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Calibrating Nepal's scientific forest management practices in the measure of forest restoration

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ABSTRACT

Various restoration programs have been implemented worldwide to recover degraded ecosystems. Nepal implemented a signature policy— Scientific Forest Management (SciFM)—with the aim of restoring and enhancing forest conditions, as well as increasing employment, timber production and economic growth in the last decade. While SciFM might achieve these objectives, it may conflict with Nepal's own biodiversity and emission reduction policies. So far, various aspects of SciFM, such as stakeholders' opinion, policy issues, and financial analysis have been conducted. However, the effect of SciFM in achieving various restoration objectives remains unexplored. Taking a case of Sal (Shorea robusta) dominated forest which resembles productive forests in the lowlands of Nepal, we evaluated land productivity, carbon, and biodiversity outcomes of SciFM. Employing the methods of policy review (n = 6), literature review (n = 35), expert consultations (n = 15), and forest and soil inventory, we found that SciFM has been beneficial for establishing regeneration of Sal. However, in the short-run, SciFM was found to be counterproductive to achieve national objectives of REDD+ (reducing carbon emissions from forestry sector), biodiversity conservation, and land productivity enhancement. Based on our analysis, we have discussed some learning areas from SciFM practices to align with the restoration objectives at a national and global scale. Implications of the findings in the other parts of the world, who are also implementing intensive forest management programs, are highlighted.

1. Introduction

Restoration of forest and ecosystem has been a growing agenda in the recent years with the recognition of its importance for biodiversity conservation, climate services and human well-being (Deere et al., 2020; Löf et al., 2019; Mackey et al., 2020). Forests cover only about one third of the global land area but it contains more than 80 % of the terrestrial biodiversity (Aerts and Honnay, 2011), provides largest terrestrial carbon sink (Domke et al., 2020), and supports livelihood of about 300 million people living in developing countries in the tropics (Erbaugh et al., 2020). Forest areas are important in serving various ecosystem services, through its both productive (i.e., food, fiber, and various forest products) and protective functions (i.e., climate and carbon services, biodiversity and habitat support, soil retention, and water regulation) to the landscape and society (Aryal et al., 2023a, 2023b). However, more than 2 billion ha of forests have been degraded globally (Stanturf et al., 2014), and it accounts for about 20 % declines in tree species richness alone and emission of 12–15 % of the global greenhouse gases (Ahmad et al., 2018; Giam, 2017). In this regard, ecosystem restoration through the restoration of degraded forestland is at the crucial stage in global discussions about conservation from both environmental frontiers and social dimensions.

Forest restoration is one of the major concern of ecosystem restoration which has been identified and discussed from the perspectives of ecological restoration, revegetation, functional restoration, and forest landscape restoration (Stanturf et al., 2014). Various restoration paradigms have been designed and implemented throughout the world depending on the landscape features, climate variability, and other socio-ecological parameters (Aryal et al., 2020; Löf et al., 2019). Ecological restoration at the landscape level is one of the popular

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restoration paradigms as envisioned through Convention on Biological Diversity (Suding et al., 2015). Afforestation and reforestation programs has been an effective restoration measures as an early practice of restoring forests and ecosystem through revegetation (Aryal et al., 2021b; Laudari et al., 2021; Neupane, 2015; Thomas et al., 2010). Restoration programs are focused on restoring the functional and structural components of forest ecosystem, ranging from a site or patch level to landscape level. It includes from enhancing land productivity for the establishment of forest stands and regeneration establishment, biodiversity and species richness, and forest carbon, including soil carbon.

The global policy process has embraced ambitious restoration targets of: (1) > 150 M ha of degraded land by 2020 (the Bonn Challenge-2011); (2) 350 M ha of degraded land by 2030 (New York Declaration on Forests); (3) restoration of > 15 % of degraded ecosystem by 2020 (Convention on Biological Diversity- Aichi target 15); (4) Halt deforestation and land degradation by 2030 (Glasgow Leaders Declaration on Forests and Land Use); and (5) achieve land degradation neutrality by 2030 (Sustainable Development Goal (SDG)- target 15.3) (FAO & Global Mechanism of the UNCCD, 2015). These estimations are highly likely, as recent global modeling found that an additional 900 M ha of canopy cover is possible in woodlands and forests, which could store about 205 GtC, enhance biodiversity by 15–84 %, and help achieve many SDGs (Bastin et al., 2019; Crouzeilles et al., 2016). Thus, over 55 countries have included major restoration targets in their national determined contributions (NDCs) for the Paris Agreement and Nepal is one of them (Maraseni et al., 2020; Poudyal et al., 2020).

Nepal's restoration program, as a project-based approach, has been initiated since the mid of 20th century (Laudari et al., 2019). Since 1980s, community based forest conservation modality has been adopted to protect forest land from deforestation and degradation (Aryal et al., 2021a; Maraseni et al., 2019). Community based forestry programs has been a primary approach not only to reverse the rate of deforestation and forest degradation but also to establish greenery through afforestation and reforestation (Aryal et al., 2019a, 2019b). Although the participatory forest management was successful in protecting forestland, the quality of forest stands, its productive potentials and biodiversity aspects were largely ignored (Laudari et al., 2019). Realizing the multi-functionality of forested landscape, its role in ecosystem functioning, biodiversity conservation and socio-economic growth, government of Nepal endorsed Scientific forest management (SciFM) in community managed forests and government managed forests (Awasthi et al., 2020). Being based on the national vision of 'forestry for prosperity', SciFM was introduced to overcome the reported loss of 91 million US Dollars per year, and also to generate at least 400,000 forestry jobs, reverse the decreasing trends of growing stocks (i.e., 178–164.76 cubic meter in 10 years period of 1999–2010), and to increase in timber production by more than 3 folds (i.e., 1.66 million cubic meter per year) (Poudyal et al., 2019a). SciFM was focused on restoring multi-functionality of forest stands in addition to forest land protection, through the application of intensive silvicultural practices.

Silviculture-based forest management is not a new concept in restoration and management of forests. Nepal however has endorsed the concept since 2000 through the revised forest policy (Aryal et al., 2022). But SciFM was not implemented in practice until 2012 when management plan of SciFM were prepared for some forest areas in lowlands of Nepal, which was formally implemented nationwide through the promulgation of SciFM guideline 2014. SciFM is a forest management approach that follows a systematic (i.e., irregular shelterwood) silvicultural system in managing forests, mostly applied in productive forest land in the southern lowlands of Nepal (Awasthi et al., 2020). Regeneration felling, thinning, and cleaning as well as various post harvesting operations are the major activities carried out in SciFM, taking a rotation period of 80 years (i.e., for *Shorea robusta* forest). Recently, government of Nepal has dismissed the SciFM guideline in 2021 while more than 113,000 ha of forestland in Nepal was managed through SciFM approach. Although policy turmoil about SciFM is persistent under the various social and political debates regarding governance issues, financial irregularities and benefit sharing mechanism, the government has aimed to restore forest, enhance forest condition, and sustainable attainment of ecosystem services (MFSC Nepal, 2014). Further, SciFM was also expected to fulfill the national commitment towards REDD+[1] and biodiversity (Poudel, 2018; Poudyal et al., 2019a).

On one hand, Nepal is committed to fulfill the global commitments of REDD+ and biodiversity and endorsed UN Decade on Ecosystem Restoration. On the other hand, as a measure to restore forestlands, Nepal proactively implemented SciFM in community-based forestry, and aimed to extend it to at least 50 % of the forest area in lowlands and 25 % in the mid-hills by 2025 (MFSC, 2016). In this context, to what extent the SciFM activities are aligned with the national and international commitments is crucial to understand. Restoration activities based on SciFM has implications to regeneration establishment in degraded forest land, forest protection, biodiversity, land productivity, and carbon sequestration, including soil carbon. Few studies can be found about the stakeholders' perspective on SciFM (Poudyal et al., 2019a), volume and biomass models of SciFM (Baral et al., 2021; Bhandari and Chhetri, 2020), costs and benefits of SciFM (Paudel et al., 2021), and other policy issues (Baral et al., 2018; Basnyat, 2020; Basnyat et al., 2020). In a previous study by Awasthi et al. (2020), regeneration dynamics and species diversity were discussed. However, no study is carried out in Nepal to explain the role of SciFM in ecosystem restoration of Nepal from the holistic perspective, navigating through the perspective of soil productivity, regeneration establishment, biodiversity, and species richness. In this study, we aim to (1) outline the impacts of SciFM in regeneration establishment, (2) examine the effects of SciFM in tree species diversity and richness, and (3) understand the impact of SciFM on land productivity and forest carbon. Besides, being based on the findings of the research we have extracted few lessons that can be learnt from SciFM practices for forest restoration, taking a case of collaborative forest (CBF) in the central lowlands of Nepal.

2. Methods

Both qualitative and quantitative approaches were employed for this research. Policy review was carried out to understand the aims and scope of SciFM for forest restoration, and to analyze various aspects of SciFM that supports or hinders restoration objectives and other national commitments for REDD+ and biodiversity conservation. For the policy review, we sorted out 6 major policy documents related to SciFM, namely, National Forest Policy (2019), Forestry Sector Strategy (2016–2025), Nepal Biodiversity Strategy and Action Plan (2014–2020), Nepal National REDD+ Strategy (2018–2022), Forest Act (2019), Scientific Forest Management Guideline (2014). Although forest policy pathways in Nepal have been shaped by Master Plan for Forestry Sector (1989), Forest Act (1993) and others, we didn't consider those documents because those were not explicit about irregular shelter-wood based SciFM practices. Concept and contents of SciFM and its expected aims and objectives for the restoration of forest and ecosystem was examined from the policy review. Similarly, review of literature was done to understand the impact of SciFM in national objectives of forest and ecosystem restoration. Literature search was done through the web-based platform, including Scopus, Web of Science Core Collection, and Sciencedirect. Search string used of the literature search was "scientific" AND "forest" AND "Nepal" in all searches. A total of 136 articles were recorded (65 from Scopus, 49 from Web of Science Core Collection, and 22 from Sciencedirect). After the removal of duplicate records, 80 articles were selected for title and abstract screening. Only the articles that were published after 2010 and in English language were selected.

[1] REDD+ is a mechanism that aims to reduce emissions from forest land through five different activities

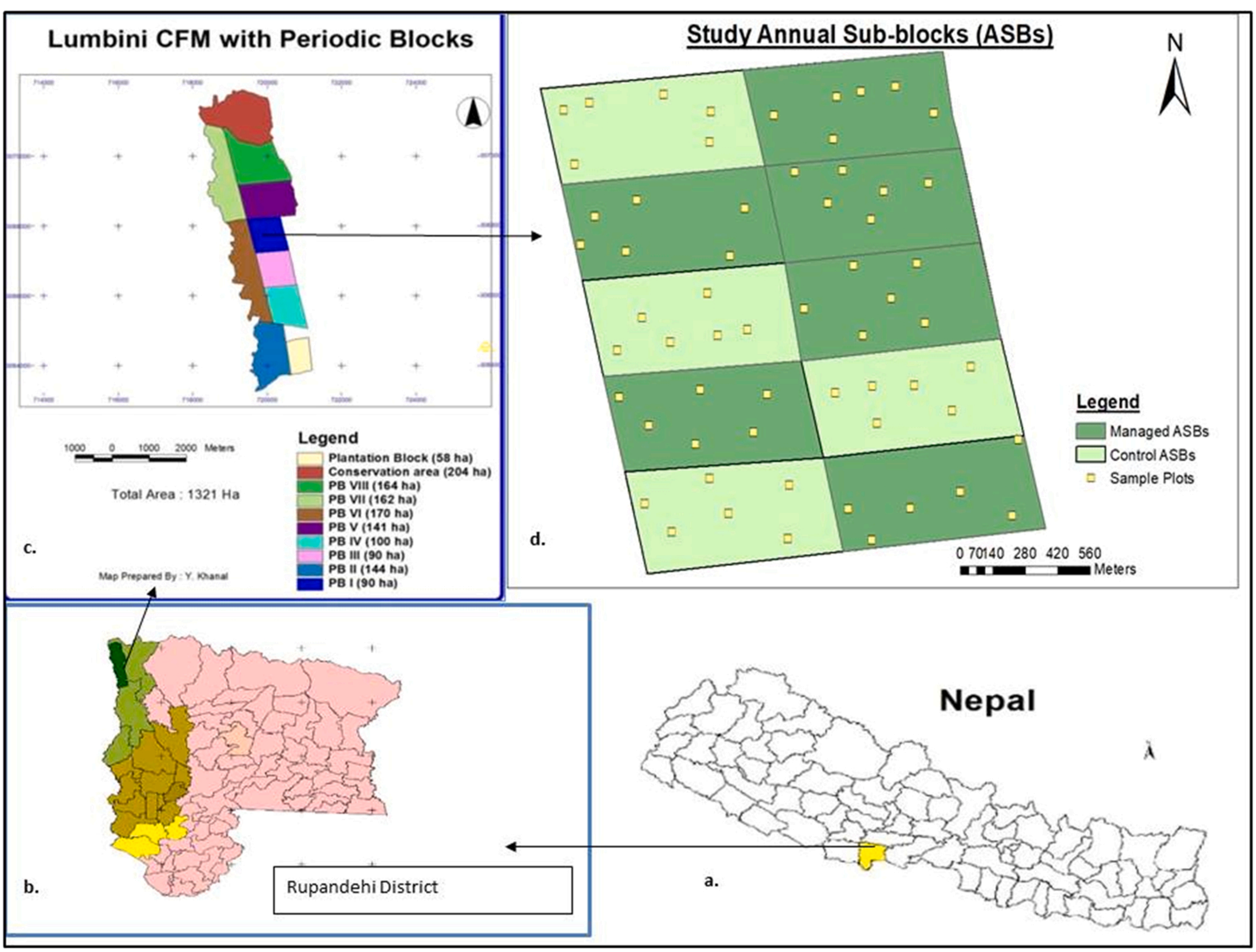
Although SciFM was implemented in practice from 2012, publications from 2010 was selected so as to capture any publications while preparing management plans of forest based on SciFM at site and/or stand level. Title and abstract screening were done based on the containment of active or productive or scientific management of forests in Nepal. A total of 35 articles were selected for full text reading and discussion about the findings. A total of 15 experts (academia = 4, federal government employee = 3, provincial forest officers = 3, civil society actors = 3, local forest users' group = 2) related to the forestry sector were consulted during this research. During the expert consultation, we assessed the perceived impacts of SciFM on forest restoration programs and its strength in achieving restoration objectives of Nepal, including REDD+ and biodiversity commitments. Expert consultation was helpful in extracting take home messages (i.e., lessons learnt) of SciFM practices for future restoration programs.

2.1. Study area and site description

Field inventory and measurement of the impacts of SciFM in regeneration dynamics, biodiversity and carbon were examined by taking a case of Lumbini CBF in the central lowlands of Nepal (Map 1). This CBF was selected because it is one of the oldest SciFM implemented forests-started in 2012, showing intermediate impacts of SciFM practice in regeneration, soil and biodiversity components (Khanal and Adhikari, 2018). Lumbini CBF occupies an area of 1321 ha (27°40'32''–27°45'13''N; 83°12'55''–83°14'24''E), ranging from the altitude of 140–342 m above mean sea level with the average temperature ranging from 18.9 to 30.7 °C and mean annual rainfall of 1745.4 mm. Lumbini CBF is a Sal (*Shorea robusta*) dominated forest, which is divided into 8 periodic blocks (i.e., forest compartments) to manage under Irregular Shelterwood system for 80 years of rotation period, considering the regeneration period of 10 years (Awasthi et al., 2020). Area control method was employed for yield regulation, for which each periodic block is further divided in to 10 annual blocks (i.e., sub-compartment) of equal size (i.e., 9 ha) for carrying out silvicultural activities sequentially as prescribed by the approved management plan (Awasthi et al., 2020).

2.2. Data collection

This study was carried out in 6 managed forest blocks and 4 unmanaged forest blocks in 2018. Unmanaged blocks were considered as the control blocks, and in the other 6 blocks, SciFM based management interventions were implemented sequentially (i.e., year-wise) starting from 2012 to 2018 (Awasthi et al., 2020). Being based on forest inventory guidelines of the government of Nepal, we employed stratified random sampling with the sampling intensity of 0.67 % (DOF, 2004). Random sample plots within each block were located using ArcGIS. We



Map 1. Map of study area, showing (a) map of Nepal, (b) studied site in Rupandehi district, (c) map of study area (Lumbini collaborative forest) with block division, 8 periodic blocks and 2 blocks for protection, (d) sampling points in the forest blocks.
Source: Awasthi et al. (2020).

selected the plot size of 10 m* 10 m for the collection of data related to vegetation and soil sampling (Awasthi et al., 2020). Taking 6 samples from each annual block, we obtained data from 60 sample plots from the periodic block. Vegetation samplings were done based on Quadrat method (Behera and Misra, 2006). Individual plants were categorized into three growth stages such as, seedlings (height < 1.3 m), saplings (height > 1.3 m and diameter at breast heights-DBH < 10 cm) and trees (DBH ≥ 10 cm). The square plot of 10 m* 10 m was laid for data collection of trees, while the two diagonally opposite (square size) sub-quadrats 5 m* 5 m was used for the measurement of seedlings and saplings (Awasthi et al., 2020). Measurement data of DBH, height and tree species were recorded for each plot. Canopy cover (%) of each sample plot was recorded in the four corners and center of the plots by Spherical densitometer, and the mean value for each plot was calculated. Similarly, soil samples were also obtained from the four corners and center of the plot (10 m* 10 m), at two depths of 0–15 cm and 15–30 cm, using soil diggers. Since management practices (including tillage) of SciFM affects only topsoil and because of the considerably few years of its implementation (i.e., 6 years), we safely assumed that the top 30 cm soils sample is enough to find the effect of SciFM. The sub-sample from each corner and center of the plot is supposed to better represent the soil properties of the sample plot. The sub-samples (i.e., 5 in each plot) were mixed thoroughly to get the single composite soil sample (approximately 250 g) per plot for each soil depth categories. Altogether, 60 samples each for two soil depth classes were collected and stored in the air-tight polybags for laboratory analysis.

2.3. Data analysis

We computed regeneration density, species richness and diversity, plant growth (mean DBH and height) and basal area by using the following formulae;

$$\text{Abundance of a species} = \frac{Total number of individuals of the species}{Total number of quadrates in which species has occured}$$

$$\text{Density}(\text{stem ha}^{-1}) = \frac{Total number of individuals of a species in all quadrates \times 10000}{Total numbers of quadrates studied \times size of quadrates (square meter)}$$

$$\text{Frequency}(\%) = \frac{Number of quadrates in which an individuals spcies occured \times 100}{Total number of quadrates sampled}$$

$$\text{Mean DBH}(\text{or height}) = \frac{Sum of DBH (or height) of the regeneration individuals in all quadrate}{total number of individuals in all quadrates studied}$$

$$\text{Basal area}(\text{m}^2) = \frac{\pi d^2}{4};\ \text{d : DBH in meter}$$

Plant species diversity was analyzed using Shannon Wiener's Index (H) (Shannon, 1948), Simpson's Dominance Index (C) (Simpson, 1949), Equitability or Evenness Index (E) (Pielou, 1975), and Margalef's Species Richness Index (S) (Margalef, 1958) as described in the Table 1.

In order to understand the difference in forest carbon in managed and unmanaged forest blocks, we used allometric equation developed by Chave et al. (2005) for calculating above ground tree biomass (AGTB-Eq. (1)), and Nepal specific biomass table for calculating above ground sapling biomass (AGSB- Eq. (2)) (Tamrakar, 2000). The soil organic carbon (SOC, ton/ha) was calculated using the equation developed by (Pearson et al., 2007) based on bulk density of soil, soil depth and percentage of SOC (Eq. (3)). Bulk density was calculated by dividing the oven dry weight with the total volume of core (Blake and Hartge, 1986). Leaf Herbs and Grass (LHG) biomass was not considered for this study because leaf litters were collected by local people from both the studied blocks for the farms, bedding, and biofuels.

$$\text{AGTB} = 0.0509 \times \rho \times \text{DBH}^2 \times \text{Height} \tag{1}$$

$$\text{Ln (AGSB)} = a + b \times \text{Ln (DBH)} \tag{2}$$

$$\text{SOC} = \rho_B \times \text{Depth} \times \text{SOC } \% \tag{3}$$

Where, ρ: density (for species specific tree in tree biomass); a and b: coefficient of model (species specific); ρ_B: bulk density of soil.

MacDicken (1997)'s root to shoot ratio (1:5) was used for below ground biomass (BGB). The estimates of biomass were converted into carbon stocks (i.e., by multiplying 0.47) following the Intergovernmental Panel for Climate Change Good Practice Guideline (Eggleston et al., 2006). Soil samples were analyzed in the Laboratory of LI-BIRD (Local Initiatives for Biodiversity, Research and Development), Nepal. Soil texture was determined by Bouyouncos hydrometer method (Bouyoucos, 1962), moisture content by Rayment and Lyons (2011) method, soil pH (1:2.5 w/v H_2O) by using digital pH meter, nitrogen content by Kjeldahl method, phosphorous using Spectrophotometer by Bray and Kurtz (1945) and potassium by using flame photometer method. Independent samples t-test was used to examine the mean differences in the regeneration density, tree diversity indices, and soil parameters of managed and unmanaged blocks under study. Pearson's correlation test followed by stepwise regression techniques was done in order to determine the relationship and strength of association between the dependent variables (regeneration density and diversity indices) and other predictor variables (canopy cover, tree ha^{-1}, BA ha^{-1} and soil parameters). Besides, qualitative data were analyzed through the inductive approach of content and discourse analysis of the relevant policy documents and selected literature.

3. Results

3.1. Regeneration establishment through SciFM

SciFM practice had substantial effect in establishment of regeneration, and seedling and sapling density. In general practice of SciFM, all the mature trees are felled in a specific regeneration felling area within the forest area (i.e., expanding gap irregular shelterwood system), designated for that particular year, except 15–25 trees which are retained as mother trees (Awasthi et al., 2020; MFSC Nepal, 2014). Consequently, we found both the seedling and sapling density higher in managed blocks as compared to the unmanaged blocks. Average seedling density in managed blocks was found to be 15,077 stems per ha, whereas that of the unmanaged blocks was 11,508 stems per ha. Similarly, sapling density in managed blocks was 4283 stems per ha, while it was only 1625 in the unmanaged blocks. The difference in seedling height is not statistically significant ($p > 0.05$) in managed and unmanaged blocks whereas both height and DBH of sapling is significantly higher ($p < 0.05$) in managed blocks than in unmanaged blocks. Regeneration of intended plant species (i.e., Sal) was found to be satisfactory under SciFM. For example, the seedling and sapling density of Sal was found to be significantly higher (p-value < 0.05) in managed blocks than in the unmanaged blocks. On the other hand, regeneration density of plant species other than Sal is higher in unmanaged block. For example, the regeneration density of species other than Sal was significantly higher ($p < 0.05$) in unmanaged blocks (i.e., 6925 stems ha^{-1}) than in managed blocks (i.e., 5600 stem ha^{-1}). The frequency and abundance of species found in managed and unmanaged blocks are included in Supplementary file. Tree density, canopy cover, and basal area were recorded higher in the unmanaged blocks than in the managed blocks. Distribution of regeneration (including that of Sal species) and tree density, basal area, and canopy cover in managed and unmanaged (i.e., control) block is presented in Table 2.

3.2. Effects of SciFM on tree species diversity and richness

Mean value of tree species diversity, evenness, and richness was observed low in managed blocks as compared to the unmanaged blocks (Fig. 1). SciFM activities were found to have significant effect on species diversity and species richness. Mean Shannon Wiener's diversity Index, dominance, evenness and species richness indices were found significantly different ($p < 0.05$) between managed and unmanaged blocks. Unlike other indices (i.e., species diversity, evenness and richness), the value of dominance was observed higher in the managed blocks than in the unmanaged blocks.

3.3. Land productivity and forest carbon in managed and unmanaged forest stands

Effects of SciFM practices in land productivity such as, soil properties and soil nutrients are noticeable. Regarding, soil texture, we found significant difference ($p < 0.05$) in mean value of sand (%) and silt (%) between managed and unmanaged blocks, sand being higher and silt being lower in managed blocks as compared to the unmanaged ones. Soil moisture (%), at the depth of 15–30 cm, was found to be comparatively higher in unmanaged blocks (18.51 ± 0.32 %) as compared to the managed blocks (17.79 ± 0.14). However, the soil moisture at 0–15 cm depth was not significantly different in managed and unmanaged blocks. Bulk density of the soil is found to be higher in managed blocks (1.19 g cm^{-3}) than in the unmanaged blocks (1.17 g cm^{-3}). Physical properties of soil (i.e., soil texture) are shown in Fig. 2.

Besides the physical properties, soil pH and soil nutrients largely determine the land productivity of forest area, which are found to be remarkably affected by silvicultural interventions under SciFM. Regarding the soil pH, soil in both managed and unmanaged blocks was found to be slightly acidic (i.e., ranging from 5.40 to 5.59). The upper soil depth (0–15 cm) was more acidic with respect to the lower soil depth (15–30 cm). Managed blocks were slightly more acidic than the unmanaged ones, but the difference was not statistically significant. The mean value of SOC (%) is significantly higher (p-value < 0.05) in unmanaged blocks than in the managed blocks, at both soil depth of 0–15 cm and 15–30 cm. Regarding the major soil nutrients, nitrogen (N) is significantly lower in managed blocks than in the unmanaged blocks, while the other nutrients (phosphorus-P and potassium-K) showed no significant difference between the managed and unmanaged blocks. Overall, we found the mean value of N (%), P (ppm) and K (ppm) was lower in managed blocks, implying that the unmanaged blocks are rich in soil nutrients as compared to the managed ones. The mean value of pH and soil nutrients is presented in Table 3.

Regarding forest carbon (ton/ha) measured in three carbon pools (i.e., above ground tree biomass, above ground sapling biomass, and below ground biomass), carbon content in managed blocks is significantly lower than that of the unmanaged blocks, except for sapling biomass carbon (Table 4). The mean value of SOC is significantly higher ($p < 0.05$) in unmanaged blocks than in the managed blocks, at both soil depth of 0–15 cm and 15–30 cm.

3.4. Relationship between regeneration, soil properties and diversity indices

We carried out correlation of regeneration density and tree species diversity indices with various predictor variables. The regeneration density (including Sal) was found to be significantly negatively correlated ($p < 0.01$) with canopy cover, tree density, and basal area. Also, the regeneration density is negatively correlated with soil moisture, SOC, and nitrogen contents of the soil. Regarding the diversity indices, it shows significant relationship with canopy cover, tree density, basal area, SOC, and nitrogen contents. Correlation between regeneration density and diversity indices with other predictor variables is presented in Table 5.

Similarly, multiple linear models for regeneration density and diversity indices with their fit statistics, and best models were developed (Table 6). Among the fitted models, higher variations in regeneration density (about 72 %) were explained by SOC, basal area, nitrogen, and soil moisture. For the Sal regeneration, higher variations were explained by canopy cover, tree density, and basal area, irrespective of the soil parameters. Likewise, diversity indices were also explained by stand and soil parameters but the fit of the model expression is lower as compared to the regeneration density.

Table 1
Description of tree species diversity and distribution indices (Awasthi et al., 2020).

Criteria	Quantifiers	Formula	Descriptions	Source
Species diversity	Heterogeneity (H′)	$H' = -\sum_{i=1}^{s}(pi)(\ln pi)$	Characterize species diversity (both relative abundance and evenness)	(Shannon, 1948)
	Dominance (C)	$C = \sum_{i=1}^{s}(pi)^2$	Describe community either homogenous or diverse; homogenous (if value close to 1) and more diverse (if value near to 0)	(Simpson, 1949)
	Evenness (E)	$E = \frac{H'}{\ln S}$	Explain about how close is the numbers of each species in a forest stand	(Pielou, 1975)
	Richness (S)	$S = \frac{(s-1)}{\ln N}$	An average count of different species in a forest stand	(Margalef, 1958)

Note: s = number of species; pi = proportion of all individuals (in numbers) that are of species 'i'; N = total number of individuals of species.

Table 2
General characteristics of managed and unmanaged forest blocks (mean ± standard error).

Parameters	Managed blocks	Unmanaged blocks
Seedling density (stem ha^{-1})	15,077 ± 291	11,508 ± 546
Sapling density (stem ha^{-1})	4283 ± 392	1625 ± 231
Seedling height (cm)	71.70 ± 1.80	67.95 ± 2.37
Sapling height (m)	3.69 ± 0.11	2.28 ± 0.24
Sapling DBH (cm)	3.62 ± 0.15	2.09 ± 0.28
Seedling density of Sal (stem ha^{-1})	10,011 ± 303	5458 ± 281
Sapling density of Sal (stem ha^{-1})	4100 ± 388	750 ± 175
Tree density (stem ha^{-1})	113 ± 24	375 ± 59
Canopy cover (%)	20 ± 1.4	58 ± 3.4
Basal area of Tree (m^2 ha^{-1})	4.47 ± 1.2	31.70 ± 5.4

4. Discussion

4.1. SciFM for revegetation and biodiversity implications

Management interventions through SciFM are found to have substantial impact on regeneration establishment and tree species diversity. As we observed significant negative correlation ($r = -0.73$) between seedling density and canopy cover, regeneration felling under SciFM opens the canopy space and allows sunlight required for the seedlings to grow (Awasthi et al., 2020). SciFM has significant positive impact on the establishment and promotion of natural regeneration of Sal (i.e., a light demander species) (Awasthi et al., 2015; Khanal and Adhikari, 2018; Shrestha et al., 2019; Gotame et al., 2020). Further, regeneration density was best explained by the stand attributes of canopy cover, tree density, and basal area by about 71 %. Similar to our findings, Peña-Claros et al. (2008) found silvicultural treatment has huge impact on regeneration density and growth rates of the target tree species in tropical forests. Managed blocks also allowed the speedy growth of seedlings into sapling due to the interventions like post harvesting operations, cleaning and thinning (Sharma et al., 2019; Shrestha et al., 2019). In some cases, as in Sal forest of Madhya Pradesh of India, canopy opening allowed the occupancy of undesired plant species (Singh et al., 2016). But, in our case we found the canopy opening as a good opportunity for the desired species (i.e., Sal) to grow.

Fencing of the regeneration felling area, cleaning (i.e., grass clearing) and loosening of the compact and bare soil through conservation tillage operations in the forest area under SciFM activities allows favorable environment for seedling establishment (Furtado et al., 2016; Meli et al., 2015). Likewise, intensive care and management of seedlings and saplings through post harvesting operations such as cleaning and tending operation improves the quality of future forest stands. Besides, removal of old grown matured tree with the newly established forest

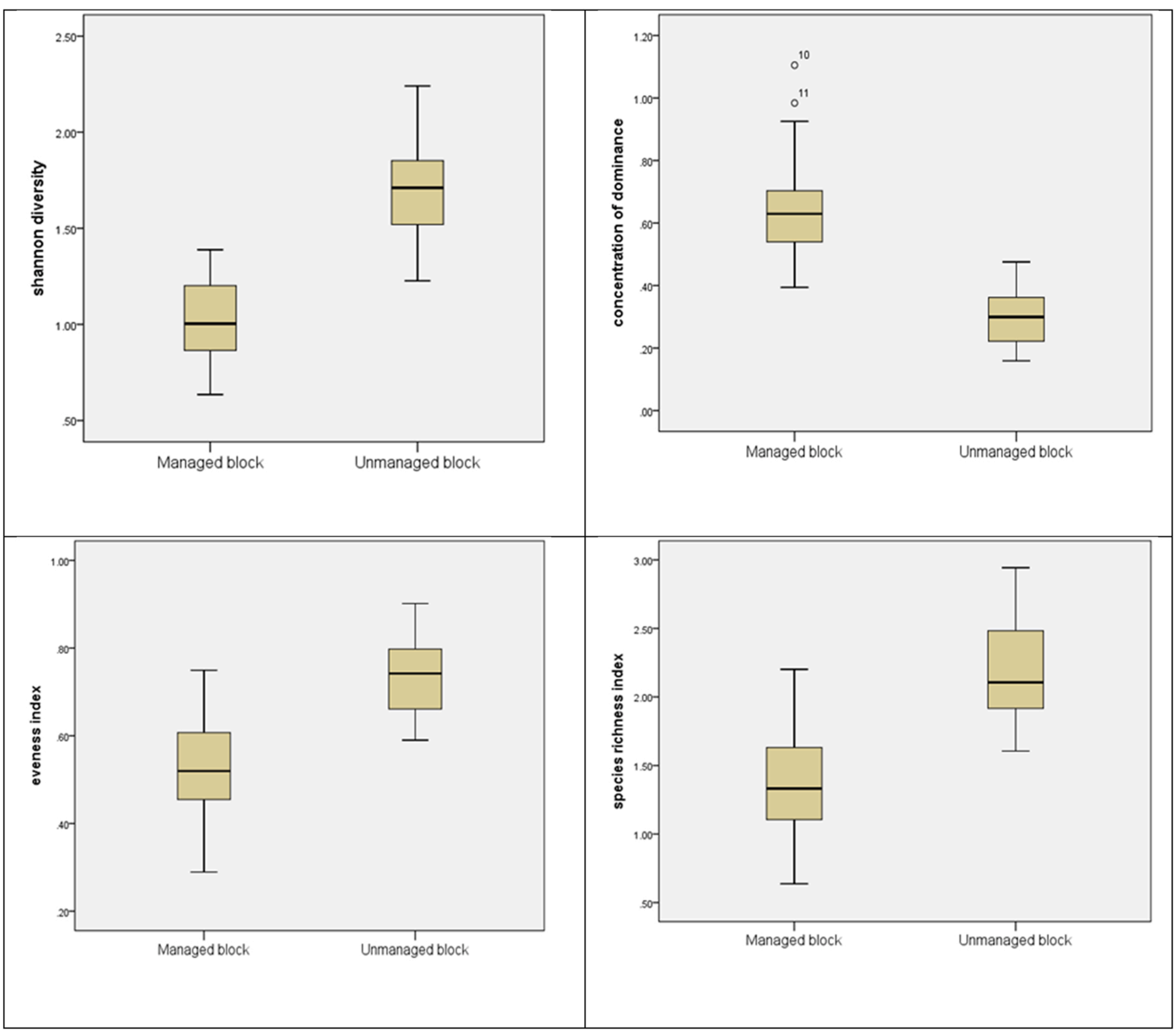


Fig. 1. Box plot (mean and standard error) of species (Shannon) diversity, evenness index, concentration of dominance, and richness indices.

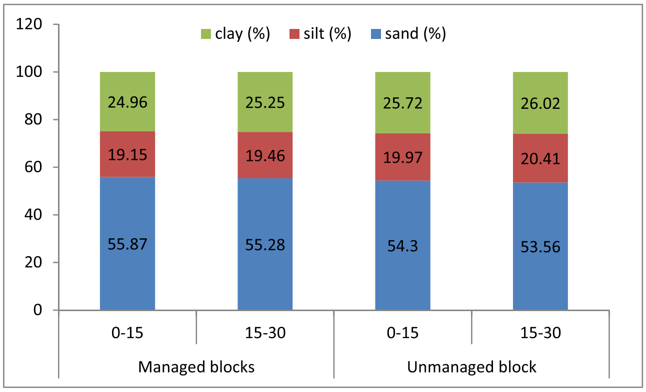


Fig. 2. Physical soil properties with respect to soil depth and management intervention.

stands tends to accelerate the rate of carbon sequestration as compared to the matured stand. As envisioned in the government policy, SciFM was also aimed to restore forest and promote regeneration in forest land through the control of forest fire, grazing, encroachment and illegal logging as well as regular patrolling (MFSC Nepal, 2014). In this regard, some scientists believe that regrowth of the secondary forest in the tropics partly counterbalance the emission from deforestation and forest degradation (Chazdon et al., 2016). However, as suggested in this study, one cannot ignore the risks of higher emission through forest soil disturbances and from the harvested forest products.

In contrary to the policy expectations of biodiversity conservation through SciFM, we found negative impacts of SciFM on plant diversity. Biodiversity is an important aspect of forest and ecosystem restoration. It encompasses broader aspects of life forms, ranging from genes to ecosystems; however, we covered only the plant species diversity at the forest stand level. Management interventions under SciFM practice are very influential in determining plant diversity, such as it affects species composition, structure and distribution patterns of plant species (Oli and Subedi, 2015; Paudel and Sah, 2015). Moreover, harvesting practices and logging intensities under SciFM are influential in determining the species diversity and richness (Behjou and Mollabashi, 2016; Shima et al., 2018). Furthermore, objectives of forest management and rotation period play important role in defining the dynamics of plant species diversity and richness (Awasthi et al., 2020; Shima et al., 2018). Plant species diversity and richness were higher in the unmanaged (or control) block. Although a meta-analysis by Duguid and Ashton (2013) in temperate forests of North America found that intensive felling had no effect on species richness and understory biodiversity in 50 years of shelterwood harvest, we found it to have significant negative impact on plant diversity in the tropical belt. Nonetheless, as the forest blocks under SciFM grows to maturity after a certain period of time, species diversity may come along; SciFM tends to reduce biodiversity for short term and intermediate time period. But at the same time, because the aim of SciFM was to focus on productivity of Sal forest, the concern of biodiversity might be a long-term issue, which needs continuous monitoring for confirmation. The lower diversity indices in intensively managed forests in our case study might be the results of intensive management operations (Behjou and Mollabashi, 2016; Shima et al., 2018), and also due to the focus of SciFM in establishing Sal dominated future stands.

SciFM practices tend to build a monoculture in forest stands, as we observed concentration of dominance (Simpson's index) was higher in managed blocks than in unmanaged blocks. The concentration of Sal species might be the results of the management interventions that are focused on removals (cleaning and tending operations) of plant species other than Sal. Similar to our study, decrease in tree species diversity was also observed linearly along the disturbance and management gradients by other researchers (i.e., Sapkota et al., 2010; Gotame et al., 2020). Moderation in logging intensity has been prescribed in previous literature to satisfy the biodiversity targets (Carreño-Rocabado et al., 2012; Roberts and Gilliam, 1995; Smith et al., 2005; Storch et al., 2019); however, Nepal's SciFM practices do not reflect this concern yet during its implementation. Our findings contradict with the study by Poudyal et al. (2019b) where they observed active forest management to support biodiversity conservation; however, they also agree that high disturbance in forest do not support species richness and biodiversity. In this regard, certain level of management operations is favorable for biodiversity conservation and species richness but high intensity felling negatively affect local biodiversity. Although the guiding principles of SciFM includes the provisioning of sensitive areas in terms of biodiversity and soil erosion as protected blocks, separate zones for protective function (i.e., isolated area) is not suitable in landscape level conservation approach for biodiversity. Low intensity felling and provisioning of other species for habitat functions, which is largely ignored in the practice of SciFM, must be mainstreamed for the future design and implementation to have the best overall outcome of SciFM for biodiversity and restoration of ecological functioning. Moreover, we recommend further research in identifying optimum number of mother trees because practice of retaining mother trees (i.e., 15–25 trees) has not been scientifically tested, which is indeed important to minimize the trade-offs between timber production and non-provisioning ecosystem services (i.e., carbon and biodiversity), and also to maximize the overall benefits from forest management.

4.2. Impact of management intervention in forest carbon and land productivity

Forest management activities have direct or indirect impact on both

Table 4
Carbon content (tons/ha) in managed and unmanaged forest blocks (mean ± standard error).

Carbon pools (tons/ha)	Managed blocks	Unmanaged blocks
Above ground tree biomass (AGTB)	52.12 ± 15.10	544.30 ± 130.89
Carbon (AGTB)	24.50 ± 7.09	255.82 ± 61.52
Above ground sapling biomass (AGSB)	19.85 ± 2.75	5.56 ± 0.87
Carbon (AGSB)	9.31 ± 1.29	2.61 ± 0.40
Below ground biomass (BGB)	10.42 ± 3.02	108.86 ± 26.18
Carbon (BGB)	4.90 ± 1.41	51.16 ± 12.30
SOC (0–15 cm)	18.79 ± 0.38	23.43 ± 0.72
SOC (15–30 cm)	11.43 ± 0.30	14.92 ± 0.45
SOC (0–30 cm)	30.29 ± 0.62	38.41 ± 0.92

Table 3
Mean and standard error of soil pH, soil carbon, and nutrients with respect to depth and management intervention (mean ± standard error).

Forest blocks	Depth class	pH	SOC (%)	Nitrogen (N, %)	Phosphorus (P, ppm)	Potassium (K, ppm)
Managed blocks	0–15	5.40 ± 0.02	1.05 ± 0.02	0.08 ± 0.00	76.17 ± 2.01	126.50 ± 4.53
	15–30	5.52 ± 0.02	0.64 ± 0.01	0.05 ± 0.00	73.92 ± 2.09	114.41 ± 3.88
Unmanaged blocks	0–15	5.47 ± 0.04	1.34 ± 0.04	0.14 ± 0.00	88.65 ± 4.83	141.89 ± 5.17
	15–30	5.59 ± 0.03	0.85 ± 0.02	0.09 ± 0.00	87.17 ± 4.89	125.67 ± 3.98
Sig.	0–15	0.13	0.00	0.00	0.00	0.03
(p-value)	15–30	0.08	0.00	0.00	0.00	0.06

Table 5
Correlation between regeneration and diversity indices with predictor variables.

Variables	Overall regeneration	Sal regeneration	Shannon Wiener's Index	Simpson's Dominance Index	Equitability or Evenness Index	Margalef's Species Richness Index
Canopy	-0.67**	-0.75**	0.67**	-0.64**	0.57**	0.63**
Tree ha^{-1}	-0.43**	-0.47**	0.40**	-0.38**	0.28*	0.48**
BA ha^{-1}	-0.50**	-0.58**	0.49**	-0.48**	0.36**	0.57**
Sand (0–15 cm)	0.33**	0.44**	-0.44**	0.42**	-0.35**	-0.39**
Sand (15–30 cm)	0.18	0.34**	-0.39**	0.32**	-0.32*	-0.32*
Silt (0–15 cm)	-0.19	-0.17	0.10	-0.16	0.09	0.11
Silt (15–30 cm)	-0.32*	-0.28*	0.18	-0.25	0.16	0.22
Clay (0–15 cm)	-0.13	-0.23	0.28*	-0.22	0.22	0.23
Clay (15–30 cm)	0.04	-0.12	0.23	-0.13	0.19	0.15
Moisture (0–15 cm)	-0.46**	-0.43**	0.31*	-0.29	0.24	0.34**
Moisture (15–30 cm)	-0.40**	-0.32*	0.18	-0.19	0.17	0.15
pH (0–15 cm)	-0.25	-0.18	0.09	-0.16	0.05	0.14
pH (15–30 cm)	-0.09	-0.08	0.12	-0.05	0.01	0.25*
SOC (0–15 cm)	-0.70**	-0.68**	0.52**	-0.53**	0.54**	0.38**
SOC (15–30 cm)	-0.58**	-0.66**	0.60**	-0.54**	0.51**	0.50**
N (0–15 cm)	-0.66**	-0.67**	0.56**	-0.54**	0.49**	0.50**
N (15–30 cm)	-0.64**	-0.66**	0.57**	-0.60**	0.48**	0.52**
P (0–15 cm)	-0.28*	-0.30*	0.26*	-0.22	0.23	0.26*
P (15–30 cm)	-0.31*	-0.31*	0.27*	-0.23	0.18	0.34**
K (0–15 cm)	-0.21	-0.18	0.19	-0.10	0.10	0.26*
K (15–30 cm)	-0.18	-0.19	0.21	-0.19	0.15	0.26*

Note: **Correlation is significant at the 0.01 level; *Correlation is significant at the 0.05 level (2-tailed).

Table 6
Fit statistics for linear regression equations of regeneration and diversity indices.

S. N.	Regression equations	R^2	RMSE	AIC
Overall regeneration density (R_o, stem ha^{-1})				
1	$R_o = 32239.02 - 13106.97 \times SOC_{(0-15\ cm)}$	0.500	2855.04	1129.06
2	$R_o = 31709.01 - 11737.63 \times SOC_{(0-15\ cm)} - 69.38 \times BA\ ha^{-1}$	0.641	2440.16	1111.17
3	$R_o = 31892.33 - 9469.97 \times SOC_{(0-15\ cm)} - 50.19 * BA\ ha^{-1} - 28309.01 \times N_{(0-15\ cm)}$	0.702	2240.98	1101.89
4	$R_o = 40305.13 - 9113.34 \times SOC_{(0-15\ cm)} - 57.78 \times BA\ ha^{-1} - 20784.31 \times N_{(0-15)} - 527.99 \times M_{(15-30\ cm)}$	0.723	2182.07	1099.61
Regeneration density of Sal				
5	$R_s = 16150.98 - 147.54 \times CC$	0.559	2957.37	1133.285
6	$R_s = 24748.87 - 106.01 \times CC - 8580.90 \times SOC_{(0-15\ cm)}$	0.691	2498.05	1113.987
7	$R_s = 25406.83 - 81.73 \times CC - 7328.47 \times SOC_{(0-15\ cm)} - 26889.18 \times N_{(0-15\ cm)}$	0.733	2341.18	1107.16
8	$R_s = -3961.59 - 82.71 \times CC - 8904.85 \times SOC_{(0-15\ cm)} - 30226.67 \times N_{(0-15\ cm)} + 5819.58 \times pH_{(0-15\ cm)}$	0.771	2189.18	1100.006
Seedling density of Sal				
9	$Se_D = 11414.90 - 91.48 \times CC$	0.539	1908.40	1080.722
10	$Se_D = 12298.25 - 165.80 \times CC + 7.95 \times tree\ ha^{-1}$	0.690	1579.31	1058.964
11	$Se_D = 12124.96 - 155.89 \times CC + 9.49 \times tree\ ha^{-1} - 33.01 \times BA\ ha^{-1}$	0.715	1528.31	1055.964
Sapling density of Sal				
12	$Sa_D = 10879.86 - 6924.76 \times SOC_{(0-15\ cm)}$	0.357	2022.11	1087.667
13	$Sa_D = 10909.61 - 4778.90 \times SOC_{(0-15\ cm)} - 22953.72 \times N_{(0-15\ cm)}$	0.479	1836.31	1077.057
14	$Sa_D = 10711.31 - 4800.14 \times SOC_{(0-15\ cm)} - 17443.56 \times N_{(0-15\ cm)} - 25.02 \times BA\ ha^{-1}$	0.519	1780.08	1074.263
Shannon weiner's diversity index (H)				
15	$H = 0.86 + 0.012 \times CC$	0.443	0.3068	32.461
16	$H = 0.768 + 0.02\ CC - 0.001 \times tree\ ha^{-1}$	0.521	0.2869	25.383
17	$H = 0.401 + 0.016 \times CC - 0.001 \times tree\ ha^{-1} + 0.66 \times SOC_{(15-30\ cm)}$	0.564	0.2761	21.695
Dominance index (C)				
18	$C = 0.724–0.006 \times CC$	0.413	0.1665	-40.890
19	$C = 0.829–0.004 \times CC - 2.552 \times N_{(15-30\ cm)}$	0.509	0.1536	-49.547
20	$C = 0.844–0.008 \times CC - 2.02 \times N_{(15-30\ cm)} + 0.0005 \times tree\ ha^{-1}$	0.550	0.1484	-52.751
Evenness index (E)				
21	$E = 0.474 + 0.004 \times CC$	0.321	0.1214	-78.765
22	$E = 0.431 + 0.007 \times CC - 0.0004 \times tree\ ha^{-1}$	0.450	0.1102	-89.444
Species richness index (S)				
23	$S = 1.175 + 0.015 \times CC$	0.394	0.4237	71.201
24	$S = 0.988 + 0.012 \times CC + 4.521 \times N_{(15-30\ cm)}$	0.442	0.4102	68.275
25	$S = 1.086 + 6.621 \times N_{(15-30\ cm)} + 0.011 \times BA\ ha^{-1}$	0.461	0.4031	66.177

Note: Ro = Overall regeneration density (seedlings and saplings density); SOC = Soil Organic Carbon (%); BA ha^{-1} = Basal area per ha of tree; N = Nitrogen (%); M = Moisture (%); CC = Canopy cover (%); Rs = Regeneration density of Sal; pH = value of H ions (acidity/alkalinity); SeD = Seedling density of Sal; SaD = Sapling density of Sal

physical and chemical properties of soil and on overall productivity of the forest land (Picchio et al., 2020; Worrell and Hampson, 1997). An effective forest management approach plays significant role in maintaining soil quality and soil functioning (Kooch et al., 2020); however, it depends on the intensity and duration of forest soil disturbances, season of intervention, concentration of tree felling, and site treatment measures (Chaves Cardoso et al., 2020; Solgi and Najafi, 2014; Sowa and Dariusz, 2008). Our study showed that the SciFM practice is not good at retaining soil moisture and maintaining good soil texture. We found higher proportion of sand and lower proportion of silt in managed blocks due to the concentrated logging activities and associated soil disturbances due to the implementation of SciFM. Regeneration felling and other management interventions in SciFM reduces both ground and canopy cover, which might help in soil compaction leading to surface run-off, nutrient leaching and soil erosion losing the nutrient contents of the soil.

Although the SciFM program has been designed and implemented so as to maintain productivity of the forest land (i.e., soil productivity) and also to support national REDD+ objectives (i.e., retaining forest and soil carbon content), we observed a significant decline in forest carbon and soil nutrients in managed blocks through SciFM. As of the current short-term assessment of carbon pools in managed and unmanaged forests, carbon stocks of the above ground tree biomass and below ground biomass in managed blocks were significantly lower than that of the unmanaged blocks. Our findings are aligned with the global estimates that two third differences in biomass stocks are explained by forest management interventions (Erb et al., 2018). Although the carbon budget might not have significant difference in the long run because of high growth rate of regeneration as well as small and medium sized trees, it is very probable to challenge the current aim of Nepal's emission reduction program (i.e., to achieve 34.2 $MtCO_2e$ carbon benefits from lowland forests in 13 districts of Nepal) over 10 years period from 2018 to 2028 (REDD IC, 2018a). In the foreground of national REDD+ objectives of emission reduction, the negative effect of SciFM in forest biomass might be counterproductive, so carbon transaction of SciFM cannot be ignored in the management planning.

Soil carbon in unmanaged blocks (i.e., 38.41 tons/ha) is significantly higher than that of the managed blocks (i.e., 30.29 tons/ha). Our assessment of SOC is aligned with the national assessment by Department of Forest Research and Survey, Nepal in 2014 where they found the SOC in lowland forests of Nepal as 33.66 tons/ha (DFRS, 2015). Interestingly, SOC in unmanaged blocks is higher and in managed blocks is lower than the national average. The lower value of SOC in managed forest blocks might be due to the dominance of young plants (seedlings and saplings) that utilize carbon during growths, and also because of the low density of large size trees and their foliage and litter, which are considered as major inputs to SOC. Moreover, high temperature due to excessive sunlight reaching the forest ground oxidizes soil carbon to carbon dioxide and SOC get lower (Nguyen et al., 2010). Although few researchers argue that concentrated felling is relatively less harmful to the forest and soil carbon as compared to the selection felling (i.e., felling of mature trees throughout the forests) because of the minimum requirement of infrastructure for harvesting and logging (Butarbutar et al., 2019; Huang and Asner, 2010; Tavankar et al., 2015), while other believes on logging intensity and concentration of harvesting activities have unavoidable impacts on forest and soil carbon (Goodman et al., 2019; Rozak et al., 2018). Further, Clarke et al. (2015) stressed that the impact of harvesting intensity on carbon and biodiversity is dependent on specific case, site and inherent practice. Nonetheless, some studies recommend low to moderate harvesting intensities in order to recover the soil nutrients deficient after harvesting (Zhou et al., 2015). But we observed relatively higher felling intensity under SciFM. Also, we observed negative correlation between regeneration density and soil properties, including SOC and soil nutrients (i.e., nitrogen phosphorus and potassium). Our findings corroborates with other literature which mentioned that soil nutrient is rich in relatively undisturbed forest because of the higher litter production, decay rate and high population of bacteria and fungi (Sharma et al., 2017). Similar to our findings, other studies (i.e., Sarma and Das, 2009; Ekka and Agarwal, 2017) also found high value of SOC and soil nutrients in undisturbed forest sites than the intensively managed sites. Likewise, a global review by Noormets et al. (2015) stated that managed forests have 50% low carbon stocks than unmanaged forests. Lower soil nutrients and SOC in managed forest blocks might be the effect of leaching and run-off, resulting from the improper logging practice, cleaning, and tending operations.

4.3. Lessons learnt from SciFM practices for forest restoration

Nepal's SciFM has created a momentum for initiating intensive forest management activities in degraded and mature old-grown forests. This practice had been mainstreamed in the national policies so as to address the demand of forest products along with its support for degraded forest restoration, carbon sequestration, biodiversity conservation, productivity enhancement, and the supply of other various ecosystem services (i.e., water regulation, soil retention, and habitat support) (MFSC Nepal, 2014). Nepal's 13th periodic plan (2013/14–2015/16) put SciFM as a priority program for forest conservation, and enhancement of forest production and productivity (NPC Nepal, 2014). Similarly, 14th periodic plan (2016/17–2018/19) envisioned the transformation of the traditional practices of collecting dead, dying and decayed timber to the SciFM practices (NPC Nepal, 2017). Further, the plan aimed at managing one hundred thousand hectares of forestland through SciFM practices. Similarly, National Forest Policy, 2019 has adopted silvicultural-based forest management as an approach to sustainable forest management (MFSC Nepal, 2019). Likewise, Forestry Sector Strategy (2016–2025) put a milestone of managing half of the lowland forests through SciFM for sustainable forest management and restoration. Nepal Biodiversity Strategy and Action Plan (NBSAP: 2014–2020) had articulated the lack of SciFM approach for reversing loss and degradation of lowland forests, as well as this policy document envisioned improved forest productivity and sustainable supply of forest product through SciFM, which then minimize the pressure on forest for illegal logging and deforestation (MOFE Nepal, 2014). Furthermore, NBSAP aimed to implement the SciFM with the aim to conserve biodiversity, for example through SciFM in collaborative forests in the lowlands of Nepal. National REDD+ strategy (2018–2022) identified weak forest management practices (i.e., unmanaged or under-managed) as one of the major (nine) drivers of deforestation and forest degradation in Nepal, implying to encourage SciFM to achieve national REDD+ objectives (REDD IC, 2018b).

Based on our findings of the effects of SciFM in regeneration dynamics, biodiversity, soil properties and productivity, we have synthesized few lessons that should be considered for achieving the restoration goals through forest management practices in Nepal and other tropical countries. First, restoration practices under SciFM should not ignore the change in forest carbon stocks (Nasi et al., 2011; Solomon et al., 2018). Because Nepal is committed to reduce the carbon emission through REDD+ program, the current trend of decrease in forest and soil carbon through SciFM could be a problem for national REDD+ objectives. SciFM is believed to support in reducing illegal deforestation and avoidance of leakages for REDD+ (Bottazzi et al., 2013), but impose negative impact on soil carbon due to intensive management intervention. Likewise, SciFM may increase biomass carbon as regeneration establishment accumulate carbon faster than old age forests (Awasthi et al., 2020), forest disturbance under SciFM however cannot be ignored regarding the achievement of national REDD+ objectives. Further, various emission reduction programs have been designed and implemented at regional and global scale, SciFM should consider its impact on change in carbon stock, especially in the face of current climate uncertainties (Pilli et al., 2016). Potential carbon emission activities through SciFM practices should be identified, and appropriate measures to minimize such activities must be developed and implemented. Although the long-term impacts of SciFM in carbon balance need future research, practice of SciFM should be revised so as to satisfy the national REDD+ program and global carbon commitments. One option, for example, could be to leave leaf litters in the forest area but by satisfying the need of local people with alternatives to collect forest products.

Second, felling intensity under SciFM is considerably higher with respect to the multi-functional role of forest area. Practice of retaining only 15–25 mother trees per ha might be adequate for the source of seeds but it has much larger impact on biodiversity and soil properties of the forest land. For example, a global assessment by Achat et al. (2015) mentioned that intensive felling can cause the emission of 142–497 Tg-C from the forest soil. Intensive felling also has the worst impact on forest biodiversity (Griscom et al., 2018). In this regard, Awasthi et al. (2020) also suggested for the moderation of the felling intensity under SciFM to sustain biodiversity and other ecosystem services from forest. Considering its impact on soil carbon, soil nutrients and tree species diversity as observed in our research, optimum number of mother trees should be scientifically tested and harvesting intensity should be revised so as to sustain multi-functionality of forest while managing through SciFM practices.

Third, the practice of harvesting and logging under SciFM also seems to negatively affect soil properties and forest carbon. As we observed reduction in soil moisture due to excessive canopy opening, changes in soil properties and decline of soil nutrients due to conventional logging practice, it should be revised and improved. The decrease in nitrogen content in soil might be due to the removal of legumes while creating future stands of single (i.e., Sal) species. Further, bulk density of soil is also higher in soils of managed forests due to the use of machinery and concentrated logging activities. Conventional logging is detrimental for the emission of greenhouse gases (Mori et al., 2018). A study by Spinelli et al. (2010) found that more than 50% of the surface soil is disturbed through conventional logging practice. As observed through multiple linear models for regeneration density, soil productivity is not that important for seedling establishment, but it showed significant role in growth of seedlings to the saplings. In this regard, reduced impact logging could be an efficient approach in SciFM because it is a proficient strategy to manage tropical forests while minimizing carbon emission, biodiversity conservation, and water regulation (Griscom et al., 2018; Miller et al., 2011; Mohren, 2019). Mechanized tree harvesting technology, improved logging and transportation of harvested timber and treatment of the post harvesting damages to the surface soil must be duly considered to minimize the negative effects of SciFM in forest carbon and biodiversity.

Fourth, SciFM is being practiced mainly in Sal dominated lowland productive forests, and this practice is being designed and implemented so as to create monoculture of Sal species in natural forests (Awasthi et al., 2020). Establishment of monoculture tree might an approach in artificially created forest stands, especially having a specific purpose of timber production or others. But, natural forests are not only a source of forest products; it has various functions of habitat support for biodiversity (Aryal et al., 2019b; Fedrowitz et al., 2014; Fei et al., 2018). The practice of removing tree species other than Sal might be counterproductive for biodiversity and habitat support. A study in Atlantic region by Iezzi et al. (2018) found that tree monoculture cause significant negative effect on mammals and bird assemblages. Likewise, Luiza-Andrade et al. (2017) noted that monoculture forest have negative impact on taxonomic and functional composition of insect biodiversity in Amazon forests. In this regard, to sustain national commitments to biodiversity and REDD+, SciFM practices should be improved so as to sustain optimum level of mixed-species forests.

Fifth, a single blueprint guideline of SciFM for all types of forests should be revised, and the management interventions should be designed and implemented in order to satisfy the specific properties of forest stands, local climatic and edaphic factors, and functional landscapes (Gustafsson et al., 2012; Mason and Zhu, 2014). Management prescription under SciFM (i.e., adoption of silvicultural practices, containment of mother trees, and consideration of financial benefits from harvesting) is more or less uniform for all types of forests, which is not suitable when considering the biodiversity hotspots, climate sensitive areas, geological fragility and others. For instance, Basnyat et al. (2018) called the blueprint approach to SciFM in Nepal as a 'silvicultural madness' which barely consider the site quality, forest stand conditions, and specific management objectives of the forests. Future course of actions towards SciFM should therefore be designed and implemented in a way that supports carbon and biodiversity commitments at the national level, and site quality and functional characteristics of forest at the local level.

We acknowledge that restoration practices cover wider scope of study, but our study is limited to a few components such as, revegetation and regeneration dynamics, plant species diversity, and soil properties. Besides, we did not consider seasonal variations which might impact species composition and soil properties which is a limitation of our research. And the results we presented were based on six years of restoration practices and based on only a case of SciFM. Our finding is good enough to set hypothesis; for the generalization however, we recommend further study about the long-term impact of SciFM in biodiversity and soil properties, and the replication of such studies in other SciFM implemented areas. Further, a study on comparative assessment between carbon emission from harvesting practices and carbon gain through newly growing regeneration is important to decide on whether the SciFM is suitable for satisfying restoration objectives, including national REDD+ commitments. Moreover, the overall contribution of specific forest management practices in achieving national targets of global commitments would further clarity the role of SciFM in restoration programs. Nonetheless, we presented an important aspect of restoration activities based on SciFM on regeneration, biodiversity, and soil functioning. We have shown that restoration practices based on SciFM is suitable for restoring productive Sal forest stands, probably at the expense of biodiversity goals, national REDD+ commitments, and land productivity.

5. Conclusion

In the emerging debates of various forest management approaches to align restoration objectives, we assessed and examined Nepal's signature program of forest management (i.e., scientific forest management-SciFM), in the face of concurrent restoration program (including national REDD+ and biodiversity objectives). We observed higher proportion of both seedling and saplings in managed blocks than in unmanaged blocks. Our finding shows that restoration activities based on SciFM are promising, at least, to restore Sal (*Shorea robusta*) regeneration in the lowlands of Nepal. Canopy opening through regeneration felling, followed by post harvesting operations (i.e., soil tillage, cleaning, and thinning) are found to be satisfactory to establish Sal regeneration. Unfortunately, Nepal's SciFM program is found to be counterproductive in sustaining biodiversity and species richness, at least for the short-term, because the species diversity, evenness, and species richness are found to be significantly lower in managed blocks than in the unmanaged blocks. Soil organic carbon is found to be significantly lower in managed forest blocks than the unmanaged ones. Similarly, biomass carbon in the managed blocks is found to be about eight times lower than the unmanaged blocks, implying a huge challenge for achieving national REDD+ objectives through the practice of SciFM program. Moreover, soil nutrients are also negatively affected by the SciFM management interventions. We found land productivity (including soil nutrients and its physical properties) is not critical for initiating regeneration but for the growth of the seedlings to establish the future forest stand.

Based on our results and analysis we observed some implications of SciFM on restoration objectives as: (1) SciFM is a promising approach to restore seedlings of the target species (i.e., Sal), (2) SciFM practice imply significantly negative impact to the national REDD+ objectives of carbon benefits, at least for the short-term, (3) SciFM is not only harmful to restore forest carbon but it also negatively impact soil organic carbon, (4) SciFM practice is counterproductive to restore and maintain biodiversity, especially plant diversity, evenness, and species richness, (5) Land productivity, which is largely impacted through SciFM practices, is important for plant species to grow to establish future stand. Although we need a long-term comprehensive analysis to conclude the inference of SciFM, intensive regeneration felling under SciFM is not aligned with the restoration objectives, including biodiversity conservation, land productivity and global climate services. However, moderation of the intensity of regeneration felling though identification of optimum number of mother trees, minimization of forest soil disturbances, and consideration of plant diversity while applying silvicultural systems could moderate the trade-offs of timber production through SciFM with carbon, biodiversity, and other non-provisioning ecosystem services.

CRediT authorship contribution statement

Kishor Aryal: Conceptualization, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nripesh Awasthi:** Conceptualization, Data curation, Methodology, Formal analysis, Validation, Writing – original draft. **Tek Maraseni:** Visualization, Writing – review & editing, Supervision. **Hari Krishna Laudari:** Methodology, Writing – review & editing. **Pabitra Gotame:** Data curation, Methodology. **Dhan Bahadur Bist:** Software, Methodology.

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Conflict of Interest

None.

Data Availability

No data was used for the research described in the article.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2023.106586.

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