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Aboveground carbon stocks and sequestration rates of forests under different management regimes in Churia region of Nepal

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The impact of forest management activities on the ability of forest ecosystems to sequester and store atmospheric carbon is of increasing scientific and social concern. This research estimated the aboveground carbon stocks and carbon sequestration rates of forests under various management regimes in the Churia region of Nepal. We used tree data from 469 permanent sample plots distributed across the region from the data archive of Forest Research and Training Centre for the study. The data from 2012 and 2017 were used. The volumes of individual trees were calculated using species–specific allometric equations, which were then converted to biomasses using their respective wood densities. The carbon content was calculated by multiplying the biomass by 0.47 and was converted to the amount of sequestrated CO_2 by multiplying by 3.67. We found that the average estimated aboveground carbon stock increased from 78.43 t ha^{-1} in 2012 to 89.20 t ha^{-1} in 2017, resulting in an average annual carbon sequestration rate of 5.34 t ha^{-1} yr^{-1} (i.e. 7.90 t CO_2 ha^{-1} yr^{-1}). The results showed significant differences in aboveground carbon stocks and annual carbon sequestration rates among different forest management regimes in the region. Generally, aboveground carbon stock was found to be the highest in protected areas in both years whereas, the annual carbon sequestration rate was found to be the highest in government–managed forests. It can be concluded that the Churia region has great potential in terms of carbon sequestration. The evidence of the strong association of carbon stock and sequestration rate with management regimes provides valuable information for policymakers to maintain and further enhance carbon storage in a geographically vulnerable region like Churia.

Keywords: Carbon assessment, Churia forests, climate change, diverse management regimes, sequestration rates, tree density

With the adverse impacts of climate change felt across the globe, the agenda of climate change has become more important than ever before (UNFCCC, 2017). The world's climate is changing at an unprecedented rate, threatening the survival of humanity (UNFCCC, 2018). Carbon dioxide (CO_2) in the atmosphere has increased to levels that are higher than they have been for 800,000 years, and it is rising (UNFCCC, 2018). Forests play a key role in the global carbon cycle by taking up CO_2 from the atmosphere and storing it in biomass (Jenkins & Schaap, 2018). Therefore, quantifying the substantial roles of forests as storehouses of carbon has become one of the most important aspects to understand and modify global climate change.

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Until 10,000 years ago, forests used to cover 6 billion ha of Earth's land area, but they today only cover 4 billion ha, with an average yearly loss of around 5.2 million ha during the last ten years (FAO, 2012). Deforestation and forest degradation can account for up to 20% of the global CO_2 emissions each year, which is more than that of the entire transportation industry (Acharya *et al*., 2009). Intending to reduce emissions from forest–based Green House Gases (GHGs), the United Nations Framework Convention on Climate Change (UNFCCC) has announced the carbon offset program of Reducing Emissions from Deforestation and Forest Degradation (REDD+) at COP 19 in 2013 (Poudel *et al.,* 2019).

Nepal ranks 11th in the world for the emission of GHGs from deforestation and other land–use changes (World Resources Institute, 2008). Forest and grassland conversion alone contributes about 80% of Nepal's GHG emissions (MoPE/UNEP, 2004). The REDD+ initiative assigns a monetary value to carbon stored in forests, incentivizing developing countries to cut emissions from forested areas and invest in low–carbon, sustainable development (Sharma & Kakchapati, 2018). Nepal is a poor country economically, and forests are one of the main sources of national income and a vital source of livelihood for the local population (Sharma & Kakchapati, 2018). Despite the opportunities, there are numerous challenges to the effective implementation of REDD+ in Nepal. One of the key barriers to the proper implementation of REDD+ in Nepal is the lack of research on the estimation of carbon stocks using established scientific methodologies for frequent assessment of emission reduction (Acharya *et al.,* 2009). More studies on the quantification of forest carbon stocks and factors affecting the forest carbon stocks and sequestration rates are needed. Such studies would be useful for the sustainable management of forest resources and increasing contributions of the forests to the national economy (Sharma & Kakchapati, 2018).

Carbon is stored in various pools in forest ecosystems. IPCC (2006) has identified five carbon pools in terrestrial ecosystems: aboveground biomass (AGB), belowground biomass, litter, woody debris, and soil organic matter. The world's forests are estimated to store 662 Gt of carbon (including all carbon pools), of which 295 Gt of carbon is stored in living biomass (FAO, 2020). The carbon amount sequestered in different pools is variable and is affected by various factors such as land use, species composition, management regimes, and soil profile (Poudel *et al.,* 2019; Shrestha & Singh, 2007). This means that the carbon removals and carbon sequestrations must be tracked regularly, which is limited in developing countries like Nepal (Poudel *et al.,* 2019).

Carbon stored in AGB of trees is often the greatest pool, which is also most immediately affected by deforestation and forest degradation (Yang, 2013). The Churia region of Nepal is the physiographic region with the highest occurrence of forest disturbances. Churia forests are disappearing at an annual rate of 0.18% (DFRS, 2015). Reducing carbon emissions from forest degradation and deforestation in this region is one of the priorities of the program and it requires information on forest carbon stock and sequestration rates. The results could be beneficial to the government for identifying actions that maintain or enhance carbon storage in Churia that supports both natural resource conservation and United Nations–REDD+ program to mitigate carbon emission issues. Moreover, with the advent of REDD+, considerable attention has been directed towards community forests, but other locally managed forest regimes, which account for three–quarters of total forest area, have been overlooked (Poudel *et al.,* 2019). Quantifying carbon stocks in other management regimes is necessary for management planning for effective climate change mitigation (Ghimire, 2019). Quantification of carbon stocks and sequestration rates of the Churia forests is not only necessary for the conservation of degraded natural resources but also for supporting the implementation of REDD+ in Nepal (Sharma & Kakchapati, 2018). Hence, the aim of this study is: (a) to estimate the above–ground carbon stocks of the forests in Churia physiographic region of Nepal, (b) to assess the average annual rates of carbon sequestration of the forests in the region, and (c) to compare the carbon stocks and sequestration rates of forests under various management regimes.

Materials and method

Study area

The study was conducted in Churia physiographic region of Nepal. The Churia region covers 12.84% of the total area of the country (Survey Department, 2001). It extends between longitudes 80^0 9' 25" E and 88^0 11' 16" E and latitudes 26^0 37' 47" to 29^0 10' 27" (LRMP, 1986, Figure 1). Its elevation ranges from 93–1,955 masl and stretches from 10 to 50 km in width (LRMP, 1986). The region's climate varies from sub–tropical to warm temperate, with hot and humid summers, heavy monsoon rain, and frigid winter. Low elevation regions fall in the sub–tropical climatic zone whereas high hills fall in the warm temperate climatic zones (DFRS, 2015). The Churia region consists of 23.04% of the total forest area of Nepal (DFRS, 2015). Forests in the region are being managed under six management regimes as i. Community forests ii. Government–managed forests iii. Protected areas iv. Private forests v. Buffer zone forests managed by the government and vi. Buffer zone community forests (MoFSC, 2015).

Sampling and data collection

We used data from 469 permanent sample plots distributed across the Churia region (Figure 1) from the data archive of Forest Research and Training Center (FRTC) for this study. FRTC used two–phase cluster sampling method for the inventory. In the first phase, the entire country was divided into 4 km grids, and a cluster of plots was established at each grid point. The clusters were sub–sampled for field measurement in the second phase.

Concentric circular sample plots (CCSPs) of radii 4, 8, 15, and 20 cm were used for the measurement of trees of DBH range 5–9.9, 10–19.9, 20–29.9, and 30 cm and more, respectively (Figure 2). Trees were identified to species level and their diameter at breast height (DBH) and heights was measured. Diameter Tape was used to measure the trees' DBH (1.3 m above ground level), while Vertex IV and Transponder T3 were used to measure their heights.

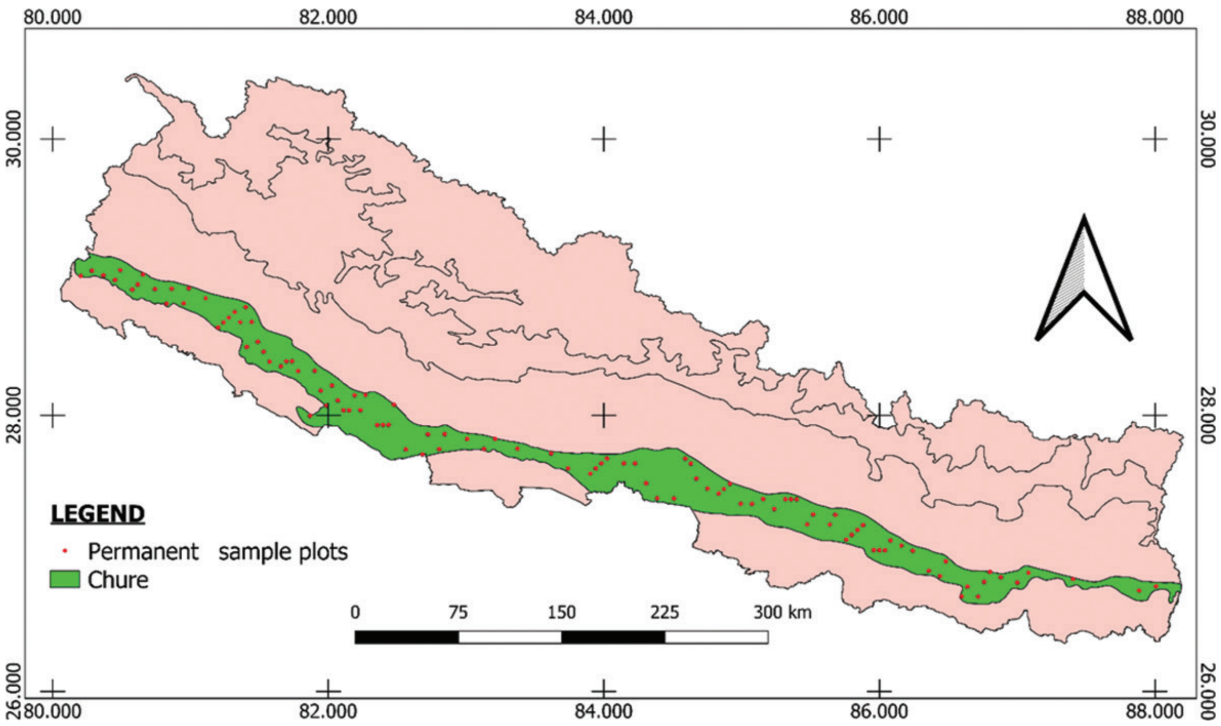

Figure 1: Map showing physiographic regions of Nepal. The Churia region, also known as Chure is marked in green color. Red dots represent the locations of 469 permanent sample plots established by Forest Research and Training Center

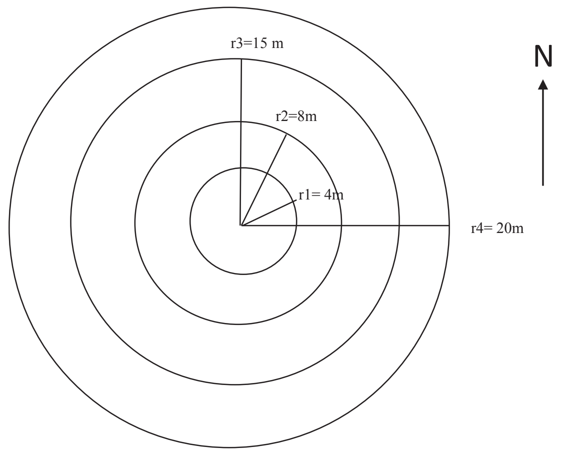

Figure 2: Layout of Concentric Circular Sample Plots (CCSP)

Data analysis

DBH and height of the tallied trees were used for the estimation of stem volume, biomass and carbon content using the following methods:

Stem volume estimation

For the estimation of stem volume, the volume equations (Eqn. 1) developed by Sharma &Pukkala (1990) was used:

$ln(v) = a + b\,ln(d) + c\,ln(h)$…………(Eqn. 1)

Where '*ln*' is the natural logarithm to the base 2.71828, '*v*' is the volume per hectare(m^3ha^{-1}), '*d*' is the diameter of the trees measured at breast height (cm), '*h*' is the height of the trees (m) and 'a', '*b*' and '*c*' are coefficients depending on species (Table 1).

The volume estimates were then divided by 1000 to convert them into cubic meters.

Table 1: Species–specific coefficients used for the estimation of stem volume of individual tree

S.N.	Species	Local Name	a	b	c	R^2
1	*Acacia catechu*	Khair	–2.3256	1.6476	1.0552	99.2
2	*Adina cordifolia*	Haldu/Karma	–2.5626	1.8598	0.8783	98.1
3	*Albizia spp.*	Siris	–2.4284	1.7609	0.9662	98.8
Other trees in Terai			–2.3993	1.7836	0.9546	98.3
Other trees in Hills			–2.3204	1.8507	0.8223	97.7

Source: Sharma & Pukkala, 1990

Stem biomass estimation

Eqn. 2 was used for the estimation of stem biomass.

Stem biomass (ton kg^{-1}) = Volume × Density……………….(Eqn. 2)

Where, Volume = Stem volume in m^3, Density = Air–dried wood density in kg m^{-3}

Species–specific wood–density values were obtained from Sharma & Pukkala (19900 (Table 2).

Table 2: Air–dried wood densities for different tree species

S.N.	Species	Local name	Air–dried wood density (kg m^{-3})
1	*Acacia catechu*	Khair	960
2	*Adina cordifolia*	Haldu/karma	670
3	*Albizia spp.*	Siris	673
	Other tree species in Terai		674
	Other tree species in Hills		674

Source: Sharma & Pukala 1990.

Above–ground biomass estimation

Tree branch biomass and foliage biomass were estimated by using species– and size–specific branch–to–stem and foliage–to–stem biomass ratios recommended by MoFSC (1988) (Table 3).

Table 3: Branch–to–stem and foliage–to–stem biomass ratios for different trees (MOFSC, 1998)

S.N.	Species	Local name	Biomass ratio					
			Branch–to stem			Foliage–to–stem		
			Small	Medium	Big	Small	Medium	Big
1	*Alnus nepalensis*	Utis	0.803	1.226	1.510	0.169	0.089	0.060
2	*Dalbergia sissoo*	Sissoo	0.684	0.684	0.684	0.010	0.010	0.010
3	*Pinus roxburghii*	KhoteSalla	0.189	0.256	0.300	0.101	0.046	0.033
4	*Schima wallichii*	Chilaune	0.520	0.186	0.168	0.064	0.035	0.033
5	*Shorea robusta*	Sal	0.055	0.341	0.357	0.062	0.067	0.067
6	Other species	–	0.400	0.400	0.400	0.070	0.057	0.040

Source: MoFSC, 1998

Then, total AGB was obtained by adding the stem biomass, branch biomass, and foliage biomass, i.e.

Total above–ground biomass (AGB) = Stem biomass + Branch biomass + Foliage biomass……… (Eqn. 3)

Carbon stock / Carbon content estimation

The above–ground carbon content (t C ha^{-1}) was calculated by multiplying total aboveground biomass (kg ha^{-1}) by 0.47 and by dividing it by 1000 (Eqn. 4) (IPCC, 2006).

Aboveground carbon content (t C ha^{-1}) = (Aboveground biomass (kg ha^{-1}) 0.47)/ 1000… (Eqn. 4)*

CO_2 sequestration estimation

The amount of sequestrated CO_2 was calculated by multiplying carbon stock by 3.67 (Eqn. 5) (Toochi, 2018).

*Amount of CO_2 sequestered in aboveground biomass (t CO_2 ha^{-1}) = Aboveground carbon content (t C ha^{-1}) * 3.67…………(Eqn.5).*

Statistical analysis

The difference between the carbon stocks and sequestration rates of forests under various management regimes was analyzed using the Kruskal–Wallis test with a post hoc Dunn test. For this, forests were grouped into four management regimes, i.e. Community forests, Government managed forests, Forest protection areas, and Others that included Buffer zone forests, Collaborative forests, and Leasehold forests. All calculations and analyses were done with Google sheet and Statistical Package software R version 3.6.1. (R core team, 2020).

Results

Major tree species

A total of 232 species of trees were recorded from the 469 permanent sample plots in Churia region in 2017. In terms of frequency, *Shorea robusta* (38.67%), *Terminalia alata* (10.35%), *Anogeisus latifolia* (4.96%), *Lagerstroemia parviflora* (3.86%), *Buchanania latifolia* (2.96%), *Syzygium cuminii* (2.11%), and *Pinus roxburghii* (2.09%) were the major tree species in the region (Figure 3). The remaining 35% was contributed by other tree species (*Mallotus philippensis, Adina cordifolia, Aegle marmelos*, etc.).

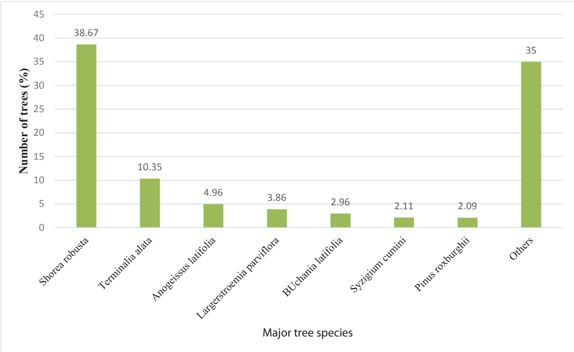

Figure 3: Frequency distribution of major tree species in the Churia region Tree stem volume and aboveground tree biomass of forests under different management regimes

Tree stem volume increased from 158.19 $m^3 ha^{-1}$ in 2012 to 180.86 $m^3 ha^{-1}$in 2017 and aboveground biomass increased from 166.88 t ha^{-1} in 2012 to 189.79 t ha^{-1} in 2017 (Table 4). Protected areas had the highest stem volume of aboveground biomass in both years (Table 4).

Table 4: Tree stem volume and aboveground tree biomass of forests under different management regimes in Churia region, Nepal

S. N.	Management regimes	No. of plots	Tree volume (m^3ha^{-1}) 2012	Tree volume (m^3ha^{-1}) 2017	Aboveground tree biomass (t ha^{-1}) 2012	Aboveground tree biomass (t ha^{-1}) 2017
1	Community forests	269	155.63	179.57	163.42	187.11
2	Govt. managed forests	94	140.47	147.72	150.85	177.93
3	Protection areas	76	191.82	193.94	200.71	221.53
4	Others	30	151.47	165.04	162.41	170.58
	Churia region	**469**	**158.19**	**180.86**	**166.88**	**189.79**

Carbon stock and CO_2 sequestration of forests under different management regimes

The total estimated carbon stock of forests in the Churia region was 78.43 t ha^{-1} in 2012 and it increased to 89.20 t Cha^{-1} in 2017 (Table 5). The total sequestrated CO_2 of the forests of the Churia region in the year 2012 was 287.85 t CO_2 ha^{-1} and it increased to 327.37 t CO_2 ha^{-1} in 2017 (Table 5).

Table 5: Carbon stock and CO_2 sequestration of forests under different management regimes in Churia region, Nepal

Management Regime			Community forests	Govt. managed forests	Protected areas	Others	Churia region
	No. of plots		**269**	**94**	**76**	**30**	**469**
Carbon stock (t C ha^{-1})	**2012**	**Mean**	77.32	68.22	95.18	76.84	**78.43**
		S.D.	42.89	45.08	47.40	57.78	**45.59**
		Median	73.14	62.45	87.31	70.49	**74.00**
	2017	**Mean**	88.51	80.94	104.96	80.74	**89.20**
		S.D.	44.54	47.70	42.09	48.54	**45.46**
		Median	83.37	74.68	98.16	79.38	**83.46**
CO_2 sequestration (tCo_2eha^{-1})	**2012**	**Mean**	283.76	250.37	349.31	282.00	**287.85**
		S.D.	157.40	165.43	173.94	212.05	**167.31**
		Median	268.42	229.21	320.42	258.69	**271.59**
	2017	**Mean**	324.84	297.04	385.22	296.32	**327.37**
		S.D.	163.46	175.07	154.48	178.14	**166.84**
		Median	305.96	274.08	360.27	291.34	**306.31**

(S.D. = Standard Deviation)

The total increment in CO_2 sequestration during these two assessment periods was 39.52 t CO_2 ha^{-1}. Similarly, the annual rate of CO_2 sequestration in the region over the two assessment periods *i.e.* 2012 and 2017 was 7.90 t CO_2 ha^{-1} yr^{-1}) (Table 6).

Table 6: Rate of CO_2 sequestration of forests under different management regimes in Churia region

Management Regime			Community forests	Govt. managed forests	Protected areas	Others	Total
Rate of CO_2 sequestration (t CO_2 ha^{-1} yr^{-1})	Annual	N	269	94	76	30	**469**
		Mean	8.21	9.33	7.18	2.86	**7.90**
		S.D.	11.81	7.99	10.54	16.18	**11.35**
		Median	7.61	8.50	7.48	5.99	**7.61**
Rate of CO_2 sequestration (t CO_2 ha^{-1})	Over a Period	Mean	41.07	46.67	35.91	14.32	**39.28**
		S.D.	59.07	39.95	52.70	80.90	**56.71**
		Median	38.03	42.50	37.38	29.94	**38.03**

(S.D. = Standard Deviation)

Kruskal Wallis test showed that there is a significant difference between annual CO_2 sequestration rates among the forests under different management regimes. Post–hoc Dunn test showed that the annual CO_2 sequestration rate of government–managed forests is significantly higher than that of forests under other management regimes (Figure 4).

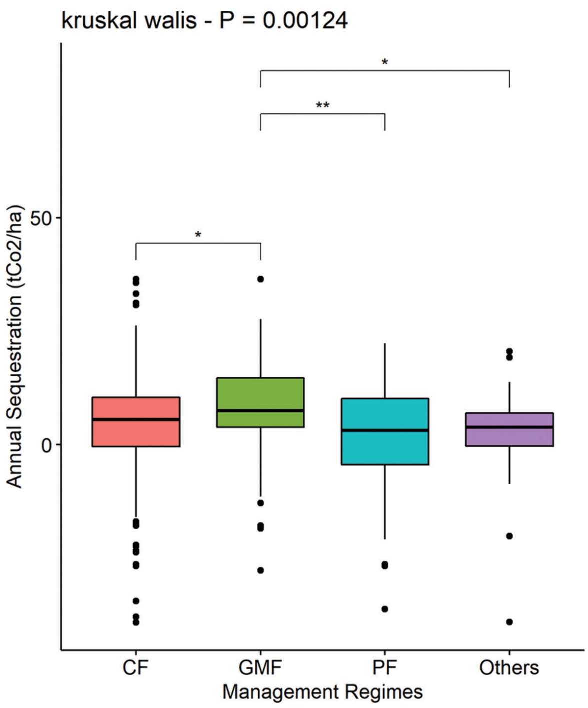

Figure 4: Annual CO_2 sequestration rates of forests under different management regimes (CF– Community Forests, GMF– Government Managed Forests, PF– Protected Areas) in the Churia region, Nepal

Discussion

The carbon store of Nepal's forests, according to the Ministry of Forest and Soil Conservation, is estimated to be as 176.95 t C ha^{-1}(MoFSC, 2015). According to the Department of Forest Research and Survey (DFRS), Churia forests have an average carbon stock of 116.94 t C ha–1 (DFRS, 2015). However, in this study, we estimated the carbon stock of the region to be 89.20 t C ha^{-1}, which seems to be relatively lower than that reported by DFRS (2015). This might be because this study only considered the above–ground carbon stock and excluded deadwood carbon stock, which was included in DFRS (2015). Furthermore, carbon stock per unit area might vary based on a variety of factors such as geographic location, tree density, species diversity, tree stem volume, DBH, canopy, and other forest management or legal considerations (Brown, 2002; Sharma *et al.,* 2011; Sharma & Kakchapati, 2018).

The estimated carbon stock in the region increased from 78.43 t C ha^{-1} in 2012 to 89.20 t C ha^{-1} in 2017 (Table 4). This increase in carbon stock in the region is probably due to an increase in stem volumes and biomass due to the increase in diameter and height of individual trees from 2012 to 2017. The volume of the stem matters when assessing the carbon stocks of forests since the stem is the main section of the tree where the majority of carbon is stored (Sharma & Kakchapati, 2018). Increased tree size results in an increment in biomass, which ultimately leads to positive changes in carbon stock. In addition, the Government of Nepal has prioritized the Churia region as an environmental conservation area, which might have reduced deforestation and consequently increased carbon storage in the region.

The average annual rate of CO_2 sequestration in the region was estimated to be 5.4 t ha^{-1} yr^{-1} (i.e. 7.90 t CO_2 ha^{-1} yr^{-1} *i.e.* 5.4 t C ha^{-1} yr^{-1}) (Table 6). This value is comparable to that reported for forests in the central Himalayan region, which ranges from 2.4 to 5.6 t C ha–1yr–1 (Rana *et al.,* 1989). The increment in CO_2 sequestration during the assessment period (2012–2017) was 39.52 t CO_2 ha^{-1} yr^{-1} (Table 6), which was around 54.3 million tonnes of carbon for the whole region, which is equivalent to 197 tonnes of CO_2. This means that about 197 tonnes of CO_2 were removed from the atmosphere by these forests over 5 years, which is lower than the actual value as the extraction of timber and fuelwood during these years was excluded in the study. Therefore, the Churia region is expected to have more potential to sequester carbon than illustrated in the results.

Our study showed that carbon stocks and sequestration rates vary significantly among the forests under different management regimes. This result is in line with the results of the study by Gurung *et al*. (2015) from Terai Arc Landscape (TAL). The highest level of carbon stock was found in protected area forests, followed by community forests, government–managed forests, and other forests. Indeed, Mbaabu *et al.* (2013) showed that the forest management practices affect the carbon stock of the forest.

The variation among forests under different management regimes could be the reflection of the degree of usage limits of forest products, primarily wood harvesting. Timber harvesting is strictly forbidden in protected areas because conservation is their major goal (Gurung *et al.,* 2015), whereas the production of timber is one of the primary goals of community forests and government–managed forests. The annual carbon sequestration rate was found to be the highest for government–managed forests, followed by community forests (Table 6). However, it was comparatively lower for protected areas, which could be an indication of the need for proper silvicultural treatments and management activities. In addition to the management activities, other biotic and abiotic factors also affect carbon sequestration rates (Newell & Stavins, 2000). For instance, young stands and fast–growing species tend to have a high sequestration capacity (Nowak *et al.*, 2013). However, the effects of such biotic and abiotic factors were not examined in the study. Having said that, the impact of other management activities on carbon stock, such as forest fire control, silvicultural activities, and other biotic factors, should not be disregarded, and more research on their effects on carbon stock is required.

It is perhaps not surprising that community forests are not the highest carbon–sequestering management regime because community forest operational plans do not include carbon value. The main aim of community forests is not the sequestration of carbon but the better growth of trees so that they can, later on, be harvested to fulfill the needs of the local users. Similarly, the difference between carbon sequestration rates of CF and GMF is not too high indicating that both management regimes have great potential for sequestering carbon.

Conclusion

We found a significant difference among diverse management regimes in terms of their carbon sequestration potentials. Carbon stocks were found the highest in protected areas where tight restrictions on the exploitation of forest products are imposed, compared to government–managed forests, community forests, and other forests where timber harvesting occurs. The forests of the Churia region have a huge carbon reservoir. Because of the region's high rates of deforestation, most of the carbon previously held in the reservoir may have been released into the atmosphere. There is a great opportunity to cut future emissions by avoiding deforestation in the Churia region.

Government–managed forests exhibited higher rates of carbon sequestration than community forests. Where carbon sequestration studies in Nepal are primarily focused on community forests, our study showed that management regimes other than community forests, too, have great potential for carbon sequestration.

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