on carbon in the eastern United States," *Sci. Rep.*, vol. 3, p. 3547, 2013. https://doi.org/10.1038/srep03547

[38] M. C. Hansen, P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D. Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C. O. Justice, and J. R. G. Townshend, "High-resolution global maps of 21st-century forest cover change," *Sci.*, vol. 342, no. 6160, pp. 850–853, 2013. https://doi.org/10.1126/science.1244693

[39] A. Ahmad and S. M. Nizami, "Carbon stocks of different land uses in the Kumrat valley, Hindu Kush Region of Pakistan," *J. Forest. Res.*, vol. 26, no. 1, pp. 57–64, 2015. https://doi.org/10.1007/s11676-014-0008-6

[40] R. S. DeFries, T. Rudel, M. Uriarte, and M. Hansen, "Deforestation driven by urban population growth and agricultural trade in the twenty-first century," *Nat. Geosci.*, vol. 3, pp. 178–181, 2010.

[41] L. Lai, X. Huang, H. Yang, X. Chuai, M. Zhang, T. Zhong, Z. Chen, Y. Chen, X. Wang, and R. Julian Thompson, "Carbon emissions from land-use change and management in China between 1990 and 2010," *Sci. Adv.*, vol. 2, no. 11, 2016. https://doi.org/10.1126/sciadv.1601063

[42] Y. Zhang, F. Gu, S. Liu, Y. Liu, and C. Li, "Variations of carbon stock with forest types in subalpine region of southwestern China," *For. Ecol. Manage.*, vol. 300, pp. 88–95, 2013. https://doi.org/10.1016/j.foreco.2012.06.010

[43] P. Sharma and S. Rai, "Carbon sequestration with land-use cover change in a Himalayan watershed," *Geoderma*, vol. 139, no. 3-4, pp. 371–378, 2007. https://doi.org/10.1016/j.geoderma.2007.02.016

[44] C. Calfapietra, A. Barbati, L. Perugini, B. Ferrari, G. Guidolotti, A. Quatrini, and P. Corona, "Carbon mitigation potential of different forest ecosystems under climate change and various managements in Italy," *Ecosyst. Health Sustain.*, pp. 1–9, 2015. https://doi.org/10.1890/ehs15-0023

[45] R. A. Chisholm and T. Dutta Gupta, "A critical assessment of the biodiversity–productivity relationship in forests and implications for conservation," *Oecologia*, vol. 201, pp. 887–900, 2023.

[46] Q. Yan, Q. Gang, and J. Zhu, "Size-dependent patterns of seed rain in gaps in temperate secondary forests, Northeast China," *Forests*, vol. 10, no. 2, p. 123, 2019. https://doi.org/10.3390/f10020123