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UNDERSTANDING THE *Phyllanthus* AND *Terminalia chebula* SPECIES POPULATION CHANGE, DEPENDENCY AND SUSTAINABILITY: A STUDY IN MALAI MAHADESHWARA HILLS WILDLIFE SANCTUARY, SOUTHERN INDIA

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Abstract

Non-Timber Forest Products (NTFPs) are vital sources of livelihood for forest-dependent communities across the globe. This study examined the NTFPs species (*Phyllanthus emblica*, *P. indofischeri*, and *Terminalia chebula)* population change determined by the dependency, disturbances, and accessibility in the dry tropical forest of Malai Mahadeshwara (MM) Hills wildlife sanctuary. The long-term monitoring population data were analyzed across three time periods; 2000-01, 2010-11, and 2020-21. The participatory research methods were used to assess the dependency and accessibility which influence the population structure. The multi-factor linkage approach was used to identify the significant drivers of population decline. The results indicated that grazing, fire, hemi-parasite infection, and *Lantana* invasion influenced the tree population structure and regeneration of study species. This study has also indicated variations and changes in the interrelationship among factors that have a significant role in shaping NTFPs species population structure. Multiple factor analysis determined that grazing, fire, and lantana have significant impacts on population structures, regeneration, and fruit production of NTFPs species. The study recommended that forest managers should consider a site-specific adaptive approach and multiple factors models and inclusive management tools provisioned in recent policies like the Biological Diversity Act -2002 and Forest Rights Act-2006 would hold great potential for developing sustainable use and co-management practices.

Keywords: Community; Dependency; Forest resources; Sustainability

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1. Introduction

Forests provide a range of socio-economic and environmental benefits that are essential for human life (Millennium Ecosystem Assessment, 2005; Food and Agriculture Organization, 2014). Globally, more than a billion people depend directly on NTFPs for their livelihoods (MEA, 2005). Another three billion people indirectly depend on NTFPs for many economic and social benefits (Agrawal et al., 2013). Thus, NTFPs are found to be a vital source of livelihood for people from forest fringe communities across the world. Many studies revealed that NTFPs realize various functions in enhancing human well-being and rural livelihoods, and it was widely acknowledged globally (Angelsen et al., 2014; Shackleton et al., 2015; Shackleton and Pullanikkatil, 2018).

In India, NTFPs species contribute 2.7 billion USD per year and provide 55% of the total employment in the forestry sector (FAO, 2014). These NTFPs are harvested for food, medicines, and handicrafts apart from subsistence use and as a source of cash income. Past studies have reported that fruit harvesting alone does not have a significant impact on the NTFPs population, site-specific multiple factors could change the population structure (Ticktin, 2004; Brummitt and Bachman, 2010; Scoles et al., 2012). Shaanker et al. (2004a), identified that dependency, degradation, and disturbance factors could contribute to the depletion of NTFPs resources in tropical forest settings. However, intermittent extraction of NTFPs has influenced stability in the population structure of NTFPS species (Kodandapani et al., 2004; Shackleton et al., 2005; Varghese et al., 2015). Moreover, resource accessibility changes dependency on NTFPs and related livelihoods (Marshall et al., 2006). These changes in local context and livelihoods might have influenced or contributed to changes in the NTFPs population structure (Endamana et al., 2016). It is also apparent that the contribution of NTFPs to income varies across ecological settings, seasons, and income levels (Marshall et al., 2006). Considering the importance of NTFPs in the livelihoods of local communities needs more attention on developing appropriate policies and evolving strategies for the better management of NTFPs.

Several attempts have been made to understand the dynamics of the NTFPs species population and identify sustainable harvesting practices (Gaoue and Ticktin, 2010; Ravikanth and Setty, 2017). Most of the NTFPs studies have exclusively focused on assessing the impacts of harvesting and other anthropogenic factors on regeneration, productivity, and population structure as well as on genetic diversity (Murali et al., 1996; Padmini et al., 2001; Ganesan and Setty, 2004; Sinha et al., 2005; Ramesha et al., 2007; Ravikanth et al., 2009). Further, studies also recommended developing effective conservation strategies, sustaining the livelihoods of dependent communities and ecology of NTFPs species using anthropogenic factors at multiple scales, times, disciplines, and linkages (Peres et al., 2003; Schmidt et al., 2011; Ticktin et al., 2012). The attributes such as harvest practices, dependency dynamics, and species response patterns are crucial to evolve an ecologically sustainable practice (Ticktin and Shackleton, 2011).

This study is intended to contribute to the knowledge of understanding the interrelationship between the dependencies; accessibility change and derived disturbance which influenced the species' response toward developing sustainable practices. It helps in developing strategies for finding nature-based solutions to address and manage forest resources. Henceforth, this study formulates the hypothesis that a combination of fruit harvest frequency, derived disturbances and accessibility play a crucial role in reshaping the population structure, recruitment rate, and fruit productivity.

2. Materials and methods

2.1. Study site

The study was conducted in Malai Mahadeshwara (MM) Hills which is located in the Chamarajanagara district of Karnataka in South India. It lies between latitudes 11˚ 55˚N and 12˚ 13˚N, and longitudes 77˚ 30˚ and 77˚ 47˚E with Cauvery Wildlife Sanctuary to its North-East and the Biligiri Rangaswamy Temple Tiger Reserve (BRT) to its South-West (Figure 1). The sanctuary covers an area of 906 km², hills and valleys are roofed with extensive forests with a chain of continuous mountain peaks (elevations ranging from 600-1380 m) and mosaic habitat. The climate of MM Hills is moderate throughout the year, hot summer and cold winter. It receives rain from the southwest monsoon between May-August and from the northeast monsoon between September-November with a pronounced dry period between January and March. The mean annual temperature is 35.3˚C and varies between 24˚C in winter to 42˚C in summer (Shaanker et al., 2004a).

The forest harbors rich fauna and flora used by local people in traditional healthcare, cultural, and religious systems. It has unlike forest types such as dry deciduous (64.34%), scrub woodland (20.50%), and scattered patches of moist deciduous and riparian forest (2.47%) (Aravind et al., 2010). The sanctuary has been invaded by *Lantana camara* which brought significant change to local biodiversity and livelihoods.

Since the 1990s, the NTFPS has played a critical role in the livelihoods of local communities in this region as there has been an increased demand for forest products in the local markets (Shaanker et al., 2004b). *Phyllanthus emblica, P. indofischeri,* and *Terminalia chebula* are common NTFPS species and fruits have been harvested as a source of income (Rist et al., 2008; Shaanker et al., 2004a). *Phyllanthus* species are widely known as Indian gooseberry, and Amla (in Hindi). *Phyllanthus* fruits have been used extensively to make pickles, jams, and herbal drinks; in Ayurvedic medicine and cosmetics. *Terminalia chebula* is commonly known as black myrobalan and it is also extensively used in Ayurveda medicine and cosmetics industries. The populations of *T. chebula* and *P. emblica* overlap in forest habitats. However, the populations of *Phyllanthus* species are spatially segregated; *P. indofischeri* occurs at lower elevations (<900m), in scrub forests, and *P. emblica* occurs at higher elevations (>800m) in dry deciduous forests (Setty et al., 2008). *T.chebula* is slow-growing shade-tolerant species and has poor seed germination capacity in natural conditions (Anitha et al., 2010).

There are 31 settlements (villages) scattered within and periphery of MM Hills forest. About eight villages constitute a homogenous community called Soligas; whereas another 23 villages are constituted heterogeneous communities called Soligas and Bedagampana. Soligas are the indigenous tribes living in MM Hills forest for centuries and they have historically been engaged in hunting, NTFP collection, and shifting cultivation for their livelihood (Harisha et al., 2015). Shifting cultivation and hunting were banned in 1972 under the Wildlife Protection Act, following which the Soligas sedentarized in settlements called 'podu' and continued settled agriculture (Murali et al., 1996). Most of the villages were notified as revenue villages in 1913. They received titles to their cultivable land ranging in size from 0.5 to 2 hectares under Forest Rights Act 2006.

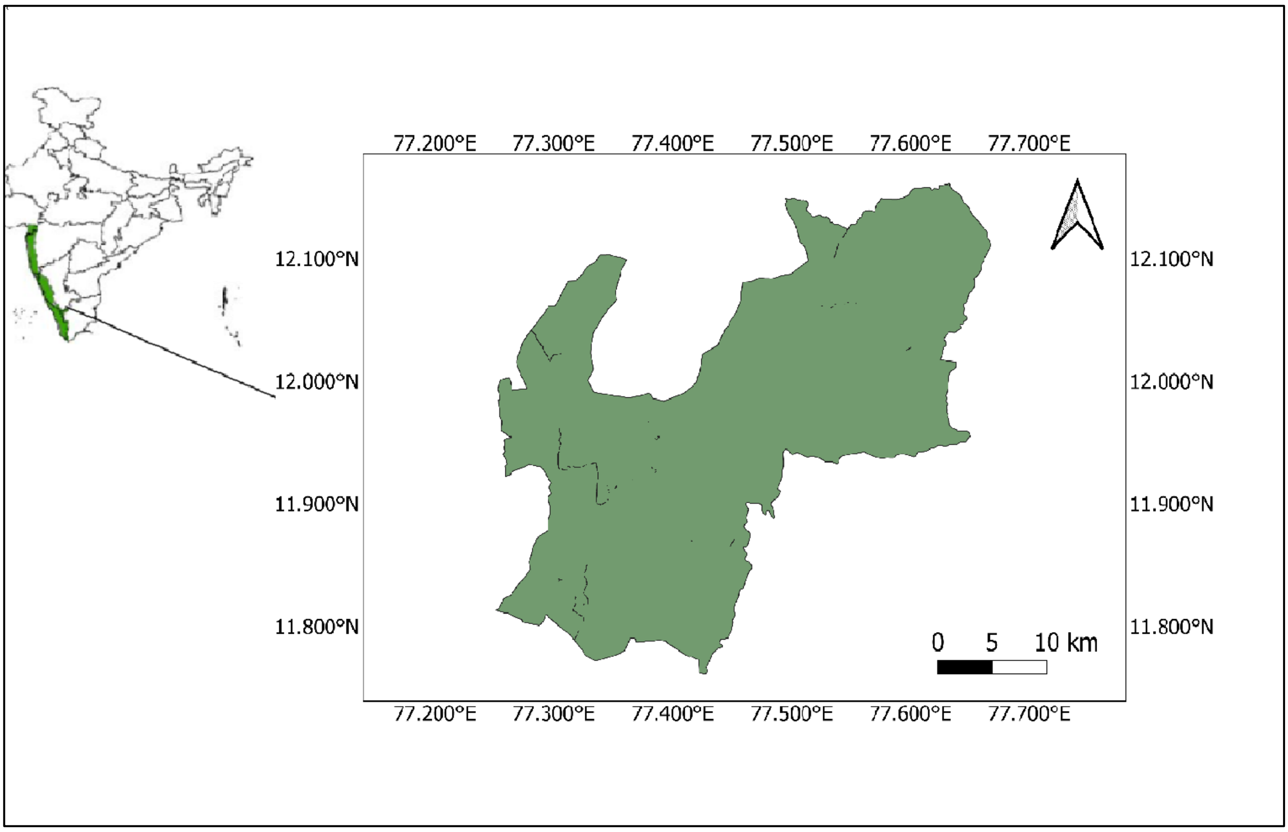

Figure 1: Location of the study area, MM Hills, Karnataka, India

2.2. Assessment of population structure and regeneration

The regeneration capacity of a species is reflected in the population size- class distribution; as the assessment of population structure is convenient and provides information on species population status. Twenty transects measuring 10m X 100m sample plots were laid for each species in the M M Hills forests in 2000-01 and monitored annually till the year 2020-21. Sample plots were used to estimate the population structure of *P.*

emblica, P. indofischeri, and T. chebula. Sample plot locations are marked based on NTFPs resource maps developed by harvesters during participatory resource appraisal (PRA) exercises. All the individuals of the study species in the sample plots were tagged permanently with aluminium tags bearing a unique number (seedlings to adult trees). The diameter at breast height (DBH) of each tree/sapling (measuring above 1 cm DBH) was recorded at 1.3 meters height.

The density of *Lantana camara* was estimated by counting the number of individual clumps in five sample quadrates measuring 5mX5m within each of the 20 plots. Similarly, grazing intensity was assessed by counting the dung and pellets within the belt transect measuring two-meter wide and 100 meters long, within each of the 20 plots. The forest fire incidents were recorded during the study periods and the extent of the area burned was also mapped in all the plots.

2.3. Assessment of fruit productivity and extraction

All reproductive adults >5cm DBH stem in the transect were identified and estimated fruit production before harvest to understand the stock of fruits and after harvest to understand the level of extraction. One month before the fruit harvest, the number of fruits was estimated. The fruit production of the tree was estimated visually by counting five fruiting branches which were selected randomly out of the total fruiting branches from each tree and also the number of fruiting branches was estimated. Later average fruits per branch were calculated for five selected branches and multiplied by the total fruiting branches. . It has been repeated during the post-harvest to understand the level of fruit extraction by the community. The number of hemi-parasite-infected branches was counted and branch cut was also recorded before and after the fruit harvest to understand the level of the tree getting damaged while harvesting the fruits.

2.4. Assessment of dependency and accessibility

The dependency and accessibility of the local community have been assessed by conducting a socio-economic survey in 2000-01, 2010-11, and 2020-21. The four forest villagers who have traditionally been involved in NTFPS collection were selected based on proximity to the road (to the transect points) and the number of people harvesting NTFPS based on the frequency of harvest. Semi-structured interviews were conducted for 92 households from four villages which were 10% of the total households per village. Villages such as Anehoa(228 hh), Kumbudukki(232), Gorasane(242), and Kokkubare(218) were located close to the sample plots and were selected for the household interview. The systematic sampling methods were used to select households for the interview by considering the family size (number of people in their family) and based on their occupation (NTFPS collection, farming, daily wage, and others) to draw reliable information. Both men and women participated in the household survey.

The household survey was conducted from October to November, before fruit harvest, and after harvest from April to May. The interviews were 1-3 hours long in the local language (Kannada) and information was validated by revisiting the households. The household survey captured the socio-economic profile, source of income, and livelihood change. The community perception of the present status of NTFPS resources, dependency, and accessibility change under the forest protection regime was also documented.

2.5. Focus group discussion

Most of the participants were NTFPs harvesters and were members of the cooperative society called Large Scale Adivasi- Multi-Purpose Societies (LAMPS). The community leaders who have been involved in the Forest Rights Act (FRA) 2006 implementation, and served as Forest Department employees for a long time in the study area have also participated. During the FGD, participants prepared resource maps and harvesting timelines for the NTFPS species. They also shared the constraints involved in NTFPS collection, the impacts of policy change on resources, and their livelihoods.

Annual fruit harvest estimate accessed from LAMPS for the past 20 years (from 2000-01 to 2020-21). LAMPs are the nodal agency for marketing, monitoring, and management of NTFPs resources. It consists of a management committee and an executive committee formed by Soliga community representatives and forest department officials.

2.6. Data analysis

We categorized the data collected across three study periods into; **indicators of population structure** (population density, regeneration rate, and annual fruit yield); **disturbance variables (**grazing intensity, lantana density, fire frequency, branch cut, and hemi-parasite infection); **Dependency variables** (LAMPs data on the quantity of fruit collected and income from NTFPS-which is a direct indicator of dependency); **accessibility change** (tenure, policy change and community perceptions on forest regime which had a significant impact on NTFPs accessibility).

Understanding the variation of variables across study periods: The population structure of study species that recruit regularly was characterized by reverse J curves (Lykke, 1998; Wright et al., 2003). The size class distribution was estimated for the study species by using population monitoring data obtained from three study periods. Repeated measure MANOVA statistics was used to evaluate the variance of mean values of population structure, disturbance, and dependency indicators across study periods.

Determine the relationship between indicators and variables: We used multiple regression analysis to determine the relationship between population structure, disturbance, dependency, and accessibility variables. The data was also used to determine the significant relationship between and within variables. The study used population density, recruitment rate, and fruit yield as response variables to determine the impact of disturbances, dependency, and accessibility.

Characterizing the variables which determine the population structure

Data on variables of dependency, disturbance, accessibility, and indicators of population structure were averaged across sampled points. The binomial distribution model was employed for seedling density and fruit production to check the distribution of data points. A generalized Linear Model (GLM) was employed to explore the link to disturbance, dependency, and indicators of the population structure of the study species. The GLM was employed for three study periods separately. The analysis started with an initial model of eight variables to reduce the co-linearity. The variables used were lantana density, grazing intensity, fire frequency, hemi-parasite infection, branch cut, and extraction rate versus population density, regeneration, and fruit production.

To assess the overall effect of each predictor variable on population structure and productivity, we have calculated AICc (second-order Akaike information criteria, used for small sample size), differences in AICc, and AICc weights for each model in the two model sets (*T. chebula* and *Phyllanthus* spp.) using the R package AICc moving. We calculated the mean and 95% confidence interval for the regression coefficient of each predictor variable by averaging coefficients across all models, weighted by the AICc weight of each model. A backward selection based on the Akaike Information Criterion (AIC) was operated to determine the best combination of factors that have a significant impact on population density, regeneration, and fruit production. Data analyses have been carried out using Microsoft Excel and R (version 3.3.1).

3. Results

3.1. Understanding the factors across study periods

3.1.1 Indicators of population structure

Size class distribution: The population (>5cm DBH.) density of species varied across the study periods. In 2000-01(*P.emblica*-20.8/ha.; *P. indofischeri* -16.9/ha.; *T.chebula*-43.2/ha.); In 2010-11 (*P.emblica*-18.4/ha.; *P.indofischeri*-15.5/ha.; *T.chebula*-41.2/ha.); and in 2020-21 (*P.emblica*-20.1/ha.; *P. indofischeri* -16.2/ha.; *T.chebula*-42.6/ha.). All three species (*P. emblica* and *P. indofischeri* and *T. chebula*) showed three different size-class distributions (including seedlings, saplings, and adults) across the study period. In the year 2000-01, for all three species, the relative frequency of seedlings and saplings was lower than in 2010-11 and 2020-21 resulting in an unstable population structure. However, in 2010-11, all three species showed a sporadic size-class distribution. In 2020-21 all three species showed a reverse j-shaped curve (stable, self-maintaining population) which indicates that the population is stable compared to previous study periods (Fig. 2).

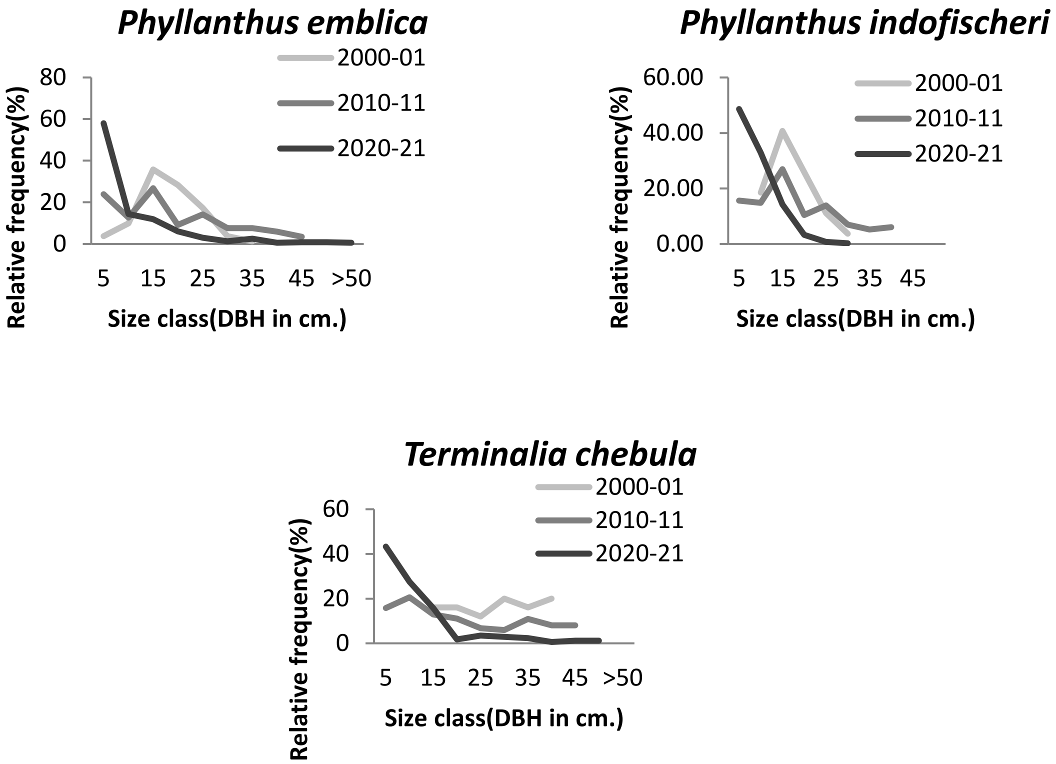

Figure 2: Size class distributions of species across study periods

Regeneration: The seedling density of *Phyllanthus* species was lower in 2000-01(89/ha.) compared to 2010-11 (114/ha.) and (205/ha.) in 2020-21. Similarly, the percentage of seedling survival rate increased from 1.8, 2.1, and 8.9 in 2000-01, 2010-11, and 2020-21 respectively. The seedling density of *T. chebula* was43/ha., 64/ha. and 104/ha.in 2000-01, 2010-11, and 2020-21 respectively. The percentage of seedling survival rate increased from 1.3, 1.8, and 6.3 in 2000-01, and 2010-11 to 2020-21 respectively.

Fruit production: The percentage of fruiting trees across study periods was 35.6% for *P. emblica,* 31% for *P. indofischeri,* and 54.6% for *T. chebula.* There were no significant differences in the percentage of fruiting trees for all the species across the study periods. Similarly, the annual fruit production for *P. emblica* was 135.5 kg./ha., 158kg./ha., and 206.72 kg/ha in 2000-01, 2010-11, and 2020-21 respectively; similarly for *P. indofischeri,* it was 115.5 kg./ ha., 114kg./ha., and 161.72 kg/ha., in 2000-01, 2010-11 and 2020-21 respectively; In case of *T. chebula* it was 235.5 kg./ha., 260.4 kg./ha. and 270.72 kg/ha. in 2000-01, 2010-11, and 2020-21 respectively.

3.1.2. Dependency variables

Annual fruit harvesting: LAMPS is a tribal co-operative society constituted by a cooperative and the forest department that purchases fruits/NTFPs buy fruits from harvesters and sells them in the open market with or without value addition. The fruit harvested by the harvesters in 2000-01 was 67.5 tons, which decreased to

4.1 tons in 2020-21 in the case of *Phyllanthus*. In the case of *T. chebula*, fruit collection was 13.7 tons in 2000-01 and it reduced to 3.1 tons in 2020-21 (Fig. 3).

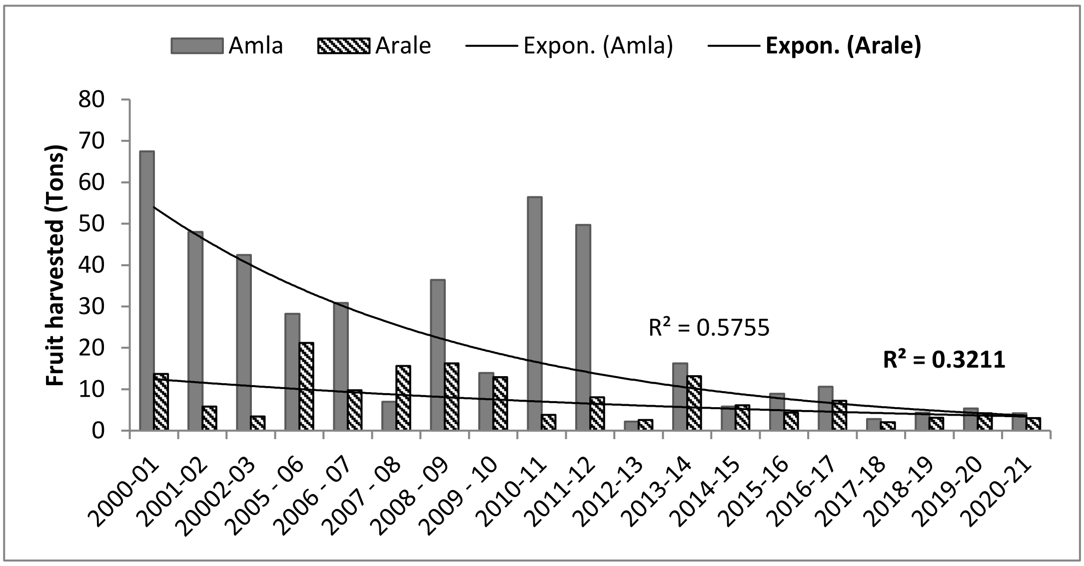

Figure 3: *Phyllanthus* and *Terminalia* fruit harvested (source: LAMPS)

NTFPs dependency and income change: Fruit collection season is from November to February, Soliga community from 31 villages in and around forest area collect and sell them to LAMPS. The number of households involved in harvesting from each village ranged from 30% to 55% and usually, both men and women participated in fruit harvest.

The percentage of income from fruit/NTFPS collection in 2000-01 was 43 % per household per capita, whereas in 2010-11 it reduced to 21% and it further reduced to 13 % in 2020-21. Fruit harvesting was mainly determined by availability, accessibility, and market linkage. The younger generation has been migrating to nearby towns for jobs and migratory income has increased by two fold in recent years. The percentage of people migration increased from 18% to 51% in 20 years that's very significant (Fig. 4).

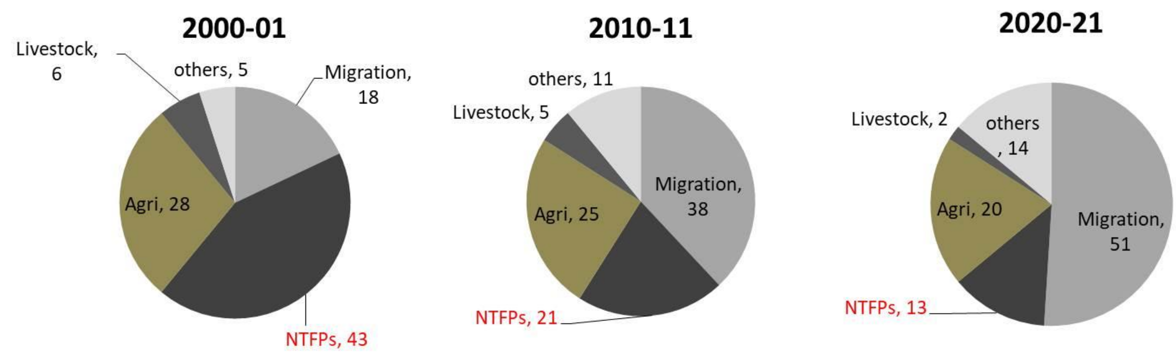

Figure 4: NTFPs dependency and income change from the past two decades.

3.1.3. Disturbance variables

Grazing intensity: The forest area was wide open for grazing until the year 2013 when the forest department declared MM Hills as a wildlife sanctuary. There were 19 cattle sheds spread across the MM Hills forest area before being declared a wildlife sanctuary. The forest department put a restriction on cattle grazing and banned cattle sheds inside the wildlife sanctuary. The grazing intensity (the number of cattle and goats) inside the forest reduced drastically from 2013 onwards. It was indicated indirectly in terms of pellet density change which was recorded during the study periods. Similarly, the cattle and goat populations in the forest villages were also reduced. According to the official record, the cattle population reduced from 6500 (in 2000-01) to 3400 (in 2020-21), and the goat population from 4900 (in 2000-01) to 2750 (in 2020-21).

Lantana density: There has been a major change in forest structure due to the invasion of *L. camara*. This species spread in the landscape after the mass bamboo felling in the 1970s and development activities in the region. In the first period (2000-01) the density of lantana was very high (6342/ha.) compared to 2010-11 (4850/ha.) and 2020-21 (3930/ha.). Local people started harvesting lantana from the forest in 2003-04 to make furniture and utility products, which resulted in a gradual decrease in lantana density.

Fire frequency: Incidents of forest fire got reduced after the declaration of the wildlife sanctuary. In 2000-01, thirteen sample plots were partially burnt whereas in 2010-11 only six sampled plots were partially burnt and in 2020-21 only three sampled plots got burned. The incidents of fire reduced across forest areas in general. In 2000-01, 1.25 hectares of forest area got burned, it was reduced to 0 .84 hectares in 2010-11, and in 2020-21 it was only 0.38 hectare got burned.

Branch cut and hemi-parasite infection: Branch cut and hemi-parasite infection were found only in *Phyllanthus* species. In *T. chebula* no hemi-parasite infection but branch cuttings were recorded. Therefore, we considered *Phyllanthus* species (*P.emblica and P.indofischeri*) for the analysis. Branch cutting was much more common in 2000-01 and 2010-11. It is because of open access to use resources in the forest, grazing livestock, and harvesting fruits. The rate of the branch cut correlated with hemi-parasite infection. Fruit harvesters have been removing hemi-parasite-infected branches during fruit harvest to check the further spread of hemi-parasite and grazers to feed their goats. In 2000-01 the frequency of branch cutting was 63% for *P.embica* and 59.3% for *P.indofischeri*. Whereas in 2020-21 branch cutting was less (11% for *P.embica* and 6.1% for *P.indofischeri*). Similarly, hemi-parasite infection was very high in 2000-01(36% for *P.embica* and 9.3% for *P.indofischeri* compared to 2020-21 (23.3% for *P.embica* and 4.6 % for *P.indofischeri*.

3.1.4. Tenure and accessibility change

Since 2013 the MM Hills forest was a reserve forest that offered open access to resource use and collection of NTFPs in the landscape. Also, the forest opened to cattle sheds inside the forest and another livestock grazing in 2013, MM Hills became a wildlife sanctuary which resulted in a ban on grazing, restriction on NTFPS collection, and other produce collected by the community from the forest (Table 1). Also, the forest department initiated strict patrolling and improved management practices (for example, issuing NTFPs collection passes, and timings), which reduced incidents of forest fire, a reduction in grazing, and a significant reduction in fruit collection.

Table 1: Showing changes in tenure rights across study periods

Attributes	2000-01	2010-11	2020-21
Forest protection status	Reserve	Reserve	Wildlife sanctuary
Using forest for grazing, firewood etc.	Open	Open	Ban
Accessibility fruit harvest	No restriction	No restriction	Regularised
Forest Right Act 2006 implementation	No policy exist	Started claiming rights	Rights over NTFPs collection received

3.2. Variables and indicators variations across study periods

The study hypothesized that variables such as population structure, disturbance, dependency, and accessibility change significantly vary across study periods (2000-01, 2010-11, and 2020-21). The analysis of variance (ANOVA) between study periods revealed that variables such as population density and percentage of fruiting trees had not changed significantly. Whereas, regeneration (F=18.52, P=>0.01 for *Phyllanthus* and F=7.47, P=>0.01 for *T. chebula*) rate, fruit production (F=5.52, P=>0.05 *Phyllanthus* and F=6.37, P=>0.05 for *T. chebula*) have seen significant change. Disturbance variables such as grazing intensity observed significant change (measured indirectly by counting pellets and dung) (F=12.52, P=>0.01 for pellets and F=9.43, P=>0.01 for dung). Similarly, lantana density (F=8.45, P=>0.05) and fire frequency (F=8.43, P=>0.05) have changed significantly between study periods (Appendix 1).

3.3. Understanding the variable's relationship with indicators of population structure.

Listed variables such as fruit extraction, hemi-parasite infection, branch cut, lantana density, grazing intensity, fire frequency, the quantity of fruit harvest, and income were used for multiple regression analysis. Dependent variables such as tree density, regeneration rate, and fruit productivity were tested with variables to evaluate the relationship and characterize the impacts on population structure.

In 2000-01 grazing intensity, hemi-parasite infection, branch cut, and forest fire had significant negative impacts on the population density of *Phyllanthus* species, in the case of *T. chebula*, grazing intensity and fire frequency had significant negative impacts on tree population density. Similar trends were seen in 2010-11 as well for all three species (Appendix 2). Whereas, in 2020-21 all of the variables had a significant positive relationship with the population density of *Phyllanthus* species and *T. chebula*.

The regeneration rate was negatively affected by grazing and forest fire for all the species during 2000-01 and 2010-11. Whereas in 2020-21 fruit productivity had a significant positive impact on the regeneration rate (Supplementary file 1). In 2000-01 and 2010-11, the fruit productivity of *Phyllanthus* species was negatively affected by hemi-parasite, branch cut, and grazing, in the case of *T. chebula* grazing had significant negative impacts (Appendix 2).

Fruit production in the case of *T. chebula* factors such as grazing (r^2 =-0.561, *P*=<0.05) had a significant negative impact on fruit production. Whereas, adult tree density (r^2=0.403, *P*=<0.05) has a positive relationship with fruit production. While branch cut showed a significant negative impact on *P. indofischeri* fruit production, in the case of *P. emblica*, hemi-parasite infection significantly affected fruit productivity. Adult tree density (r^2=0.413, *P*=<0.05) also had a positive relationship with fruit production in both the species of *Phyllanthus* (Appendix 2). The branch cut reduced fruit production for *Phyllanthus* species.

3.4. Characterizing the roles of the variable on indicators of population structure

The model selection was based on coefficient value, associated standard error, and corresponding *p-value* of the covariates in the model that influence species population density, regeneration, and fruit productivity. Based on theoretical as well as field knowledge, there were seven models with different combinations of variables/covariates were used to test against the population density, regeneration, and fruit productivity. The detailed model selection procedure for covariates which influenced population density, regeneration, and fruit production for all three species across the study periods was provided in (Appendix 3a,3b,3c). In the supplementary file three best models with covariates influencing population density, regeneration, and fruit production of study species was listed.

Population density: In 2000-01 and 2010-11 the variables such as grazing, fire, and hemi-parasite had a significantly negative influence on the population density of *P.emblica*. In 2020-21, lantana density and hemi-parasite had a significant negative influence on population density. Similarly, *the P.indoficheri* population structure had a significant negative association with variables such as branch cut; grazing, and fire in 2000-01 and 2010-11. But in 2020-21 lantana density and forest fire had a significant negative influence on population density. In the case of *T. chebula*, grazing and fire had a significant negative role in shaping population structure in 2000-01, whereas in 2010-11 variables like grazing, lantana density, and fire had a significant impact on population density. But In 2020-21 only lantana density and fire had a significant impact on the population density of *T. chebula* (Table 2).

Table 2: Summary of the best model with covariates that influence population density of the study species.

Species	Year	Covariates	*wi*	AIC	AICc	Δ AICc	*K*	Coefficients	SE	*p*
PE	**2000-01**	HP+GI+FF	0.92	108.72	106.83	0.16	4	HP:-0.064	0.005	<0.05*
								GI: -0.299	0.008	<0.05*
								FF:-0.183	0.064	<0.05*
	2010-11	HP+GI+FF	0.91	112.43	108.32	0.01	4	HP:-0.064	0.008	<0.05*
								GI: -0.299	0.069	>0.05
								FF:-0.192	0.031	>0.05
	2020-21	HP+LD	0.83	102.41	103.16	0.06	3	HP:-0.064	0.041	<0.05*
								LD:-0.076	0.231	<0.05*
PI	**2000-01**	BC+GI+FF	0.89	117.86	113.91	0.12	5	BC:-0.001	0.006	>0.05
								GI: -0.258	0.064	<0.05*
								FF: -0.076	0.008	<0.05*
	2010-11	BC+GI+FF	0.79	111.92	106.03	0.04	4	BC:-0.064	0.086	<0.05*
								GI: -0.103	0.067	>0.05
								FF:-0.214	0.041	<0.05*
	2020-21	LD+BC	0.86	105.32	105.89	0.05	3	LD:-0.319	0.031	<0.05*
								BC:-0.031	0.072	>0.05
TC	**2000-01**	GI+FF	0.94	104.14	102.65	0.10	4	GI: -0.010	0.004	<0.05*
								FF: -0.038	0.007	<0.05*
	2010-11	GI+ LD+ FF	0.86	119.82	114.68	0.23	4	GI:- 0.062	0.013	<0.05
								LD: -0.246	0.092	<0.05*
								FF:-0.031	0.021	<0.05*
	2020-21	LD+FF	0.91	102.34	104.31	0.04	3	LD:-0.049	0.012	<0.05*
								FF:-0.031	0.031	>0.05

TC=*Terminalia chebula*; PE=*Phyllanthus emblica*; PI=*P.indofischeri*; LD=Lantana density; GI=Grazing intensity; FF=Fire frequency; TD=Tree density; FT=Fruiting trees; BC=Branch cuts; AIC=Akaike Information Criterion; AICc= AIC corrected for small-sample bias; Δ AICc= difference in AICc values between each model and the model with the lowest AICc; wi=AICc model weight; *K*=Number of parameters estimated by the model; SE=Standar Error.

Regeneration: Hemi-parasite, branch cut, and lantana have affected the regeneration of *P.emblica*. Similarly, the regeneration of *P.indoficheri* is affected by grazing, fire, and lantana. In the case of *T. chebula* variables like grazing, fire, and lantana had a significant impact on both seedlings and saplings across study periods (Table 3). This indicated that seedlings and saplings were more sensitive to grazing and fire during drought years which caused high mortality in seedlings and saplings.

Lantana density had a positive association with seedling density but the sapling survival rate was poor across study periods and species. It is shown that lantana influences regeneration by controlling soil erosion and increasing soil moisture and nutrition. But transforming from seedling to sapling differed between vegetation type and presence and absence of *L. camara*. The positive association between lantana and seedling density in the dry deciduous forest for all the study species was observed. It indicated that unregulated disturbance other than fruit harvest in the forest had greater impacts on population structure. Dry tropical tree species are more prone to physical damage by branch cut, grazing, and fire during drought years (2000-01 and 2007-08).

Table 3: Summary of the best model with covariates that influence regeneration of the study species.

Species	**Year**	**Covariates**	***wi***	**AIC**	**AICc**	**Δ AICc**	***K***	**Coefficients**	**SE**	***P-value***
	2000-01	GI+FF	0.94	102.15	101.5	0.06	3	GI: -0.299	0.064	<0.05*
								FF:-0.021	0.041	<0.05
PE	**2010-11**	GI+FF	0.91	108.43	105.91	0.13	3	GI: -0.113	0.008	<0.05*
								FF: -0.057	0.069	>0.05
								RF: 0.021	0.031	>0.05
	2020-21	FF+LD	0.89	119.82	114.68	0.23	3	RF: 0.031	0.013	<0.05*
								LD: 0.311	0.092	>0.05
	2000-01	GI+FF+LD	0.93	123.81	120.41	1.62	4	GI: -0.001	0.006	>0.05
								FF:-0.051	0.064	<0.05*
								LD: 0.258	0.052	>0.05*
PI	**2010-11**	GI+LD+FF	0.97	113.92	108.31	0.61	4	GI: -0.064	0.086	<0.05*
								LD: 0.103	0.067	>0.05
								FF:-0.031	0.030	<0.05*
								RF: 0.052	0.051	>0.05
	2020-21	FF+LD	0.88	117.41	114.81	0.41	3	RF: 0.031	0.431	<0.05*
								LD: 0.046	0.836	>0.05
	2000-01	GI+FF	0.94	104.14	107.32	0.061	3	GI: -0.010	0.004	<0.05*
								FF: -0.038	0.007	<0.05*
	2010-11	GI+FF	0.86	116.82	119.45	0.089	3	GI:- 0.062	0.013	<0.05*
TC								FF:- 0.246	0.092	<0.05*
								RF: 0.062	0.032	<0.05*
	2020-21	FF+LD	0.91	109.56	113.84	0.082	3	RF: 0.021	0.084	<0.05*
								LD: 0.039	0.073	>0.05

TC=*Terminalia chebula*; PE=*Phyllanthus emblica*; PI=*P.indofischeri*; LD=Lantana density; GI=Grazing intensity; FF=Fire frequency; TD=Tree density; FT=Fruiting trees; BC=Branch cuts; AIC=Akaike

Information Criterion; AICc= AIC corrected for small-sample bias; Δ AICc= difference in AICc values between each model and the model with the lowest AICc;

wi=AICc model weight; *K*=Number of parameters estimated by the model; SE=Standard Error

Fruit productivity: Hemi-parasite and branch cuts have affected the fruit productivity of *P.emblica*. Similarly, the fruit production of *P.indoficheri* is affected by grazing, and branch cutting. In the case of *T.chebula* variables like grazing, branch cut, and density of fruiting trees had a significant impact on fruit production (Table 4).

Table 4: Summary of the best model with covariates that influence fruit productivity of the study species.

Species	Year	Covariates	*wi*	AIC	AICc	Δ AICc	*K*	Coefficients	SE	*P-value*
PE	**2000-01**	HP+BC	0.92	102.53	104.32	0.14	3	HP: -0.064	0.005	<0.05*
								BC: -0.076	0.008	<0.05*
								RF: -0.299	0.064	<0.05*
	2010-11	HP+BC	0.91	118.31	119.69	0.01	3	HP: 0.113	0.008	<0.05*
								BC: 0.057	0.069	>0.05
								RF: 0.142	0.042	<0.05*
	2020-21	HP	0.95	111.83	112.19	0.31	2	HP: 0.041	0.052	<0.05*
								RF: 0.524	0.034	<0.05*
	2000-01	BC+GI	0.89	121.04	121.89	0.51	3	BC: -0.001	0.006	>0.05
								RF: -0.258	0.064	<0.05*
								GI: -0.076	0.008	<0.05*
	2010-11	BC+GI	0.97	106.32	107.82	0.02	3	BC: 0.064	0.086	<0.05*
								RF: 0.103	0.067	>0.05
								GI: 0.210	0.083	<0.05*
	2020-21	RF+FT	0.88	114.02	115.19	0.43	3	RF: 0.412	0.042	<0.05
								RD: 0.023	0.039	>0.05*
								FT: 0.028	0.105	<0.05*
TC	**2000-01**	GI+BC	0.94	104.14	106.43	0.08	3	GI: -0.010	0.004	<0.05*
								RF: -0.038	0.007	<0.05
	2010-11	GI+BC	0.86	112.82	114.94	0.21	3	GI: 0.062	0.013	<0.05*
								RF: 0.246	0.092	<0.05
	2020-21	FT	0.93	108.5	109.43	0.05	2	RF: 0.531	0.712	>0.05*
								RD: 0.217	0.372	>0.05
								FT: 0.071	0.619	<0.05

TC=*Terminalia chebula*; PE=*Phyllanthus emblica*; PI=*P.indofischeri*; HP=Hemi parasite; GI=Grazing intensity; FF=Fire frequency; BC= Branch cut; RF= Rainfall; RD= Rainy days; FT=Fruiting trees; BC=Branch cuts; AIC=Akaike Information Criterion; AICc= AIC corrected for small-sample bias; Δ AICc=

difference in AICc values between each model and the model with the lowest AICc; wi=AICc model weight; *K*=Number of parameters estimated by the model; SE=Standard Error.

4. Discussion

4.1. Understanding the indicators across the study period

The life strategy of a species largely depends on adding more new individuals to its population. Long-term monitoring of the regeneration history (the frequency and abundance of seedling establishment) was one of the methods used across the globe to understand population change (Charles,1998). Results demonstrate that the size class distribution of the study species was stable (reverse 'J' shaped curve) in 2020-21 compared to previous years. A significant decrease in disturbances, low human dependency, and restrictions on fruit harvest improved regeneration and reduced mortality in 2020-21.

In contrast, in 2000-01 and 2010-11 species population showed very poor seedling and sampling establishment and the distribution curve reflects that regeneration is severely limited. Grazing, fire, and branch cut were high in 2000-01 and 2010-11 compared to 2020-21. Frequent drought and high accessibility (open to access resource) during the period from 2000-01 to 2010-11 in the forest were practiced. These findings were consistent with population studies elsewhere in the tropical deciduous forest (Kodandapani et al., 2004; Mandle et al., 2012; Varghese et al., 2015). Results suggest that grazing, branch cut, and the fire was the main contributors to decreased population density and poor regeneration. These drivers were common across tropical forests with similar forest habitats and climatic conditions like in India (Sinha et al., 2005; Ticktin et al., 2012). The study suggests that fruit harvest alone did not have a significant impact on population structure, regeneration, and fruit production.

Similarly, fruit productivity was low in 2000-01 and 2010-11 compared to 2020-21, which indicates that combined effects of disturbance factors such as hemi-parasite infection, branch cut, and grazing resulted in low fruit productivity in *Phyllanthus* species.

4.2. Evaluating the relationship between the indicators

The study found a significant relationship between changes in size class distribution and variables. The population structure of *Phyllanthus* species was shaped by hemi-parasite, grazing, and fire, in the MM Hills forest. Hemi-parasite is impacting mainly the tree population and significantly increases tree mortality. Grazing and fire had affected the seedling establishment and sampling transformation into an adult. A high rate of seedling and sapling mortality was happening in areas where the high intensity of grazing and frequent fire occurred. Several studies have reported similar impacts in many tropical forest studies elsewhere in India (Kodandapani et al., 2004; Tiktin et al., 2012).

In the case of *T. chebula*, rainfall, grazing, and fire played a role in seedlings and saplings development. *T.chebula* also has significant constraints in the fruit set due to predation apart from microclimatic conditions that were vital for seed germination (Varghese et al., 2015). *Lantana* density alone does not have a significant impact on the tree density of *Phyllanthus* and *T.chebula*. However, in fire-prone areas, *Lantana* density had a significant impact on the seedling and sapling density of both *Phyllanthus* and *T. chebula* species. High grazing usually had low lantana density, which also had a low chance of fire but poor regeneration of seedlings and a low rate of sapling establishment for both species. The areas such as low-grazing, medium lantana density, and less fire-prone areas showed good regeneration of seedlings and a high rate of sapling establishment for both species. Areas with high-density lantana with low grazing were prone to high fire and had poor regeneration and sapling establishment. These patterns revealed that in tropical forests elsewhere in India, South Asia, and Africa (Shackleton et al., 2005; MEA, 2005). During drought years, grazing in fire-prone areas was subjected to a major change in population structure as recorded during study periods 2000-01 and 2007-08. On the contrary, the low-grazing, less frequent fire, and medium lantana density have supported the regeneration, seedling, and sapling density in 2014-15 for both *Phyllanthus* and *T. chebula* species.

The change in fruit productivity was determined by rainfall, rainy days and hemi-parasite, and branch cut in the case of *Phyllanthus* species. In the case of *T. chebula*, rainfall and rainy days, and grazing determined fruit productivity. These findings were consistent with fruit productivity surveys elsewhere in the Western Ghats (Murali et al., 1996; Mandle et al., 2012). The disturbance factors such as grazing and branch cut were the common factors that limited fruit production across study species. The infestation by hemi-parasite was an additional factor that played a significant role in limiting fruit production in the case of *Phyllanthus* species. Previous studies reported significant impacts of hemiparasites on fruit production (Shaanker et al., 2004b; Setty et al., 2008; Mandle et al., 2012). The adult tree density and the number of fruiting trees were the sources of stocks for fruit productivity for most of the NTFPs species. Several studies have shown that fruit harvest had a less significant impact on fruit productivity (Murali et al., 1996; Mandle et al., 2012; Varghese et al., 2015) similar to our study results. Fruit harvest had less impact on the flowering and fruiting phenology of woody species unless populations were subjected to other stressors like continuous drought, hemi-parasite, fire, grazing, and lantana invasion.

4.3. Dependency and harvester's perspective

The change in fruit productivity and regeneration was discussed during the focused group discussions with harvesters. The harvesters observed a high rate of adult mortality due to hemi-parasite infection, prominent in the case of *P. emblica*. They had been practicing branch cutting to avoid further infection of hemi-parasite during fruit harvest (Rist et al., 2008). They also observed a high rate of fruit abortion and fruit predation in the case of *T. chebula.* Research studies also reported that the low fruit set rate is due to poor pollination and a high rate of immature fruit abscission (Varghese et al., 2015). All three species had high fruit predation and were severely affected by grazing and fire and lantana invasion (Shaanker et al., 2004a; Ticktin et al., 2012).

The focus group discussion revealed that their dependency on NTFPs species had reduced drastically since the last decade. The reasons for the reduction in dependency were; a) change in resource accessibility and imposition of rules and regulations which inhibit people from NTFPS collection b) migration to nearby towns and cities to work as laborers facilitated by increased transportation facilities c) volatile markets for fruits harvested from forest and d) socio-economic welfare schemes from the government such as MNREGA, public distribution systems, etc. These reasons were drivers of livelihood change among forest-dependent communities across India (Gadgil et al., 1995; Lele and Rao, 1996; Rajindra, 2015).

The combination of fruit abortion, fruit predation, hemi-parasite, fire, grazing, lantana invasion, and drought has played a significant role in shaping the population structure of study species. Harvesters also mentioned that hemi-parasite infections have increased over the years. Usually, the harvesters remove the hemiparasites on *Phyllanthus* trees during fruit harvesting. The fruit harvesting decrease in recent years led to high infestation and increased mortality of trees.

4.4. Accessibility

The community also revealed that more than 80% of people, below the age of 35 migrate as laborers to granite quarries and cities for construction work. Around 45% of the women migrate seasonally to work in the coffee estates. About 60% of people, above the age of 50 years do farming and local labor work. The NTFPS cooperative societies (LAMPS) and forest department staff played an important role in the collection of NTFPs (Lele and Rao, 1996). Lack of accessibility and a volatile market also influenced the reduction of NTFPs collection.

The People's perceptions of policy implications, livelihoods, and resource accessibility in the forest have been recorded. About 82.6% of people perceived that wildlife sanctuary status largely affected their livelihoods and resource accessibility compared to other conservation policies in the region (Lele and Rao, 1996). Similarly, 62% of people felt that the Wildlife Protection Act of 1972 impacted their livelihoods. However, 96.7% of people mentioned that the Forest Rights Act 2006 would positively affect their livelihood (Roshni et al., 2019). About 86% were disappointed with the delay in implementation, especially for NTFPS accessibility rights (community forest rights). The Declaration of wildlife sanctuary resulted in the banning of NTFPS harvest, increased patrolling, and fire preventive measures restriction on human activity (grazing, fuelwood collection, and NTFPS collection) inside the wildlife sanctuary.

4.5. Characterizing the potential indicators

The NTFPs species in the tropical forest are subject to multiple disturbances, and the magnitude of individual and combined effects had been poorly studied. Our results illustrate that untangling the effects of common drivers was critical for developing effective management strategies. The mix and match between indicators played a significant role in shaping the population structure, regeneration, and fruit production of the study species. As previous studies suggest translating as many indicators/drivers as possible into models using a multi-model inference-based approach which would be more helpful for understanding the population structure. In this study, we used disturbance, dependency, and accessibility variables in general linear model (GLM) analysis along with population structure variables. Moreover, Akaike Information Criterion (AIC) was used to determine the combination of factors, which might have had an impact on the population structure. This would provide useful insights for developing management and conservation strategies for NTFPs species.

The combination of the availability of adult trees and an increase in fruit trees would lead to higher regeneration. Similar patterns were observed across the country with similar climatic and habitat conditions (Sundaram, 2011; Varghese et al., 2015). During the study period, fire intensity was recorded from 2000 to 2020. Fire season was correlated with drought year generally; dry deciduous forests, sites close to villages, and cattle camps were identified as fire-prone areas. Because of intensive grazing and frequent fire, consecutive droughts from 2001 to 2003 and in 2012 and 2013 resulted in poor regeneration and low seedling establishment for the species, in general.

Specifically, hemi-parasite control is essential as it harms the tree population of *Phyllanthus* species and increases adult mortality (Rist et al., 2008). Moreover, the decline of the *Phyllanthus* species population from 2000-01 to 2010-11 was unable to explain by the invasion of *Lantana camara* alone (Sundaram, 2011). Instead, hemi-parasite, fire, and grazing along continuous drought could be impacted. The causes of this mortality are consistent across plots and other parts of the forest (Ganesan and Setty, 2004). Moreover, the long-term monitoring revealed the indirect effects of lantana on the NTFPs population (Sundaram, 2011).

Recent studies suggest that the population dynamics of fruit harvesting species may be perplexed with other drivers, but these indicators have not been considered (Schmidt et al., 2011 Sundaram, 2011; Gooden et al., 2009). For instance, effective management requires addressing the drivers affecting most of the population's decline. As studies revealed low regeneration even in low lantana density areas (Schmidt et al., 2011). Similarly, hemi-parasite was found to be a major threat to *Phyllanthus* species in both BRT and MM Hills forest and it affected other species as well (Rist et al., 2008; Setty et al., 2008; Shaanker et al., 2004a).

The pattern of regeneration in *T. chebula* was determined by the low level of genetic diversity, due to high levels of inbreeding (Ravikanth and Setty, 2017; Shaanker et al., 2004b; Anitha et al., 2010). In addition, a low level of germination and a high proportion of seeds with a lack of embryos and pollinator deficiency has been proposed as possible contributors to low regeneration in the case of *T. chebula* (Varghese et al., 2015) however, these need a further vigorous investigation.

4.6. Implications for forest management and conservation

The sustainability of NTFPs species in tropical forests subjected to multiple stressors and the importance of identifying potential factors which have a greater impact on the population is yet to be answered clearly. However, fruit harvest was blamed for observed declines in the study species and state policy imposed a ban on fruit harvest in protected areas. Prohibiting the fruit harvest was ineffective and would not improve the status of these populations; instead, it resulted in negative economic repercussions for harvesters (Sandemose, 2009). Therefore, it is necessary to direct inclusive conservation policies to frame action plans to reduce the disturbance identified. For example, effective control of grazing, and monitoring the distribution of invasive species like lantana could aid the regeneration of the species.

Moreover, effective control strategies for hemi-parasite infection and branch-cut could be the participatory monitoring and adaptive management strategy. It was emphasized in the Forest Rights Act 2006 to ensure the sustainable use of resources and the regeneration of the study species (Roshni et al., 2019). Promoting indigenous control methods for hemi-parasite infection, controlled grazing, and an enterprise-based Lantana Craft Center(LCC) model would help in the management of lantana invasion and better management. Lantana density could be a prime factor in reducing fire intensity and grazing during drought years. A better understanding of the interrelationships between disturbances, dependency, and accessibility could shape the population structure, regeneration, and fruit production and develop effective forest management policy. The use of a long-term, multidisciplinary and inclusive approach allowed us to determine the combination of factors/indicators that should be the focus that could help in developing management strategies.

It is important to assume that unpredictable climatic factors could change the whole scenario and affect the population structure. Moreover, forest fire and developmental activities in and around natural forests could impact the health of the forest and the stability of the NTFPs species population. The poor implementation of inclusive policies such as the Forest Rights Act 2006 could affect the resource sustainability in the forests.

5. Conclusions

The study found that the impact of disturbances, dependency, and accessibility on shaping the NTFPs species population was very significant. Our results suggested that invasion of *L. camara*, grazing, hemi-parasite, and branch cuts are major drivers impacting the population structure of both *Phyllanthus* species and *Terminalia chebula*. The cumulative effect of hemi-parasite infection, grazing, and branch cut had a significant negative impact on fruit production and regeneration of study species. However, with changes in dependency, accessibility, and disturbance due to protected area status, the adult tree density, and fruiting trees would have a significant positive impact on regeneration.

Control of grazing, hemi-parasite spread, and reduction in branch cut would be the better strategy to retain a stable tree population and regeneration. The multi-factor linkage would evolve to identify drivers of population decline and formulate effective conservation policy. NTFPs species and the population are at risk due to multiple disturbances, and it is essential to have inclusive management strategies and practices. Moreover, site-based adaptive management and participatory resource monitoring approach as provisioned in the recent Forest Rights Act-2006 would hold great potential for developing sustainable use and co-management practices in the study area.

Authorship contribution

RPH and SSR contributed to the study conception, design, conceptualization, methodology, software, investigation, and data curation. The first draft of the manuscript was written by RPH. Material preparation, data collection, and analysis were performed by RPH. RPH, SSR, and RKG supervised and validated the work. All authors commented on previous versions of the manuscript, and read and approved the final manuscript.

Declaration

The authors declare that they have no conflict of interest.

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