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Mitigation Co-benefits of Ecosystem-Based Adaptation Measures: Learnings from Catalyzing Ecosystem Restoration for Climate-Resilient Natural Capital and Rural Livelihoods in Degraded Forests and Rangelands of Nepal

Keshav Prasad Khanal[1], Top Bahadur Khatri[1], Santosh Mani Nepal[1], Buddi Sagar Poudel[2], Raju Sapkota[2], Binod Thapa[1], Digambar Singh Dahal[1] and Bhola Dhakal[1]*

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Ecosystem-based Adaptation (EbA) interventions, while primarily aimed at enhancing resilience to climate impacts, can also produce measurable climate mitigation benefits. This study evaluates the carbon sequestration and emission reduction potential of EbA interventions implemented in degraded forests and rangelands of Nepal to quantify their climate mitigation outcomes. Carbon sequestration was estimated using secondary data from national sources and literature for two types of interventions: reforestation of 1,393 hectares and Sustainable Forest Management (SFM) over 10,000 hectares. Standardized carbon stock increments from similar ecological zones were applied over 20 years. Reforested areas sequestered an average of 83.4 tons of CO_2 per hectare per year, while sustainably managed forests contributed 4.4 tons of CO_2 per hectare per year. Over 20 years, these measures are projected to sequester approximately 1,134 t CO_2/ha from plantations and 533 t CO_2 /ha from SFM. EbA interventions in Nepal not only build adaptive capacity but also provide significant climate mitigation benefits. The observed carbon gains highlight the importance of incorporating ecosystem restoration into national climate policies, especially in forest and rangeland landscapes where adaptation and mitigation collaborations can be achieved.

Keywords: Carbon emissions, Climate change, EbA co-benefits, Ecosystem-based adaptation

Ecosystem-based Adaptation (EbA) involves the sustainable management of ecosystems and utilizing their services to help communities adapt to climate change. By increasing the resilience of both ecosystems and livelihoods, EbA lowers climate-related vulnerabilities and provides co-benefits such as biodiversity conservation and climate change mitigation (CBD, 2009; Munang et al., 2013). EbA strategies can also support climate change mitigation by boosting carbon sequestration and reducing emissions from deforestation and forest degradation (Locatelli et al., 2015).

Many ecosystems, such as forests and wetlands, store significant amounts of carbon. Conserving and restoring these ecosystems through various EbA measures can help sequester carbon dioxide from the atmosphere, reducing greenhouse gas concentrations and mitigating climate change (Díaz et al., 2019). Similarly, protecting and managing forests to reduce deforestation and forest degradation can curb major sources of carbon emissions. By conserving these carbon sinks, EbA can help mitigate climate change (UNEP, 2014). Additionally, sustainable land management practices, such as agroforestry and sustainable agriculture, can enhance soil health and decrease the need for chemical fertilizers, leading to lower emissions of nitrous oxide, a potent greenhouse gas (Smith et al., 2007).

The effectiveness of EbA measures in reducing climate change impacts depends on various factors, such as the type of ecosystem (e.g., forests, wetlands, and grasslands), its ecological health, and socio-

[1] United Nations Environment Program (UNEP). *Email: keshav_khanal@hotmail.com
[2] Ministry of Forests and Environment, Singhadurbar, Kathmandu, Nepal

economic and environmental conditions in the local context (Munroe et al., 2011; Griscom et al., 2017). A study by Vignola et al. (2009) reported that customizing EbA measures to specific ecosystems and local settings improves their ability to deliver co-benefits. It highlights that such tailored approaches are essential for successfully achieving both mitigation (e.g., carbon sequestration) and adaptation (e.g., increased resilience) goals. While the main aim of EbA measures is to strengthen resilience against climate change effects, their mitigation benefits are important additional advantages. These co-benefits make EbA an attractive strategy for addressing both climate change adaptation and mitigation (Andrade et al., 2011).

The project "Catalyzing Ecosystem Restoration for Climate Resilient Natural Capital and Rural Livelihoods in Degraded Forests and Rangelands of Nepal" (EbA II) is funded by the Global Environment Facility (GEF) and the Least Developed Country Fund (LDCF). Launched in May 2018 and concluding in April 2025, the project aimed to reduce community vulnerability to climate change and improve local adaptation capacities through EbA measures in degraded forests and rangelands of the mid-hills (Salyan and Achham Districts) and high mountain areas (Dolakha District) (UNEP, 2019). This paper seeks to analyze and quantify the mitigation benefits of EbA by evaluating the intervention measures implemented under the EbA II project in Dolakha, Salyan, and Achham districts of Nepal, with a particular focus on assessing the resulting carbon sequestration and emission reductions.

Materials and methods

Study area

The study sites for this research were located in two hill districts (Salyan and Achham) and one high mountain district (Dolakha) of Nepal. The project spans 18 wards across 10 municipalities. Table 1 shows the total forest area covered in this study. This research includes 1,393 hectares of reforested areas and 1,000 hectares of sustainably managed forests within 132 community forests.

Baseline data

This study primarily depends on secondary data from reputable national and peer-reviewed sources to estimate carbon emissions and sequestration. In the absence of site-specific baseline data, we referenced the DFRS (2015) carbon stock report. Peer-reviewed literature from ecologically similar regions in Nepal was utilized to validate assumptions and strengthen data triangulation.

We acknowledge that field-based validation through primary data collection or qualitative assessments (e.g., stakeholder consultations, focus group discussions) was not conducted during this study due to time and logistical constraints. While this limits the contextual depth and local verification of data, the chosen secondary sources are consistent, nationally recognized, and widely cited in similar carbon assessments in Nepal. Future research should incorporate mixed-method approaches, including stakeholder interviews, participatory forest monitoring, and carbon sampling to enhance data accuracy and local relevance. Here is a general outline of the method we used to calculate the carbon impact of forest conservation.

Carbon stock calculation

Carbon stock for plantation and rehabilitated forests was estimated based on assumed annual increment rates derived from the literature. For new plantations, we assumed full growth by year 20, and yearly stock was adjusted proportionally from year 1–9 using incremental factors (0.2–0.9). To estimate forest carbon stock and annual carbon sequestration for plantation and sustainably managed forests, we reviewed studies from similar forest types and ecological zones.

A study conducted in the Syangja district of the middle hills of western Nepal, at elevations ranging from 979 to 1320 meters above sea level, examined the carbon sequestration of community forests. It found the total carbon stock, annual carbon sequestration rate, and total CO_2 mitigation potential to be 122.29, 0.45, and 1.64 tons per hectare, respectively (KC et al., 2013). Similarly, a study on Hill Sal Forests of Nepal reported a carbon sequestration rate of 2.6 Mg

Table 1: Forest Area of EbA II project intervention sites

Project Sites	Achham	Salyan	Dolakha	Total
Total Forest Restoration Area by EbA II project (Ha)	348	873	172	1393
Total Sites	35	18	21	74
Sustainable Forest Management (Ha)		10000		

Data source: EbA II project report

tons per hectare per year (Thapa & Shrestha, 2015). Another study on community forests in Nepal found the average annual carbon increment to be 2.19 tons per hectare (Shrestha et al., 2013). Additionally, an assessment by ICIMOD at the ICIMOD Knowledge Park in Godavari, Nepal, found a carbon sequestration rate of 2.65 tons of carbon per hectare per year (Karki et al., 2016).

These studies present consistent data on baseline carbon stock and annual carbon sequestration rates in the middle hills of Nepal, closely aligning the data from DFRS. Therefore, we used the data provided by DFRS (2015) as the baseline carbon stock for the project sites.

Emissions reduction and carbon sequestration

The potential emissions reduction from preventing of deforestation or forest degradation was calculated by finding the difference between the current carbon stock (baseline) and the possible carbon emissions if the forest were converted to other uses, such as agriculture or urban development.

According to the Carbon Stock Report of the Forest Resource Assessment (DFRS, 2015), the carbon stock of plantation forests is 79.43 tons of carbon per hectare. We assume that plantation forests reach this carbon stock level after 10 years. For the years from the second to the ninth year of plantation, we applied factors of 0.2, 0.3, 0.4, up to 0.9 to the 79.43 tons of carbon per hectare value.

Time horizon

Carbon sequestration is a long-term process, so understanding the timeframe is crucial for accurate calculations. We assumed that full forest growth can be achieved within 20 years of planting or conservation.

Calculation of the carbon storage potential of plantation forests and natural forests

Carbon calculation of plantation forests:

The carbon storage potential of plantation forests was estimated, predicting how much carbon these forests would store over time. The calculation can be complex, and the value may vary based on factors like tree species, age, site conditions, and forest management practices. However, we assume that the forest will reach its full growth in 20 years, and we use the same amount of carbon stock for planted forests as that of the natural forests in the study sites. For this, we use the Forest Resource Assessment (DFRS, 2015) data on the carbon stock of middle mountain forests.

Enhance carbon sequestration due to SFM:

We used the current tree carbon sequestration rate for tropical moist forests, based on the IPCC default value (Tier 1). According to the IPCC, the above-ground biomass is 3 tons per hectare, with 25% of this amount as below-ground biomass. Therefore, the total carbon stock for one hectare of forest would be 3 tons of above-ground biomass plus 25% of 3 tons (0.75 tons) for below-ground biomass, resulting in a total of 3.75 tons per hectare.

We assumed a 5% increase in carbon biomass after five years of sustainable management, resulting in an improved carbon sequestration rate of 3.9375 tons per hectare per year (3.75 tons + 0.05 × 3.75 tons). For the first through fourth years of sustainable forest management, we applied factors of 0.2, 0.4, 0.6, and 0.8 to this value (3.9375 tons) to estimate the annual carbon increase. After the fifth year, we assumed the annual carbon increase would rise by 10% each year until the forest reached the rotation age of 20 years. Details on Carbon emission reduction and carbon sequestration are provided in Appendix 1.

Results

The carbon sequestration from planting 1,393 hectares of forest was found to be 116,178 tons annually. Similarly, the annual carbon sequestration from the sustainable management of 10,000 hectares was 44,364 tons. Combining both plantation and sustainable forest management practices, the total annual carbon sequestration was 160,542 tons.

Table 2 displays the annual and total CO_2 emission reductions and sequestrations from the project implementation. It shows that the project actions can result in a reduction or sequestration of 711,527 tons of CO_2 each year. Over the five-year period of the project, a total of 1,001,108 tons of CO_2 can be sequestered or reduced due to these actions.

Table 3 and Figure 1 show the annual CO_2 sequestration and emission reduction from the EbA project. They reveal that the EbA project sequestered nearly one million tons of CO_2 over five years.

Discussion

This study illustrates the potential of Ecosystem-based Adaptation (EbA) measures, specifically forest plantation and sustainable forest management

Table 2: CO_2 emission reduction/carbon sequestration (tCO_2 e) from year 1 to year 20

CO2 emission reduction/sequestration (tCO_2 e	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Per year	28,875	138,890	208,336	277,781	347,226	389,240	431,268	473,311	515,369	557,442
Cumulative	28,875	167,765	376,101	653,882	1,001,108	1,390,348	1,821,616	2,294,927	2,810,296	3,367,738

CO2 emission reduction/sequestration (tCO_2 e	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20	Annual	Total of one rotation
Per year	579,244	602,076	625,988	651,034	677,270	704,754	733,549	763,719	795,332	828,461	711,527	10,329,164
Cumulative	3946982	4549058	5175046	5826080	6503350	7208104	7941653	8705371	9500704	10329164	tCO_2e/a	tCO_2e

Table 3: Annual and total CO_2 sequestration due to project interventions of the EbA II project

Annual Carbon Sequestration from EbA Project	**711,527**	**Ton CO_2e**
Carbon Sequestration within the project period (5 years)	1,001,108	Ton CO_2e
Total Carbon Sequestration within 20 years from EbA Project Implementation (One whole rotation period of forest crop)	10,329, 164	Ton CO_2e
Total	10.33	Million TCO_2e

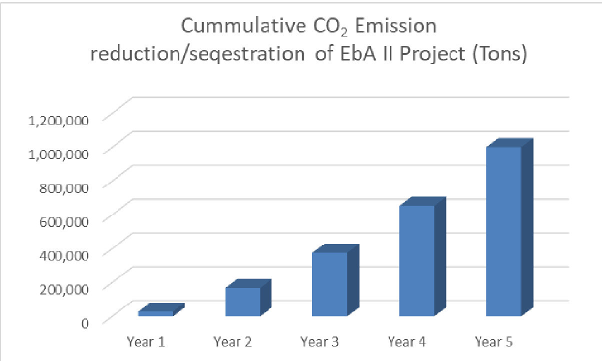

Figure 1: Cumulative CO_2 emission reduction of EbA project (Tons)

(SFM), to significantly contribute to climate change mitigation through carbon sequestration. The carbon sequestration results reported here are consistent with findings from other community forestry and EbA projects in the region. For example, Shrestha et al. (2015) and Karki et al. (2016) documented annual carbon sequestration rates of 2.2 to 2.6 tons per hectare in Nepal's middle hills, similar to those found in this study's SFM areas. Additionally, the high sequestration potential of plantation forests observed here aligns with data from large-scale restoration projects in South Asia and Latin America. The Bonn Challenge and AFR100 initiatives have reported sequestration rates of 5 to 20 tons of CO_2 per hectare annually, depending on species composition and management strategies (Chazdon et al., 2016; IUCN, 2017).

These findings reinforce the global understanding that forest restoration, especially when integrated into an EbA framework, not only supports mitigation but also improves ecosystem resilience and community livelihoods (Munang et al., 2013; Seddon et al., 2020). The effectiveness of these efforts, however, largely depends heavily on local ecological and socio-economic conditions. Customized approaches that incorporate indigenous knowledge, community participation, and site-specific ecological and environmental characteristics have been shown to significantly boost the co-benefits of EbA (Vignola et al., 2009; Andrade et al., 2011).

Although this study mainly focused on carbon benefits, the broader value of EbA interventions lies in their multi-functional nature. Evidence from other studies shows that besides addressing climate change, forest-based EbA improves biodiversity, stabilizes soil, regulates water cycles, and supports local economies through non-timber forest products (Locatelli et al., 2015; Reid et al., 2019). The interventions of the EbA II project, although not measured explicitly for these co-benefits in this study, probably provide similar ecosystem services that help build long-term resilience.

A key implication of these findings is the need for long-term monitoring and adaptive management. Carbon sequestration is not a static process; it changes with forest age, species composition, climate variability, and anthropogenic pressures. Successful EbA requires a feedback system that involves ongoing learning, participatory governance, and flexible strategies that can adapt to changing conditions (UNEP, 2014; Seddon et al., 2020).

This study relied on secondary data and literature-based estimates, which restricts the ability to verify findings through ground-truthing or participatory assessments. Future research should include field-based carbon measurements, stakeh older interviews, and participatory monitoring systems to improve accuracy and social legitimacy. This will not only strengthen the scientific foundation of EbA interventions but also promote local ownership and sustainability.

Conclusion

In this study, we examined the carbon sequestration and emission reduction resulting from the EbA project interventions using secondary sources. Our findings show that while the primary focus of the ecosystem-based adaptation project is on climate adaptation for local communities, it also significantly contributes to climate change mitigation. Climate change mitigation is an important co-benefit of the EbA project.

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Author contributions

KPK: Conceptualization, methodology, formal analysis, data curation, visualization, validation, writing original draft, and review. **TBK** and **BSP**: Supervision, review, and editing. **SMN** and **RS**: Review and editing. **BT**, **DSD**, and **BD**: Data collection (field).

Declaration of competing interest

The authors declare there is no conflict of interest.

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Appendix 1: Calculation of annual unit ton CO_2 emission reduction/sequestration

Item / Description	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20	Annual	Total
Carbon sequestration in plantation forest [1] (Ton)		22,129	33,194	44,258	55,323	66,388	77,452	88,517	99,581	110,646	116,178	121,987	128,087	134,491	141,215	148,276	155,690	163,475	171,648	180,231	116,178	2,058,766
Enhance carbon sequestration due to sustainable management[2] (Ton/Ha)	7,875	15,750	23,625	31,500	39,375	39,769	40,166	40,568	40,974	41,384	41,797	42,215	42,637	43,064	43,494	43,929	44,369	44,812	45,261	45,713	44,364	758,278
Total carbon sequestration (Ton)	7,875	37,879	56,819	75,758	94,698	106,156	117,619	129,085	140,555	152,030	157,976	164,203	170,724	177,555	184,710	192,206	200,059	208,287	216,909	225,944	194,053	2,817,045

[1] Plantation area 1393 Ha; Calculation / Source: Assume 79.43 Ton Carbon per Ha of plantation forest after year 5 of plantation

[2] Total area of SFM: 132 CFs with approximate area of 10,000 Ha; Calculation / Source: Present tree carbon sequestration rate /ha/yr (IPCC) for Tropical moist forest = 3+3*25% (AGB+BGB) = 3.75 ton/ha/yr; assume to increase by 5% in 5 years. So, enhance carbon sequestration after 5 years, $3.75 + 0.05 \times 3.75 = 3.9375$