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Forest restoration enhances plant diversity and carbon stock in the sub-tropical forests of western Himalaya☆

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ABSTRACT

In the present study we compared the community composition, structure, regeneration status and carbon stock of a human managed arboretum (restoration site) during three decades with a natural forest in western Himalaya. Results reveal that ecological restoration activities in the arboretum enhanced the species richness of woody plants by 66.4% with a total of 125 species as compared to 42 species in natural forest. Similarly, above ground carbon stock in the arboretum was ~38% higher (49.5 Mg/ha) as compared to the natural forest (30.8 Mg/ha). Plantation success in the arboretum was ~52% with a higher survival rate for temperate and Himalayan native species. Tree density in the arboretum was 322.6/ha with 50% higher density of small girth trees (<50 cm gbh) as compared to the natural forest with a tree density of 184/ha. Similarly, basal area was 41.5% higher in the arboretum (23.8 m^2/ha) as compared to the natural forest (13.9 m^2/ha). In case of the ground vegetation layer, shrubs, saplings and seedlings show a density of 23.5, 12.2 and 7.6 individuals/25 m^2 in the arboretum as compared to 10.1, 3.0 and 4.1 individuals/25 m^2 in the natural forest. Hence, our results indicate that the ecological restoration in the sub-tropical forests of the western Himalaya contribute 1.36% annual increment of above ground carbon stock in addition to improvement of the community composition, structure and regeneration in the forest. Therefore, similar institutional restoration projects have ample potential for reducing carbon emissions to mitigate the climate change impact. Such projects will aid in the implementation of the national commitment for REDD+ goals in addition to biodiversity conservation in the Himalaya.

1. Introduction

Mountains covering nearly 30% land surface area, 23% forests and 14% of the world's human population, provide a wide range of ecosystem goods and services to the communities (Ehrlich et al., 2021; Gleeson et al., 2016; Price et al., 2011; Sayre et al., 2018). Among the global mountains, Asia has the largest, highest and most populated mountain system - the Himalaya (Ehrlich et al., 2021; Spicer, 2017). The Himalaya as provider of goods and range of ecosystem services, is vital for sustaining life of millions of people in uplands and billions in lowlands (Rawal et al., 2021). The Himalaya representing one among the 36 global biodiversity hotspots (www.cepf.net), harbor more than 10,000 species of plants (Rana and Rawat, 2017), nearly 1000 species of birds (Mohan, 2021) and 300 species of mammals (Sharma et al., 2015). The region with a moderate to dense cover of forest forms a large reservoir of carbon pool. The forests in the Indian Himalayan region (IHR) have been estimated to store nearly 3000 million tonnes of carbon stock, which represents nearly 40% of total carbon pool of India's forests (Rawal et al., 2021). The Himalayan forests estimated to sequester nearly 65 million tonnes of carbon annually (Tolangay and Moktan, 2020) thus have an ample potential to mitigate climate change and global warming.

Global forest ecosystems with nearly 80% of the aboveground carbon plays an important role in maintaining the carbon balance and climate change mitigation (Streck and Scholz, 2006; Whitehead, 2011). Therefore, conservation and management of forest resources are imperative to combat global climate change (Giri et al., 2019; Negi et al., 2019). The biomass and carbon stock of the forests are important indicators of forests productivity, energy potential and capacity to sequester carbon (FAO, 2016). Role of the forests as carbon dioxide sink has received increasing attention since the adoption of Kyoto Protocol to UNFCC in

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1997. Subsequently, REDD+ (Reducing Emissions from Deforestation and Forest Degradation) emerged as a forest mitigation approach for conservation and sustainable management of forests in the developing countries (Maniatis et al., 2019). In order to enhance the restoration activities across different ecosystems from global to local scale on the earth, United Nations has declared the current decade (2021–30) as the Decade on Ecosystem Restoration. As part of the action during this decade, restoration of degraded land through plantation of multifarious species in the Himalayan region would ensure biodiversity conservation, flow of forest goods and climate change mitigation (Rawal et al., 2021). India joined the Bonn Challenge pledge in the year 2015 during the UNFCCC Conference of Parties (COP) at Paris. India has largest pledges from Asia with an eco-restoration aim for 13 million hectares of degraded land by 2020, and an additional eight million hectares by 2030 (Bhattacharjee, 2020) (https://www.bonnchallenge.org). Effective implementation of forest landscape restoration (FLR) principles across deforested landscape, is one of the most practical ways of achieving these national targets and international commitments (Borah et al., 2018). India has acted as an important stakeholder in shaping the mechanism of REDD+ by emphasizing the role of conservation and sustainable forest management in mitigating carbon emissions (Sharma and Chaudhry, 2013). Complementary strategies for securing the irreplaceable biodiversity and forests carbon stock are very important in the human dominated landscapes which holds greater potential for synergizing conservation and climate change mitigation (Osuri et al., 2020).

Estimating biomass is a useful measure for comparing structural and functional attributes of forest ecosystems across a wide range of environmental conditions (Brown et al., 1999). Particularly, forest biomass measurements are critical for implementing land-based climate mitigation strategies (Goetz et al., 2015). Long-term forest inventories are most useful for evaluating the magnitude of carbon fluxes between aboveground forest ecosystems and the atmosphere (Brown, 1997; Chave et al., 2005, 2014; Grace, 2004). Ecological restoration plays an important role in reversal of the prevailing biodiversity loss and enhancement of terrestrial carbon sequestration in the forest ecosystems, which in turn will help in mitigation of the climate change impact (Alexander et al., 2016; Brudvig, 2011; Harris, 2009). Active restoration of degraded forests results in significant enhancement of biomass and carbon stock. For example, a decade long restoration projects in China contributed an annual carbon sink of 74 Tg C/year which is 56% of the total carbon stock in the forest ecosystems thus contributing substantially to CO_2 mitigation (Lu et al., 2018). Similarly, 7–15 years of restoration in degraded tropical rainforest of the western Ghats in India resulted in recovery of forest structure, composition, and carbon storage (Osuri et al., 2019). Thus, ecological restoration especially in the fragile mountain ecosystems is necessary for biodiversity conservation and climate change mitigation.

In the Himalaya, due to increasing human pressure and developmental activities, forest degradation is very common which needs immediate restoration to arrest its environmental degradation (Baland et al., 2010; Prabhakar et al., 2006; Singh et al., 2019). Increasing anthropogenic impacts and deforestation in the Himalaya is causing the loss of many rare and endemic species (Mehta et al., 2020; Pandit et al., 2007, 2014). The cumulative impact of natural and human induced pressure in the forests of the Himalaya has enhanced the rate of degradation (Wang et al., 2019). Ecological restoration projects in the degraded and open forest lands in the Himalaya are thus very important for the conservation of its biodiversity and enhancement of carbon sequestration. Afforestation projects for ecological restoration of the open and degraded forests in the Himalaya are of utmost importance in the scenario of changing climate (Negi et al., 2015; Semwal et al., 2013). The Himalaya being a forested landscape inherently becomes the major region of interest for FLR programmes particularly during the UN decade on ecosystem restoration (www.decadeonrestoration.org). In the Himalayan region, many restoration projects have been implemented or are under progress, but only few have made significant impacts. G.B. Pant National Institute of Himalayan Environment (GBP-NIHE) being an organization for environmental research and development has successfully converted the conceptual idea of eco-restoration into implemented projects in different parts of the Indian Himalayan region (Maikhuri et al., 1997; Negi et al., 2015; Semwal et al., 2013). Present study is an attempt to compare an ecologically restored forest site with a surrounding natural forest at similar elevation to evaluate the plantation success, improvement in forest composition, structure and carbon stock during last three decades.

2. Materials and methods

2.1. Data collection

The study compared phytosociological and biomass attributes of a natural sub-tropical forest (GPS: 29.6355°N, 79.5991°E) with a managed forest (GPS: 29.6416°N, 79.6213°E) by GBP-NIHE, located at ~1200 m asl in Almora, Uttarakhand, India (Fig. 1). The institute, in addition to its main campus, adopted a patch of natural nearby forests named as Surya kunj arboretum and conducted plantation during the period of 1992–2014. The region is dominated by Chir Pine (*Pinus roxburghii*) forest with its co-dominant tree species such as *Quercus leucotrichophora, Myrica esculenta, Pyrus pashia, Celtis australis, Alnus nepalensis* etc. Chir Pine forests predominantly occupy the elevational range of 800–1700 m asl in the western Himalaya. These forests are relatively open in structure and are prone to forest fires due to the availability of dry litter in the forest floor and presence of resin on the trees. In addition, this elevational belt is inhabited with a significantly large human population with interspersed agricultural fields and villages. Thus, these forests face both natural and human induced pressure and are considered relatively poor in quality as compared to other forest types in the Himalaya.

We compiled a list of 172 tree species planted in the arboretum and assessed their nativity from USDA-GRIN website (https://npgsweb.ars-grin.gov) and climatic affinity following (Wu, 1991). We used natural elevational ranges of the planted species to conduct their niche comparison with the study site and tested the role of similar niches on plantation success in the arboretum. We further sampled woody plant species in the arboretum and the surrounding natural forest to test the role of restoration on improvement of species composition, community structure, regeneration and carbon sequestration. We marked the boundary of the arboretum using a GPS (Model: Garmin Etrex-30) and calculated a total area of 8.5 ha. All the trees >30 cm in girth inside the arboretum were numbered with tree-tags, identified at species level and girth at breast height (gbh) was recorded for each individual tree. In order to compare the phytosociological and biomass attributes of the managed forest with natural conditions, we selected a natural forest outside the arboretum. Trees were sampled in 50 plots of size 0.1 ha (31.7 × 31.7 m) with a total area of 5 ha, at random locations in the comparable elevation. Within each plot, name of the species and gbh of all the individual trees with girth >30 cm was recorded.

In addition, we sampled shrubs, saplings and seedling in plots of size 25 m^2 (5 × 5 m) in both the sampling areas. Two plots in each quadrat for trees (100 plots) were sampled in the natural forest whereas in the arboretum a total of 54 plots were sampled at every encounter of previously unrecorded species. Number of individuals for each species of the shrubs, saplings and seedlings encountered in every plot were recorded. Tree species with a girth size of 10–30 cm were considered as saplings and <10 cm girth were considered as seedlings. All species were identified on site using the regional and local flora. Species were photographed, preferably during flowering or fruiting stage in order to confirm the identification.

2.2. Data analysis

In order to test the level of under-sampling for the estimation of

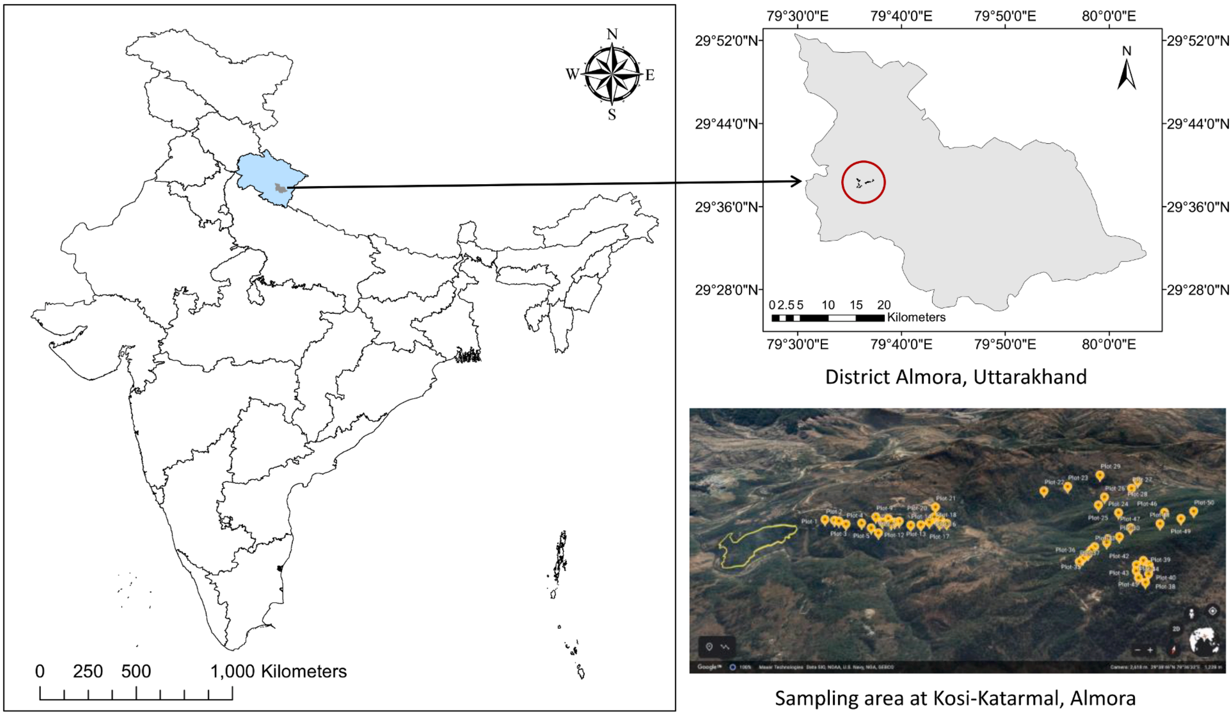

Fig. 1. Left panel: map of India showing location of the study area in district Almora of state Uttarakhand. top right panel: location of the sampling sites in the Almora district (red circle), bottom right panel: boundary of Surya kunj arboretum (yellow line) and GPS locations of the 50 plots (yellow points) in the natural forest, source: https://earth.google.com/web.

species richness and comparison of tree diversity in the natural forest and managed arboretum, we plotted individual based rarefaction and extrapolation curves using "iNEXT" package (Hsieh et al., 2016) in R (R Core Team, 2018). For rarefaction curves we used three important indices of the Hills number, i.e., species richness, Shannon index and Simpson index (Chao et al., 2014) to compare the species richness and diversity in the two sampling areas. We further compared species abundance distribution between the 5 ha sampled area in natural forest and 8.5 ha area of the arboretum using R package "sads" (Prado et al., 2018). We calculated species abundances and plotted the number of species against the abundance classes in ascending order. Various models for species abundance distribution (McGill et al., 2007) were compared with the distribution of trees in the two sampling areas and two models with lowest AIC values, i.e., log-normal and log-series distribution were plotted. In addition, girth classes representing increasing girth sizes of all individual trees were compared between the natural forest and the arboretum. Further, average girth size for most abundant and common species in the two sampling areas and unique species which are cultivated in the arboretum were plotted for comparison of growth patterns.

We calculated the total above ground biomass and carbon stock for all trees >30 cm girth size in the arboretum and natural forest in order to test the contribution of carbon in the forest ecosystem due to the plantation efforts in the arboretum. For calculation of above ground biomass we used the R package "BIOMASS" (Réjou-Méchain et al., 2017) which uses a corrected version of generalized allometric model given by Chave et al. (2014) and has the following expression:

$$AGB = \exp(-2.024 - 0.896.\ E + 0.920\ .\ \ln(WD) + 2.795\ .\ \ln(D) - 0.0461[\ln(D)]^2]$$

where D is the diameter of individual trees, WD is the wood density of the species and E is the bioclimatic compound parameter as given in (Chave et al., 2014). The bioclimatic compound parameter E is derived from three bioclimatic variables, i.e., temperature seasonality, precipitation seasonality and maximum climatological water deficit. The R program uses predicted tree heights by building a local height–diameter allometry (using the coordinates of the study area) based on the models of tree heights inferred from pantropical or regional models (Réjou-Méchain et al., 2017). Wood density values at species level for calculation of above ground biomass are assigned from a reference data (Chave et al., 2009, Zanne et al. 2009, https://doi.org/10.11...61–0248.2009.01285.x). In case species level wood density values are not available in the dataset, an average of the wood density for the specific genera is taken for the calculation. We calculated the above ground carbon stock values for each individual tree by multiplying the above ground biomass value with a factor of 0.47 for angiosperms and 0.51 for the gymnosperms as suggested by (Thomas and Martin, 2012). Total above ground biomass and carbon stock was calculated for the whole forest inside the sampling areas as well as for different species within the sampling area.

3. Results

3.1. Plantation history in Surya kunj

A total of 172 species of trees were planted during last three decades in the Surya kunj arboretum out of which 89 species are presently growing at different stages. Among the species selected for plantation, 136 native Himalayan species showed better performance with a success rate of 52.2% as compared to 54 non-native species with a success rate of 50% (Fig. 2b). In terms of climatic affinities, 47.2% tropical species and 57.6% temperate species grew successfully in the arboretum (Fig. 2d). The plantation history showed an overall success of ~52% which is consistent for species with different nativity, taxonomic levels and climatic affinities (Fig. 2). Bivariate plot of the lower range limits against the upper limits of planted species show comparable niches for majority of species with overlapping range at ~1200 m (Fig. S1). Nearly 15% species have incomparable elevational ranges out of which half of the species have successfully grown whereas many species from the comparable elevation were unable to establish in the arboretum.

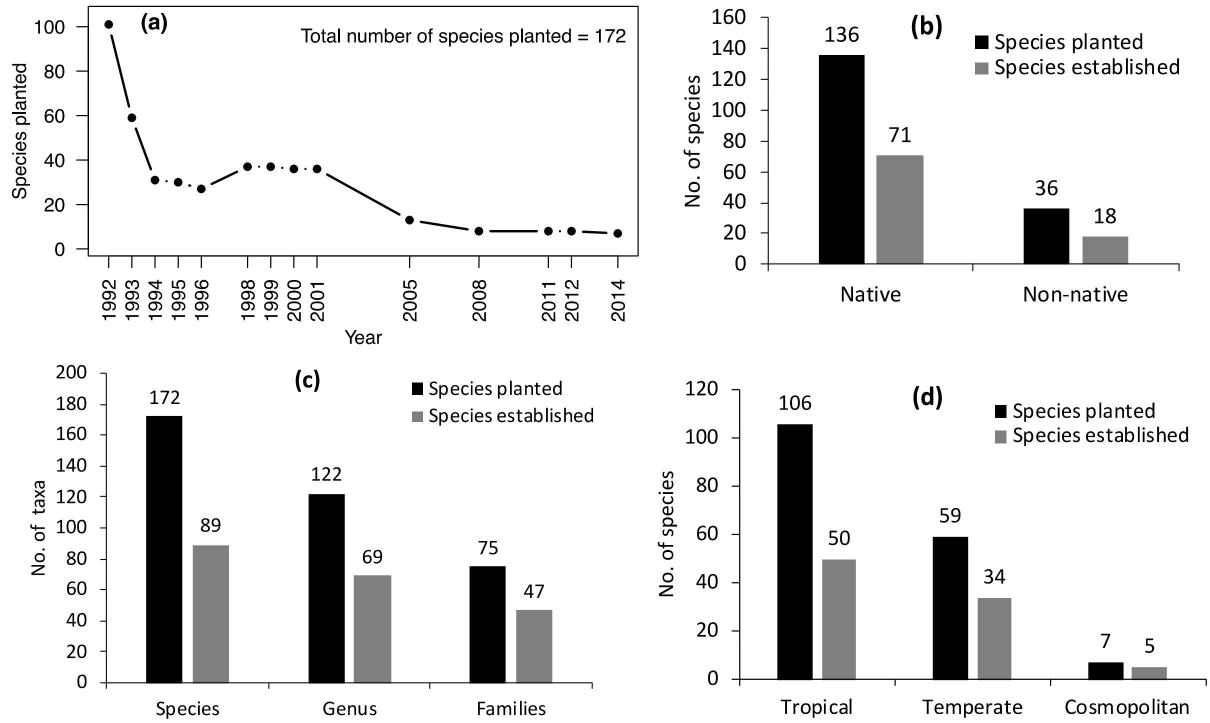

Fig. 2. Plantation history and success of plantation in the Surya kunj arboretum. (a) Species wise plantation (b) Nativity of the total number of planted and established species (c) Number of taxa planted and established (d) Climatic affinity of the planted and established species.

3.2. *Species richness, diversity and regeneration*

We encountered a total of 125 woody species in the Surya kunj arboretum including 99 trees and 26 shrubs. Among the trees 74 species were in adult stage (>30 cm girth) whereas 25 species were in sapling or seedling stage (Table S1). In comparison, we encountered only 33.6% species in the natural forests, i.e., a total of 42 woody species including 22 trees (17 species >30 cm girth, 5 species <30 cm girth) and 20 shrubs (Table S1). Tree density in the arboretum was 43% higher than the natural forest, i.e., 322.6 trees/ha in arboretum as compared to 184 trees/ha in the natural forest. Similarly, total basal area for trees above 30 cm girth in the arboretum (23.8 m^2/ha) was 40.3% higher as compared to the natural forest (14.2 m^2/ha; Table 1). The species richness increased by 66.4% in the arboretum as compared to the natural forest due to the plantation intervention during last three decades. The slope of rarefaction and extrapolation curve based on the Hills numbers shows that sufficient sampling was conducted in the natural forest for estimation of alpha diversity or species richness (Fig. 3). Shannon index and Simpson index values also indicate sufficient sampling in the natural forest to capture the diversity. Trees sampled in the natural forest constitute 90% (20 out of 22) of the species present in the arboretum indicating it to be a part of the natural forest before the restoration interventions.

The regeneration status of trees in the arboretum was higher (11.9 sapling/25 m^2 and 7.6 seedling/25 m^2) as compared to the natural forest (3.01 sapling/25 m^2 and 4.07 seedling/25 m^2). Similarly, species richness of shrubs was higher in the arboretum (26 species) as compared to the natural forest (20 species). Density of shrubs in the arboretum was 13.5 individuals/25 m^2 as compared to 10.05 individuals/25 m^2 in the natural forest (Table 1). Dominant shrub species in both the sampling area are *Rubus ellipticus* and *Pyracantha crenulata* followed by *Berberis aristata* in the natural forest and *Rosa moschata* in the arboretum. Highest density of tree saplings was recorded for *Celtis australis* followed by *Quercus leucotrichophora* and *Pyrus pashia* in the arboretum whereas in natural forest later two species showed highest density. However, highest density of seedlings was recorded for *Pinus roxburghii* in both sampling areas followed by *Celtis australis* in arboretum and *Pyrus pashia* in the natural forest (Table S1).

Table 1
Comparison of the phytosociological and biomass attributes of restored arboretum and natural forest in Almora, Uttarakhand.

Parameter	Surya kunj	Natural forest
Total area sampled (ha)	8.5	5.0
Trees sampled (>30 cm girth)	2742	920
Tree species richness (>30 cm girth)	74	17
Tree species richness (<30 cm girth)	25	5
Tree density (individuals/ha)	322.6	184
Tree basal area (m^2/ha)	23.8	14.2
Above ground biomass (Mg/ha)	99.5	61.9
Above ground carbon stock (Mg/ha)	49.5	30.8
Shrub species richness	26	20
Shrub density (individuals/25 m^2)	13.5	10.05
Sapling density (individuals/25 m^2)	12.2	3.01
Seedling density (individuals/25 m^2)	7.6	4.07

3.4. *Patterns of species abundance and girth size*

The species abundance distribution shows expected pattern of decreasing abundance in the natural forest although the forest in the human managed arboretum was more diverse (Fig. 4). The results show that majority of the species are rare in the natural forest, e.g., 70.5 % of species have less than one percent abundance as compared to 17.3 % species in the arboretum. Very less number of species in the natural forest remain dominant whereas this natural pattern of abundance was altered to some extent in the arboretum due to restoration interventions. However, when we compared the natural distribution with the distribution of the sampled species, both areas showed similar best fit models, i.e., for log-series (Natural forest AIC: 130.6, Surya kunj AIC: 558.7) and log-natural (Natural forest AIC: 133.5, Surya kunj AIC: 566.9).

The pattern of girth class distribution in the two sampling areas shows dominance of small girth size in the arboretum where density of 30–49 cm girth size trees is 95.2 trees/ha as compared to 47.8 trees/ha

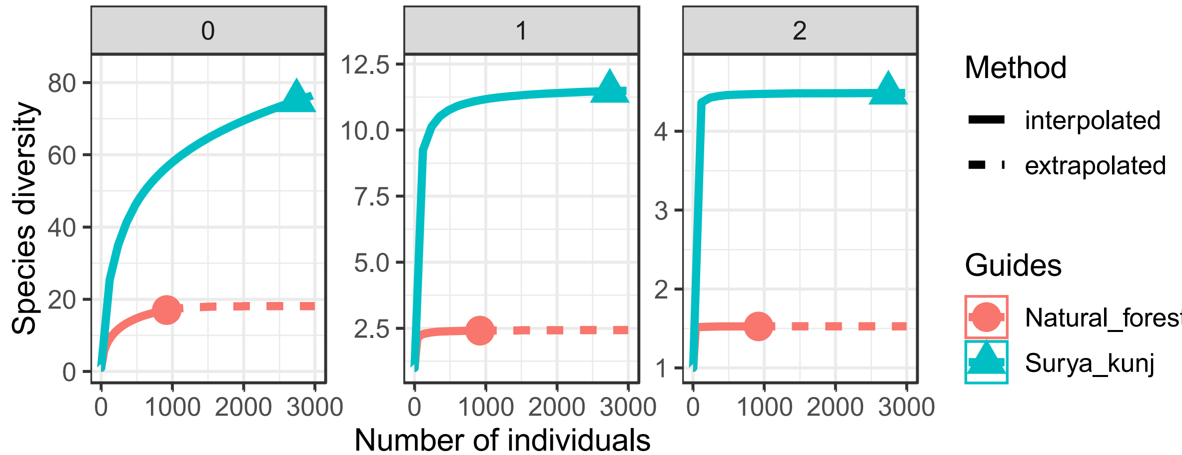

Fig. 3. Sample-size-based rarefaction (solid lines) and extrapolation (dashed lines) of tree species diversity based on the hill numbers (0): species richness, (1): shannon index and (2): simpson index) for the Surya kunj arboretum and natural forest. The 95% confidence intervals (shaded regions) were obtained by a bootstrap method based on 200 replications.

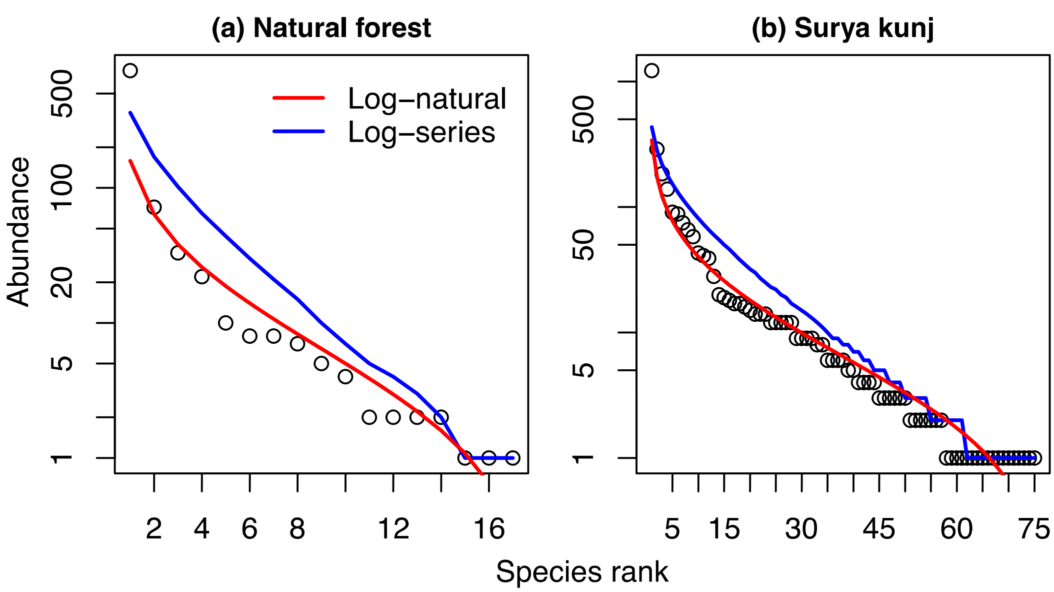

Fig. 4. Species abundance distribution in the restored arboretum and natural forest in Almora Uttarakhand. Red line shows log-natural distribution and blue line shows log-series distribution of the species abundance in the two sampling areas.

in the natural forest (Fig. 5). However, trees with >50 cm girth show similar pattern of decrease in number of individuals with increasing girth size. Higher species richness and higher density of trees with dominance of small girth class and higher regeneration success in the arboretum indicates better protection of the restored forest. *Pinus roxburghii* is the dominant tree species in both sampling areas with a density of 144.1 trees/ha in arboretum and 148 trees/ha in the natural forest followed by *Quercus leucotrichophora* with a density of 34 trees/ha in arboretum and 14.4 trees/ha in natural forest. Both the dominant species grow naturally in the region and are not planted in the arboretum. In spite of the differences in dominance, average girth size of common species between the two sampling areas show similar trend (Fig. S2). Among the planted trees in the arboretum *Grevillea robusta* is most dominant with a density of 21.7 trees/ha followed by *Cupressus torulosa* with a density of 10.7 trees/ha (Table. S1). The average girth size of the planted species in the arboretum varies in spite of similar plantation history which indicates differential growth rates in the different species. Trees of *Pinus roxburghii* have largest girth size among the native species (Fig. S2) whereas *Populus ciliata* and *Melia azedarach* have the largest grith size among the cultivated species (Fig. S3).

3.5. *Above ground biomass and carbon stock*

Total above ground biomass which is commensurable to carbon stock is 37.7% higher in the arboretum (AGB: 99.5 Mg/ha, AGC: 49.5 Mg/ha) as compared to the natural forest (AGB: 61.9 Mg/ha, AGC: 30.8 Mg/ha; Table S1). *Pinus roxburghii* contributes highest amount of carbon stock in the arboretum (32.9 Mg/ha) and in the natural forest (20.2 Mg/ha). The second highest carbon stock contributing species in the arboretum is *Celtis australis* (3.2 Mg/ha) and in the natural forest is *Quercus leucotrichophora* (3.64 Mg/ha; Table S1). The top carbon stock contributing species also constitutes the key dominant native species in the region and thus plays an important role in the biochemical cycling and trophic balance. Among the exotic and planted species in the arboretum, *Grevillea robusta* contributes highest carbon stock (1.9 Mg/ha) followed by *Populus ciliata* (1.8 Mg/ha), *Salix tetrasperma* (1.1 Mg/ha), *Cupressus torulosa* (1.09 Mg/ha) etc. As expected, the volume of carbon stock of a species shows a very strong correlation with the density of the species both in natural forest ($r = 0.99$) as well as in the arboretum ($r = 0.98$; Fig. 6). In terms of regeneration, density of saplings shows a weaker correlation with the adult tree density both in natural forest ($r = 0.69$)

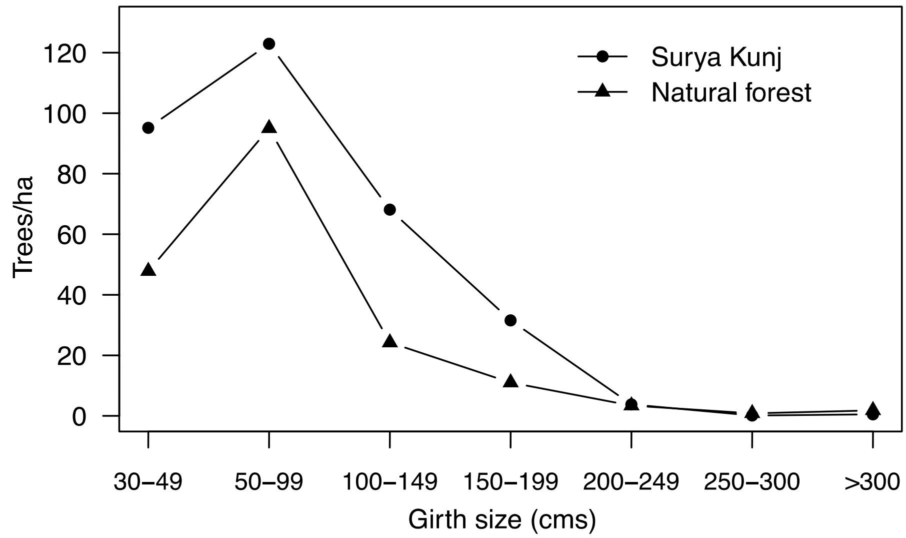

Fig. 5. Comparison of tree girth classes between restored arboretum and natural forest in Almora, Uttarakhand.

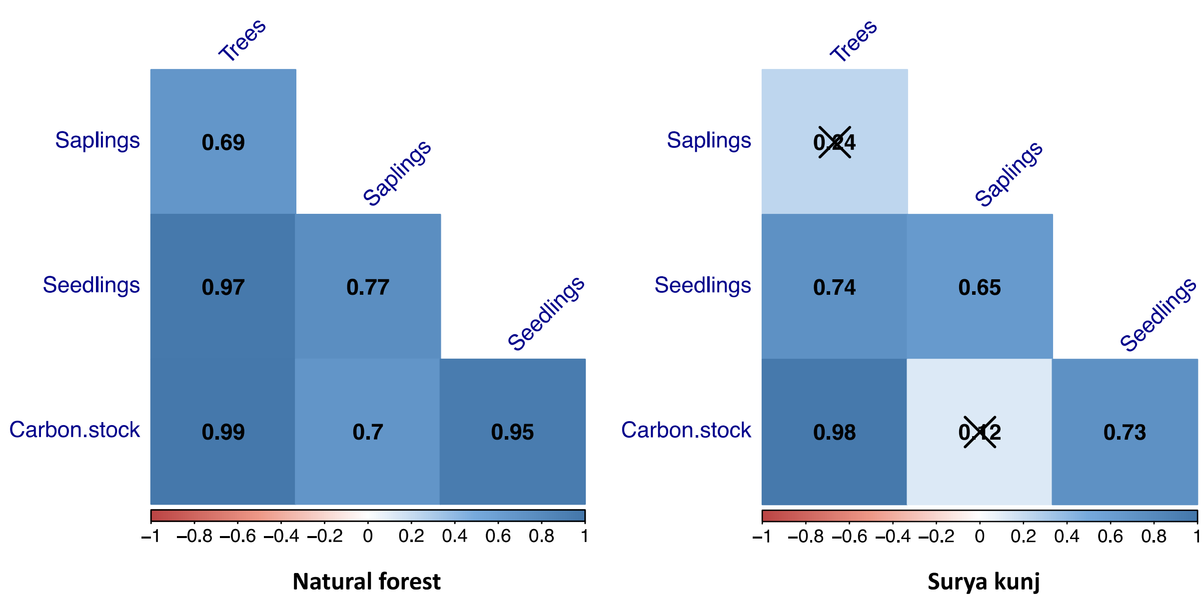

Fig. 6. Correlation matrix of various ecological metrices in the restored arboretum and natural forest at Almora, Uttarakhand.

and the arboretum ($r = 0.24$) whereas seedling density shows a much stronger correlation with tree density (natural forest, $r = 0.97$; arboretum, $r = 0.74$). The correlation between density of seedlings and saplings is stronger in the natural forest ($r = 0.77$) as compared to the arboretum ($r = 0.65$) showing a better regeneration success in the natural forest (Fig. 6).

4. Discussion

International conventions (e.g., CBD 2012), and intergovernmental platforms (e.g., IPBES 2013) have recognized ecological restoration as one of the global priorities for biodiversity conservation, combating desertification, and limiting the impacts of anthropogenic climate change (Aronson and Alexander, 2013; Young and Schwartz, 2019). In the Himalayan region, GBP-NIHE has developed various methods and models for ecological restoration and rehabilitation to minimize deforestation and land degradation (Bhatt et al., 2020). Surya Kunj arboretum is one such example of restoration and *ex-situ* conservation by the institute. Nearly three-decade long forest restoration activities have resulted in quantifiable improvement in the community composition, structure and carbon sequestration in the Surya Kunj arboretum. The successful establishment of tree species in the arboretum indicates an enhancement of species richness by 66.4% and carbon stock by 37.8% as compared to the natural forest. The slope of rarefaction curve based on the Hills numbers show that both species richness and diversity was sufficiently captured in the natural forest thus such differences are real. Ecological restoration through afforestation is an important measure for improvement of species composition, structure and carbon sequestration (Guo et al., 2013; Osuri et al., 2019; Zobel et al., 1998). Among the species selected for plantation in the arboretum, Himalayan natives showed better survival and growth performance in the arboretum which is consistent to the previous findings that native species are ideal for restoration of the degraded forests due to their higher adaptability in the environment (Lu et al., 2017; Thomas et al., 2014). The overall plantation success in the arboretum was only ~52% although native elevational ranges of majority of the species was similar to elevation of the arboretum indicating an important role of the species biology and plantation history in establishment of the introduced species

(Bucharova and Kleunen, 2009; Theoharides and Dukes, 2007).

Above ground biomass of trees is strongly correlated with trunk diameter which can be employed to estimate the carbon stock and changes using forest inventory data (Brown, 1997). In order to estimate the forest biomass, general allometric regression models have been used extensively in spite of lacking directly tested equations on many species which have different wood densities (Chave et al., 2009, 2001). Additionally, variations in environmental factors such as topography, hydrology and edaphic characteristics may also complicate attempts to generalize allometric equations at regional or landscape scale (Clark and Clark, 2000). Estimation of biomass and carbon stock in forest ecosystems needs careful consideration while using relevant allometric models (Salunkhe et al., 2018; Shi and Liu, 2017). Thus, to develop universal allometric equation for estimation of above ground biomass Chave et al. (2014) used climatic variables, tree diameters, heights, and wood densities from global tree inventory data. These equations are thus widely used for estimation of above ground biomass of forests at local, regional or global scales particularly for regions where species specific allometric equations are not available (Kunwar et al., 2021; Sainge et al., 2020; Zhou et al., 2021). Because the species specific allometric equations were not available for most of the sampled species, we used the generalised allometric equation by Chave et al. (2014), with certain modification by Réjou-Méchain et al., (2017) to calculate the above ground biomass and carbon stock of the managed and natural forest.

The managed forest in arboretum holds 37.8% higher above ground carbon stock (49.5 Mg/ha) as compared to the natural forest (30.8 Mg/ha). Similarly, carbon stock contribution of the dominant species (*Pinus roxburghii*) was 31.5% higher in the arboretum as compared to the natural forest in spite of slightly higher tree density in the later. This shows a higher rates of carbon sequestration in the arboretum which might be a result of higher level of protection in the arboretum (Keith et al., 2014). On contrary, second dominant species *Quercus leucotrichophora* which form the lower canopy of the Pine forest, has two times higher tree density in the arboretum but the above ground carbon stock of the species was almost two times higher in the natural forest. This indicates that species biology and competition also plays important role in the forest growth and restoration (Köhl et al., 2017; Yang et al., 2019). Lesser accumulation of carbon stock in the species is possibly due to restrained growth in the denser managed forests. Many previous studies have demonstrated that restoration of forests at local scale through human interventions can improve carbon sequestration substantially. Restoration efforts at local scale are very important for achieving national and global commitments for carbon reduction and climate change mitigation (Bernal et al., 2018; Lu et al., 2018; Osuri et al., 2019; Zanini et al., 2021). Such efforts are not only helpful in reduction of carbon emission but are also beneficial for improvement of species composition and regeneration. For example, after three decades of natural regeneration in an Atlantic forest, above ground carbon stocks was increased by nearly 20% with a recovery of 65% threatened and 30% of endemic species of the region (Matos et al., 2020). A comparison of the above ground tree biomass of natural and cultivated forest in northeast Himalaya showed 20% higher biomass in the later (Baishya et al., 2009). Afforestation and restoration projects have a significant impact on the carbon sequestration in the forest ecosystems (Dabas and Bhatia, 1996; Nave et al., 2019) thus needs to be promoted at large scale for combating the climate change impacts in the mountain ecosystems including in the Himalaya.

In addition, the ground layer of vegetation was improved significantly in the arboretum. Shrub richness and density in the arboretum was higher than the natural forest. However, regeneration status of trees was better in the natural forest as compared to the arboretum. This indicated a higher degree of competition between the seedlings and saplings of regenerating trees in the arboretum which is attributed to higher number of species. Ecological interactions of species after plantation have both negative (competition) and positive (facilitation) effects necessitating the understanding of limiting factors affecting plant establishment in restoration (Löf et al., 2019; Palmer et al., 1997). The comparison of girth size between the two areas show ~50% higher abundance of small girth (30–49 cm) trees in the arboretum than the natural forest. Trees in early growth stage show highest rate of carbon sequestration thus contribute relatively higher amount of carbon stock in the forest ecosystem (Köhl et al., 2017; Wang et al., 2016). Globally, regions with relatively cool temperatures and moderately high precipitation are known to store highest volumes of carbon stock which is attributed to faster growth but slow decomposition (Keith et al., 2009; Myneni et al., 2001). In our dataset, the average girth sizes of majority of the common species between the two sampling areas are similar. This indicates that increment in the species richness and carbon stock is a result of the plantation but the girth size of trees is controlled more strongly by species biology and environmental factors than the anthropogenic disturbances or human interventions. This is also evident from the fact that both areas show best fit with log-series species distribution model which is applicable when generally rare species are present in a community (McGill et al., 2007; Slik et al., 2015). Species abundance distribution in a natural community provides meaning full information for conservation prioritization as most of the species in a community are rare and very few species are common (Arellano et al., 2015; Enquist et al., 2019; Preston, 1948).

Restoration of degraded lands in the Himalayan ecosystem is also prone to associated challenges. For example, major challenges faced during the process of the restoration in the Surya Kunj arboretum includes forest fires, livestock grazing and unavailability of sufficient water for regenerating plants. Historically, forest fires and livestock grazing have been a major part of the sub-tropical Chir Pine forests in the western Himalaya (Fulé et al., 2021; Ingty, 2021; Kala et al., 2002). During the last three decades of restoration in the arboretum, forest fires were frequently witnessed both in the surrounding areas as well as inside the arboretum. Although, most of the forest fires in the arboretum were controlled and stopped with a few hours or days, but such fires have impacted the regeneration of the species occasionally. Further, in spite of a strong boundary fencing around the arboretum, the local villagers occasionally drive their livestock inside the arboretum resulting in grazing of many regenerating plants. Similarly, availability of water is not uniform throughout the year for the regenerating plants with maximum water available during the monsoon season. Thus, to overcome these challenges, the institute adopted various strategies like strict monitoring and guarding of the arboretum, construction of bunds and water reservoirs for rainwater harvesting etc. Major recommendations from this case study, to achieve successful ecological restoration in other regions particularly in the sub-tropical and temperate regions of the Himalaya would be; selection of species with appropriate nativity, matching niches, genetic variability and other limiting factors. Further, a strong mechanism for the control of prominent pressures like forest fires, livestock grazing, tree felling, litter removal etc. is an utmost necessity for successful implementation of restoration projects in the degraded and disturbed lands of the Himalaya.

5. Conclusion

In order to implement the commitments of the national CBD and REDD+ policy, various stakeholders including the academic and research institutions needs to implement actions for increasing the carbon stock and decreasing carbon emissions in the forests ecosystems of the country. The present study reveals that institutional projects on ecological restoration of the sub-tropical forests in the Himalaya have ample potential for mitigation of climate change impact as well as conservation of biodiversity. The research activities of GBP-NIHE through implementing various projects have made a considerable impact on the attitude of local inhabitants with a positive change in their perception for conservation and natural resource management. Such projects will significantly enhance the carbon sequestration, in addition to multitude of indirect impacts like nutrient balancing, biogeochemical cycling, water balance, improvement of community composition, structure and regeneration status etc. Our results further indicate that even when the plantation is managed by humans, the natural processes like biotic interaction and abiotic factors plays an important role in establishment of the species and communities follow the natural rules. Overall such ecological restoration projects have relevance for both national and global level environmental significance through various impacts like biodiversity conservation, strengthening ecosystems services, prevention of desertification, climate change mitigation etc.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2022.100201.

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