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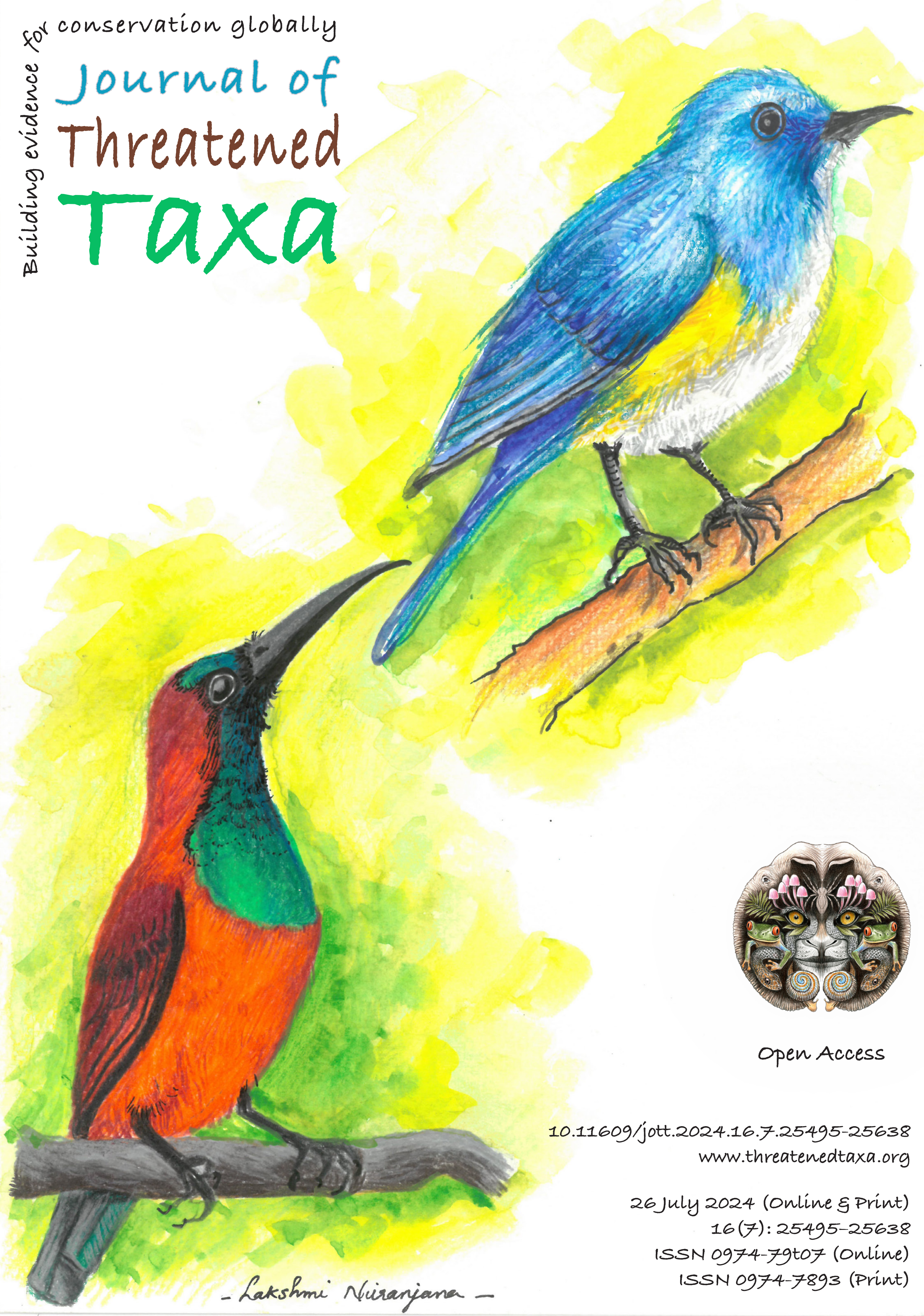

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ARTICLE

Impact of root harvest on *Decalepis hamiltonii* Wight & Arn. population across habitats in Savandurga Reserve Forest, Karnataka, India

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Abstract: *Decalepis hamiltonii* Wight & Arn., is a woody climber, endangered due to the destructive harvest of fragrant roots and substituted for *Hemidesmus indicus* (L.) R.Br. (Nannari). We assessed the density, size class, distribution across habitat types, disturbance types, and environmental variables that influence the *D. hamiltonii* population in the Savandurga Reserve Forest (SRF). Method: The entire forest was divided into 1 km² grids, with 10 plots of 5 x 5 m established in each of the 24 grids, totaling 240 plots. Disturbances were categorized as low, medium, and high, while plots were classified into dense, mixed, and rocky outcrop habitats. Results: *D. hamiltonii* density ranged from 0.1 ± 0.32 to 5.2 ± 2.66 per 25 m² across the grids with an overall mean density of 675 ± 455 stems per ha. The size class distribution showed a typical inverted "J" curve, with fewer saplings (3.01–6.0 cm class), indicating potential future population instability. Stem density was lower in dense vegetation and higher in mixed vegetation and rocky outcrops, with greater densities in areas of higher disturbance. Adult density was mainly influenced by harvesting (78% variation), saplings by NDVI (2.09%) & altitude (18.72%), and seedlings by aspect (4.44%), increasing from the south to the north. **Conclusion:** Strict monitoring and periodic assessment of the population are essential to protect the seedlings to the sapling stage, regulation of selective harvesting of the adults, and control of the herders feeding the leaves. Encouragement of local and large-scale cultivation to reduce pressure on the wild source and to improve livelihood. Capacity and confidence building of the community with citizen science reporting of destructive harvesting will help the forest department to save the declining population.

Keywords: Aspect, density, inverted "J" curve, MPCA, NDVI, Nannari sharbat, NTFP, root harvesting, size class, woody climber.

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INTRODUCTION

In India, over 1,178 medicinal plants are commercially demanded for raw drugs. Of these 53% of plants are destructively harvested by collecting roots, wood, bark, or the entire plant (Goraya & Ved 2017). The concern is among the non-timber forest product (NTFP), harvesting of roots, whole stems, bulbs, and bark, especially in perennials is usually lethal or fatally weakens the plant species, and further achieving sustainability becomes difficult (Davenport & Ndangalasi 2002; Ticktin 2004; Hernandez et al. 2015). Of the 242 species in high commercial demand, 72% are sourced from the wild and they lack information on the impact of harvesting on the wild population (Fuller 1991; Cunningham 1993a; Ticktin 2004; Goraya & Ved 2017). These conditions make ecological conservation even more critical when there are increased collections. Research from the perspective of assessing the threats and the impact of harvesting of climbers are less studied compared to other life forms likewise there is a dearth of information on root-harvested plants also (Ticktin 2004; Stanley et al. 2012). Most of the studies on woody climbers have focused on community level analysis, in fact, generally climbers are neglected and less included in ecological studies (Gerwing 2004; Pandi et al. 2022). *Decalepis hamiltonii* is a woody climber, a medicinal non-timber forest product (NTFP), destructively harvested for fragrant roots, coupled with habitat loss the population is declining (IUCN ver. 3.1, Ravikumar & Ved 2000). We focus on studying *D. hamiltonii* which is harvested for roots and quantify the density, size class, and distribution of the population from the perspective of harvesting impact which is fairly unique. This attempt enhances our understanding of the status and also from the literature by touching upon studies related to woody climbers as well as root harvested plants.

For sustainable management of resources Shankar et al. (1996), emphasize the need for information on extraction and productivity levels per unit area which are unknown for most of the species being harvested. Studies have demonstrated that both natural and anthropogenic disturbances are crucial for the sustainability of the population of many such species (Mandle & Ticktin 2012; Mandle et al. 2013; McKechnie & Sargent 2013). Illegal collections have driven certain species population to an endangered status (Pfab & Scholes 2004). Destructive practises of harvesting plant parts such as bark, foliage, fruit, pith, seeds, and cone have led to population decline (Ticktin 2004; Stanley et al. 2012; Krishnamurthy et al. 2013). Best lessons have also been adopted from traditional ecological knowledge for root harvesting methods, life history & mode of reproduction to sustain the population from studies conducted on *Dichelostemma capitatum, Harpagophytum procumbens, Nardostachys grandiflora* and *Neopicrorhiza scrophulariiflora* (Anderson & Rowney 1999; Ticktin & Johns 2002; Stewart & Cole 2005; Ghimire et al. 2008; Ticktin et al. 2012). Trade and demand for roots affected the population of *Rauwolfia serpentina* as the gatherers were offered high prices at the retail level, which led to a sixfold increase in the harvesting rate of immature stages of the rhizomes and roots (Mishra 2001). *Asparagus racemosus* (Satawari), *Chlorophytum borivilianum* (Safed Musli), and *Cyperus rotundus* (Nagarmotha) are some of the well-known tubers /rhizomes facing destructive harvesting. Unsustainable harvesting practices like uprooting plants at the immature stage, not placing them back in the soil with proper coverage, or the entire primary /core root cut reduces the chances of survival. Root harvested plants remain exposed to sunlight leading to death and collection done throughout the year, roots/tubers of all age groups being harvested are highly unsustainable. Such activities reduce the quality and quantity, and pose a challenge to the survival and sustenance of the individuals (Mishra 2000; Prasad et al. 2002; Mishra & Kotwal 2003, 2007; Mishra et al. 2003).

Excessive harvesting has resulted in a typical population with many resprouts (small diameter sizes) but very few mature stems in both disturbed and severely disturbed sites (Hall & Bawa 1993; Ndangalasi et al. 2006). Over collections of fragrant medicinal roots of *Mondia whitei,* and other species under trade led to the extermination of the population locally in South Africa (Cunningham 1993b). Extraction likely impacts negatively on plant population leading to changes in population structure found in perennials, e.g. some trees and climbers (Ganesan & Setty 2004; Bitariho & Emmanuel 2019; Soumya et al. 2019b). *Loeseneriella apocynoides* is a slow-growing woody climber and its whole plant stem is harvested, so it takes over 20 years to reach a harvestable size (Muhwezi 1997). Long-term harvesting had a strong impact on reducing the root size over a period of time and noted changes in the biology of *Philodendron corcovandense* population (Valente & Negrelle 2011). *Coscinium fenestratum* is another woody climber species that is harvested for both stem and roots (Ved & Goraya 2007). The study by Thriveni et al. (2015) across disturbance levels found that none of the *C. fenestratum* individuals recorded a diameter of more than 3.5 cm, but the forest department records suggested the existence of individuals that were larger than 25.0 cm diameter indicating the intense effect of harvesting which has resulted in a smaller size class representation. Likewise, McGeoch (2004) found *Mondia whitei* roots preferentially harvested for adults and juveniles which had led to disjunct patches of over or under abundance of size class representation with very few fruiting individuals. Since the root is an organ available in the plant from the initial growth stage found in all size classes, it is not a part like flowers/leaves/ fruits which are produced, every year to shed. Rather the role of a root is on a long term for storage, transport, anchoring, developing new shoots after disturbance and much more. Unless the marketable size is specific to only a certain size or quality, demand for the material can lead to harvest of all size classes.

Woody climbers grow well in forest edges, gaps and disturbed habitats compared to undisturbed forest which is one of their characteristic features (Schnitzer & Bongers 2002). It is observed in *C. fenestratum* population tolerating a wider range of light levels, and was found to have lowest survival under the lowest light treatment (Kathriarachchi et al. 2004). Similarly, McGeoch (2004), found *Mondia whitei* growing well in all habitats as it is a wind dispersed species and germinated very well in disturbed areas. Light levels (sunflecks) effected the local demography in root harvested ginseng *Panax quinquiefolius* (Wagner & McGraw 2013). Lack in information on over-harvesting and quantification of the resources leads to decline of the population and could lead to conflicts among the stakeholders (Homma 1992; Chamberlain et al. 1998; Dovie 2003).

According to the International Union for Conservation of Nature (IUCN ver. 3.1), *Decalepis hamiltonii* Wight & Arn. (Apocynaceae) is assessed as endangered due to destructive root harvesting and habitat loss (Molur & Walker 1997; Ved et al. 2015). It is endemic to the Deccan plateau, found wild in Karnataka, Tamil Nadu, Telangana, Andhra Pradesh, and Kerala, within an altitudinal range of 1,200 m (Ravikumar & Ved 2000; Reddy & Murthy 2013). It is a woody *climber* found in seasonally dry forests, mixed and dry deciduous forests, and semi-evergreen forests (Muthumperumal & Parthasarathy 2010; Anburaja et al. 2012; Rao & Reddy 2022; Pandi et al. 2022). Roots of this plant are traded nationally at 100–200 MT (Goraya & Ved 2007) and traders have reported a decrease in availability through the years which is a forewarning (Goraya & Ved 2017). Roots are medicinal, aromatic and substituted for *Hemidesmus indicus,* and it is known as "Makaliberu" in Kannada, "Magali kizhangu" in Tamil, "Maredu kommulu" or "Nannari kommulu" in Telugu, and Swallow root in English. Collectors prefer *D. hamiltonii*'s stout and thicker tuberous roots, which yield 40–45 kg per plant, over those of *H. indicus*. To meet the demand for roots, other *Decalepis* species like *D. arayalpathra* and *D. salicifolia* are also used as substitutes. However, both species are narrow endemics with limited ecological range and small populations, making them vulnerable to extinction (Mishra et al. 2015, 2017; Rodrigues et al. 2021). Sourced largely from the wild but origin of collection sources in the wild are not known. Unfortunately, there is no large-scale cultivation to meet the demands for the future or reduce the pressure on wild resource except for few farmers.

Studies have reported that the *D. hamiltonii* root extracts have the potential to cure many diseases, it has insecticidal, antifungal, and antioxidant properties (Reddy & Murthy 2013; Sharma & Shahzad 2014; Pradeep et al. 2016; Kharat & Mokat 2020; Ahmad et al. 2022). Potentially a new ecofriendly bioinsecticide and grain protectant of natural origin for agriculture (Mohana et al. 2008; Rajshekhar et al. 2010). Phytochemical investigations find a cocktail of active principles (Srivastava & Shivanandappa 2009) and researchers consider it to be an inspiration for discovering new herbal drugs and active compounds to treat many incurable diseases in the future (Naveen & Khanum 2010). It is considered as a wild food resource in the diet of tribal communities for enhancing nutrients, therapeutic practices, and strengthening their relationship by sharing the tubers frequently among themselves (Harisha et al. 2021). Roots are of multiple uses, required for Ayurvedic formulations, pickling and beverage industries, and to prepare traditional health drinks such as *Nannari Sharbat* or *Rayalseema sharbat* (Raju & Ramana 2009). Sold in local vegetable markets for pickling in households, the recent increase in people's preference is for 'makali' root juice and tea recipes are naturally drawing crowds at local food festivals (Vedavathy 2004). Naturally, the tubers of this endangered plant are highly exploited for medicinal, culinary, and confectionary uses and applications through destructive harvesting methods. Hence, its conservation in the wild is crucial. There is a need for alternative methods to meet the growing demand and reduce the pressure on wild resources through local or mass cultivation. Recent increase in the awareness of this plant for natural flavor extracts has created huge interest and its commercial cultivation by farmers can provide scope for looking at unexplored R&D avenues of *D. hamiltonii* (Shankar 2022).

The scope for demand increases because these roots are 10 times stronger than a 20-fold Vanila Bourbon concentration (John et al. 2007). The plant's tuberous roots possess a characteristic vanillin-like aroma due to the compound 2-hydroxy-4-methoxybenzaldehyde (2HMB) (Nagarajan et al. 2001). Biotechnological approaches are reviewed and recommended to mass multiply, and produce this vanillin flavour in tubers naturally in large scale (Shankar 2022). Globally vanillin biosynthesis is essentially becoming a need to meet the growing demand for natural vanillin productivity in a sustainable and efficient way (Xu et al. 2024). Though, there are several methods extensively reviewed (Reddy & Murthy 2013; Shankar 2022) plant tissue culture is also one of the methods to have demonstrated the scope to increase the yield of tubers. Increasing the vanillin and vanillic acid (Matam et al. 2017; Xu et al. 2024) and field transfer in rooted plantlets have been successful (Giridhar et al. 2003, 2004, 2005). Shoot multiplication and elongation methods have produced 40–48 plants from a single explant within four months followed by transfer from green house to field which resulted in survival of approximately 80–90% of the plantlets (Giridhar et al. 2003). Further, a higher yield in tuber biomass and maintenance of relative content of flavour compounds was also observed (Kamireddy 2017; Shankar et al. 2022). These studies provide evidences that can contribute towards local and mass cultivation and reduce pressure on the wild resource.

Field studies on *D. hamiltonii* revealed several issues related to its population and ecology. For instance, Raju & Ramana (2009) identified bottlenecks in sexual reproduction and seedling establishment. Meanwhile, in the Bili Giri Rangan hills (BR hills), root extraction experiments showed that the population is sensitive to even small intensities of 25% harvest and recommended the need for curtailment of wild collection (Murali 2008). A population estimation study in the Seshachalam hills using Adaptive Cluster Sampling utilized decadal data from the Girijan Co-operative Corporation (GCC), and aimed to estimate productivity (Mishra & Naidu 2014). The focus was on quantification of the root yield but not population status, structure or rotation period and the study recommended a long-term monitoring to suggest sustainable harvesting practices. Apart from species specific focus there are studies specific to climbers where the presence of *D. hamiltonii* has been recorded from various sites (Muthumperumal & Parthasarathy 2010; Anburaja et al. 2012; Pandi et al. 2022; Rao & Reddy 2022).

Conditions for *D. hamiltonii's* inadequate regeneration is reported to be the impeding factors such as the hard seed coat, and the short viability of seeds and the need for a good aerated substrate (Anandalakshmi & Prakash 2010). Factors regulating the population size of *D. hamiltonii* in natural areas are found to be extended flowering pattern, pollinator limitation, self-incompatibility, abortion of a considerable percentage of seedlings prior to establishment and absence of seed dormancy (Raju & Ramana 2009). The tuberous roots of *D. hamiltonii* are over exploited prior to reproductive maturity due to their economic and medicinal values and this is the main cause for the gradual decline of population (Anandalakshmi & Prakash 2010; Shankar 2022). As it is a tropical species, it requires higher alternate temperature of 20/30 ^{o} C or 30^{o} C rather than low temperature for germination and it was observed that among the three tests seed germination showed better results for the ones kept in between the paper than placing it on top of the paper or in the cocopeat (Navya et al. 2019). Similarly, soaking in hot water (60°C) for 24 h significantly improved the germination percentage from 83% to 98% on moist filter paper than on sand (Anandalakshmi & Prakash 2010). Storage of seeds at lower temperature of 15^{o} C, having at least 8% moisture results in maintenance of seed viability and longevity (Navya et al. 2019). Storage of seeds at ambient temperature probably favored the increase of those enzymes, which positively affected germination.

Novelty in research information was found to exhibit significant variations observed in the quantity of phenolics, flavonoids in the tubers that were collected from different natural habitats which showed 10–16 % difference in the content of 2H4MB, Biligiri Rangaswamy Temple (BRT) being the highest, followed by Mysore, Tirumala, Kurnool, Trichy, and Palakkad (Pradeep et al. 2019). A similar study on *Ichnocarpus frutescens demonstrated* variations between the two phytogeographical zones and also within the same zone, as they were affected by various edaphic factors which is indicating that the micro-environment of the location plays a considerable impact on the yield of secondary metabolite contents in plants (Nirala et al. 2024). The composition of secondary metabolites is influenced by a range of biotic and abiotic factors, diverse environmental conditions that significantly impact the composition of medicinal plants (Li et al. 2020). Since roots serve as the primary channel for nutrient uptake from the external environment to the plant's internal system, edaphic conditions mainly play a pivotal role in metabolite production (Liu et al. 2022). Recent findings on *D. hamiltonii* study revealed that compared to the first stage (12 months old) tuber there was a decrease in the expression of vacuolar transporters at second stage of the tubers (48 months old), indicating that the normal functioning of vacuoles in first stage transforms into a storage organ/tuber for 2HMB accumulation in the second stage (Kamireddy et al. 2021). It is indicative of the accumulation of fragrant compound in *D. hamiltonii* gradually increasing at the older stage of 48 months, than the first stage and this information is helpful in avoiding root harvesting of small size class individuals and it can also be chosen as a parameter for standardizing root harvesting. It is evident from the study that *D. hamiltonii* plants may adapt to various ecological / microclimatic conditions in the habitat and vary in accumulation of secondary metabolites.

Around 150 ha area in SRF has been designated as medicinal plant conservation area (MPCA) for in situ conservation of medicinal plants which includes *D. hamiltonii* population also (Somashekhar 2013). The botanical survey resulted in 355 medicinal plants including *D. hamiltonii* (Ved et al. 2004) and Dhatchanamoorthy et al. (2021) studied exclusively grasses. Trainings have been imparted to the community on conservation and sustainable harvesting methods of medicinal plants which includes root harvesting of *D. hamiltonii* also (Kinhal & Jagannatha 2006; Kinhal et al. 2006; Jagannatha & Kinhal 2008). However, attempts have not been made so far to assess the species-specific population size, density, demography, threats/disturbances for the complete landscape of SRF. Hence, addressing this primary need of assessing and quantifying the population status will be helpful in formulating management plans, assessment of Red List status, sustenance and conservation of the population in the wild.

The major objective of this study was to understand the population status of *D. hamiltonii* with key research questions such as (a) what is the density and size class distribution of the *D. hamiltonii* population in Savandurga RF?, (b) what is the differences in *D. hamiltonii* densities and regeneration across different habitats?, (c) Does the density and regeneration vary across harvesting regimes?, (d) What are the environmental variables influencing the density and demography of *D. hamiltonii*? Therefore, in the current study we aim to understand sustainable use and suggest conservation strategies to save its population.

MATERIALS AND METHODS

Study area

The SRF is situated approximately 70 km west of Bengaluru and 12 km from Magadi town in Karnataka, India. The largest monolith in the area, the Savandurga hill, stands at 1226 m, and is part of the Deccan plateau. The hill comprises two peaks, the black hill (Karigudda) and the white hill (Biligudda), separated by a deep valley. The scrub, dry deciduous natural forest vegetation in the area is characterized by large bald rocky surfaces. The rocks include the Closepet granite series, peninsular gneiss, granites, basic dykes, and laterites. The forest type is classified as a shrub and tree savanna type comprising the *Anogeissus latifolia - Chloroxylon swietenia - Albizia amara* series (Champion & Seth 1968; Pascal & Ramesh 1996). Accepted name of *Anogeissus latifolia* is *Terminalia anogeissiana Gere & Boatwr. as per* POWO (2024). The forest between 750 m and 1,200 m has a sparser distribution of trees such as *Wrightia tinctoria*, *Wrightia arborea*, *Holarrhena pubescens*, *Polyalthia cerasoides* (Accepted name–*Huberantha cerasoides*) *Albizia amara*, *Terminalia anogeissiana*, and *Pterocarpus marsupium.* However, SRF is invaded by weeds such as *Lantana camara*, *Chromolaena odorata,* and *Pterolobium hexapetalum*, which affect the vegetation distribution. The forest's vegetation, combined with factors such as altitude, slope, sunlight, and edaphic factors, create a habitat for species growth, leading to three main vegetation categories: dense vegetation (closed canopy, no sunlight), rocky vegetation (open canopy, extreme sunlight), and mixed vegetation (sparse vegetation with sunlight penetration) at the boundary between the two types. The dense and mixed vegetation comprises loamy soil mixed with rocks and open rocky areas that receive sunlight have patches of soil deposited on the rocky slopes.

Population sampling

To assess the population size, distribution, and habitat characteristics of *D. hamiltonii*, sampling was conducted between April end to September 2019 in the SRF. Considering the financial constraints, accessibility issues, manpower constraints, and the wind dispersal of this climber species, fixed area plots were adopted as a sampling design. First, the forest boundary was digitized using Google Earth, and the entire area was divided into 1 × 1 km grids with QGIS. Only grids with over 50% forest coverage were selected for sampling, while those located in fringe forest areas were excluded from the analysis. Consequently, the study included 24

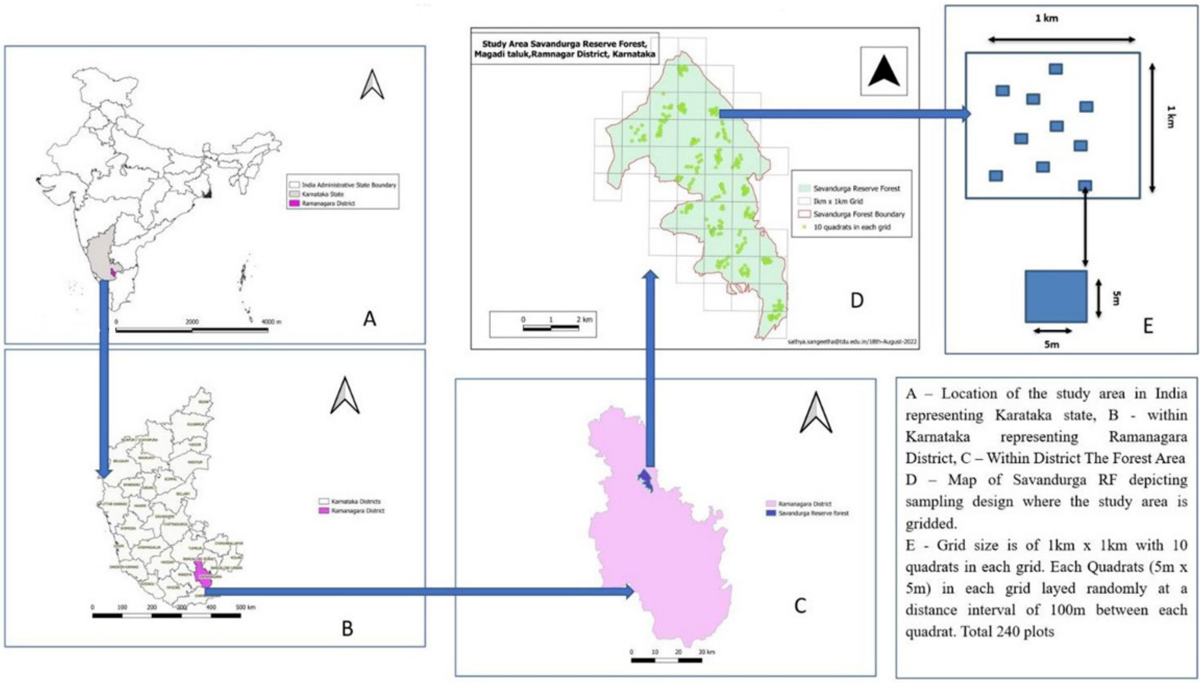


Figure 1. Study area and schematic representation of sampling quadrants of 5 × 5 m within 1 × 1 km grids (Total 24 grids).

Table 1. List of study sites selected for sampling *Decalepis hamiltonii* in Savandurga Reserve Forest.

No.	Grid	Site Code	No.	Grid	Site Code
1	G10	KTK	13	G39	JKB
2	G16	ITM	14	G40	DAD
3	G17	GKM	15	G45	NK
4	G18	BKM	16	G46	KOH
5	G22	ITG	17	G47	DBO
6	G23	ITE	18	G53	HCG
7	G24	SFH	19	G54	MST
8	G25	MPCA	20	G60	MR1
9	G31	AAS	21	G61	MR2
10	G32	DGK	22	G62	MR3
11	G33	VBD	23	G69	KPN
12	G38	VTK	24	G76	KPS

grids measuring 1 × 1 km, covering around 2,300 ha of forest area (Table 1). In each grid, 10 sample quadrants measuring 5 × 5 m were established randomly (Figure 1). Each 5 × 5 m quadrant was surveyed to identify and enumerate all stems of *D. hamiltonii*. The girth was measured at 1.3 m from the rooting point, referred to as the point of measurement (POM) (Gerwing et al. 2006). However, Gerwing et al. (2006) recommends a minimum diameter limit of 0.5 cm for density, species richness, regeneration, and succession studies to help accurate representation of stem size. Smaller diameter classes can capture the dynamics of the community, including growth, mortality, and recruitment. If the seedlings were small and not yet established, they were measured using digital vernier callipers, otherwise, big ones were measured with a measuring tape. Each quadrant's reproductive status was recorded, and its habitat was evaluated and classified as dense, mixed, or rocky. Elevation, latitude, longitude was recorded for each plot by using the Garmin GPS (map 64) instrument.

Climber inventories generally captured evidence from a community perspective but with variations in research objectives, methods, plot sizes, and stem diameter. Studies enumerated stems ≥1 cm dbh (Proctor et al. 1983; Putz & Chai 1987; Chalmers & Turner 1994; Rice et al. 2004; Burnham 2004; Muthuramkumar et al. 2006; Reddy & Parthasarathy 2003, 2006; Campanello et al. 2007; Ding & Zang 2009) studies enumerating stems ≥1.6 cm dbh (Padaki & Parthasarathy 2000). However, it is important for identifying small-sized regeneration of climbers to know the consequences of forest dynamics (Gerwing et al. 2006), but such studies received little attention (Chazdon 2003). Some studies enumerating smaller stems to mention are ≥0.5 cm dbh studied by Dewalt et al. (2000), Yuan et al. (2009), and much lesser stem girth of ≥0.2 cm dbh by Mascaro et al. (2004), Cai et al. (2009), and Chettri et al. (2010). The above differences considered in the studies make comparison of data across the tropics difficult. In the present study, we have considered all size classes beginning from 0.5 cm onwards to capture the population of all size classes. Though, studies by Gerwing (2004), Schnitzer et al. (2004), and Anbarashan & Parthasarathy (2013) show a positive correlation between disturbance and climber abundance, lower climber densities in more disturbed areas have been observed by Rice et al. (2004). No relationship between disturbance and climber abundance was observed by Mascaro et al. (2004). However, Hall & Bawa (1993), emphasize the importance that monitoring an annual species for which the entire individual is harvested requires a completely different sampling design from monitoring a large tree species from which only fallen fruits are harvested. Likewise, sampling designs may differ based on the life form, history, method, and plant part harvested. The sampling design chosen here is on a targeted woody climber species and the attempt here is to capture the type of disturbances, habitats, and the influencing factors that determine the population density. Our study is from the perspective of a single climber species population disturbed by root harvest, which is unique.

Description of stages of plants and size-class distribution

The stems were classified based on their girth size, with adults having a GBH ≥6 cm onwards, saplings having a GBH between 3 cm and 6 cm, and seedlings having a GBH >3 cm (0.5 to 3cm). The measurements for all *D. hamiltonii* stems followed the protocol of Schnitzer et al. (2006) and Gerwing et al. (2006).

Seedlings: Seedlings range in size from 0.5 cm to 3 cm, they stand stiff without support up to 30–40 cm in height (Image 1a). Leaves may wither due to deciduous nature, grazing, or other disturbances like small fires. 1 cm stem girth corresponds to at least 750 g of underground roots (Sathya Sangeetha: Unpublished Thesis). As stem girth increases from 2 to 3 cm, climber length increases by 1 to 1.5 m, falling on taller grasses, herbs, and nearby shrubs. Between 0.5 cm to 3 cm the un-established seedlings (height <1 m) and established seedlings (height >1 m) are included.

Saplings: Individuals with stem girths ranging from 3.1 to 6 cm experience growth in length but do not exhibit flowering (Image 1b). Increase in length is noted in the stem between the two nodes and are found to be greenish pink in colour. It was observed from the overall survey that the flowering and fruiting started above 5 or 6 cm onwards. At this stage, climbers establish support through multiple hosts as they grow typically, the plant twines onto from the nearby grasses, herbs, and shrubs ascending onto the nearest branch extension of the host tree, choosing the shortest distance towards light. If no hosts are found, the stems lie on rock boulders.

Adults: Individuals with stem girths more than 6.1 cm are considered adults, as they flower and fruit (Image 1d). At this stage, the plant has 4–5 branches with flowers in terminal and axillary cymose inflorescences. Each branch has about 15–20 inflorescences and increases based on the stem size and length of the branch. After pollination, fruits develop, with each weighing around 40–50 g and measuring 20–35 g when dried. The number of branches, flowers, and fruits increases with stem size. The colour of the stem varies from greenish pink, to maroon and as they grow old the colour turns to dark brown and finally blackish grey with prominent lenticels (Image 1g & h).

Overall, the stem girth size was divided into 11 size classes with equal intervals of 3 cm ranging from 0.5 to 31 cm. The size classes are as follows: a) 0.5–3 cm; b) 3.01–6 cm; c) 6.01–9 cm; d) 9.01–12 cm; e) 12.01–15 cm; f) 15.01–18 cm; g) 18.01–21 cm; h) 21.01–24 cm; i) 24.01–27 cm; j) 27.01–30 cm; k) 30.01–33 cm (Figure 7; Image 1). The largest size class of one or two adult stems was observed in closed canopy areas, where they were found within the large trees in dense forests. These stems were identified by the presence of fruits hanging above the closed canopy. (Note–0.5 cm, 0.8 cm, 0.9 cm stems are placed within the 0.5–3 cm range).

Associated vegetation was also recorded from each plot. Trees, shrubs, climbers, herbs, and grasses were identified in the field, and the doubtful species were compared with the authentic specimens in FRLH herbarium and also the field images. The herbarium specimen was deposited in FRLH Herbarium (Voucher specimen number: 122072, Date: 25.05.2019, Location: Savandurga MPCA). All trees measuring >10 cm DBH and the stems of shrubs (ranging from 1 to 10 cm DBH) were counted, and the species were identified. Disturbances affecting the *D. hamiltonii* population in the SRF were recorded through field observations and each of the 24 grids was categorized based on the number of stems harvested, uprooted or had branches chopped, as well as the occurrence of fire, grazing (Image 2 a–g), presence of weeds and distance from each site to villages and roads (Appendix 1).

Habitat variables

To investigate the potential factors that may be influencing the distribution and abundance of *D. hamiltonii*, the study selected eight habitat variables (Table 2). Normalized Difference Vegetation Index (NDVI), elevation, slope, aspect, hill shade illumination,

Image 1. Sampling *Decalepis hamiltonii* population in Savandurga Reserve Forest. a—Seedling | b—Sapling | c—Measuring the stem girth of an adult plant | d—Adult climber supported on *Euphorbia antiquorum* | e&f—Laying sample plots and assigning plot numbers | g—Large adults–woody climber | h—Adult plant grown luxuriously on rocks and surrounding grasses, herbs, and shrubs. © M. Sathya Sangeetha.

associated species, and the distance from the forest boundaries, as well as two categorical variables: habitat types and harvesting regimes. The NDVI, elevation, slope, aspect, and hill shade illumination variables were obtained from satellite imagery, namely LANDSAT-8 (Scene ID LC81440512019104LGN00; acquired in 2019; http://glovis.usgs.gov/) and elevation data from ALOS (JAXA Global ALOS portal; scene ALPSMLC30-N014E077–

Image 2. *Decalepis hamiltonii* population facing anthropogenic pressure and other disturbances: a—Large adult plant from rocky area extracted for roots by breaking the rock slope into pieces | f—Large adult plant roots extracted from loamy soil by digging and twilting the rock boulders | b—Fire set only to the sample plot where *D. hamiltonii* sapling was killed (note the assigned plot no 55) | c—Fruiting branches pulled and chopped by herders for feeding goats | d—Goat eating the leaves of *D. hamiltonii* which was growing near the *Euphorbia antiquorum* plant | e—Supporting plant *E. antiquorum* branches chopped while root harvesting observed in the interior most site which is the peripheral edge of SRF | g—Small mud roads created inside the forest by clearing the vegetation. © M. Sathya Sangeetha.

Table 2. Summary of the eight environmental variables included for the regression analyses, apart from the two categorical variables (Habitat types and harvesting regimes).

Variable	Mean	Median	Range
Elevation (m)	844.7	847	754.0–960.0
Slope (Sexagecimal degree)	0.9246	10.0301	0.5072–30.1230
Eastness	-0.1384	-0.3698	-0.9997–0.9994
Northness	0.05566	0.04859	-0.99925–0.99992
Hill shade illumination	170.6	172	79.0–236.0
NDVI	0.14757	0.14377	0.07176–0.33512
Associated species	21.18	21	1.00–57.00
Distance to forest boundary (m)	563.7	530	70.0–1700.0

DSM) and Google Earth (http://earth.google.com). The NDVI values for vegetation quadrants were derived from the Landsat image with a 30 m resolution, using Band 4 (Red) and Band 5 (NIR). The NDVI was validated in the field. In the SRF, the NDVI ranged -0.1–0 for water bodies, 0.1–0.17 for bare soil and rock regions, 0.18–0.2 for sparse vegetation, and 0.2–0.4 for less dense vegetation up to the closed canopy. The topographical variables, including slope, elevation, aspect, and hill shade illumination, were extracted from the digital elevation model (DEM) raster with 30 m resolution. These variables represent the basic elements used when analyzing and visualizing ecological problems related to forest and wildlife habitat suitability site analyses (Al-Kindi et al. 2017). The aspect was transformed into a linear north-south gradient (Northness) and an east-west gradient (Eastness) by performing cosine and sine transformations, respectively, to facilitate statistical analysis. Northness ranged from -1 (south-facing) to 1 (north-facing), while Eastness ranged from -1 (west-facing) to 1 (east-facing). The values were extracted using the ARCGIS 10.2, 3D analyst tool/raster surface option, and Q GIS 3.10.2 and ArcMap 10.2 were used for data extractions. Furthermore, surrogates of disturbance such as settlements, villages, and the distance from quadrants to villages and roads were also mapped. Distribution of plant species on a landscape depends on surface soil moisture balance, moisture holding capacity of the soil which is related to topographical variables like elevation, aspect, slope, hillside position, curvature (Franklin et al. 2000). Soil moisture is strongly correlated with the amount of radiation received on the Earth's surface and the sun's radiation is described often by aspect (Najafifar et al. 2019). Aspect plays an important role in evaporation, temperature change and solar radiation these conditions create micro niches for the plant's establishment and survival period.

Environmental variables

A total of 10 environmental variables were considered: NDVI, altitude, slope, northness, eastness, habitat types, harvesting intensities, hill shade illumination, associated species, and the distance from the forest boundaries (Table 2). Prior to regression analysis, collinearity among predictor variables was assessed using Pearson's cross-correlations (Figure 2) and the variance inflation factor (VIF) (Neter et al. 1996). The VIF measures the increase in variance of an estimated regression coefficient due to collinearity. Whenever high collinearity was observed (Pearson's r ± 0.40 and VIF >10) (Neter et al. 1996), ecologically more relevant predictors were retained, while others were discarded. Therefore, the final set of explanatory variables consisted of nine variables, excluding habitat types, as they were highly correlated with the NDVI (Figure 3).

Although the quantile-quantile plots and Shapiro-Wilk test for normality indicated non-normal variance in all the response variables, the approach by Chapagain et al. (2019) was employed to address the large number of zeros in the datasets. Moreover, the best-fitting multiple regression model was determined based on the lowest value of the bias-corrected Akaike's Information Criterion for small samples (AICc; Burnham & Anderson 2002) among all potential regression models (equation X).

$$AICc = AIC + \frac{2k\,(k+1)}{n-k-1} \text{ equation} X$$

where, AICc is the lowest value of the bias corrected AIC,

n is the sample size,

AIC is Akaike's Information Criterion, and is given as:

$$AIC = 2k - 2ln\,(L)$$

where, k is the number of parameters in the statistical model,

L is the maximum value of the likelihood function for the estimated model.

The resultant best predicted variables were used to explain the variations observed in the *D. hamiltonii* distributions across SRF.

Data analysis

The data analysis focused on comparing the densities and relative densities of *D. hamiltonii* across three habitat types (rocky vegetation, mixed vegetation, dense

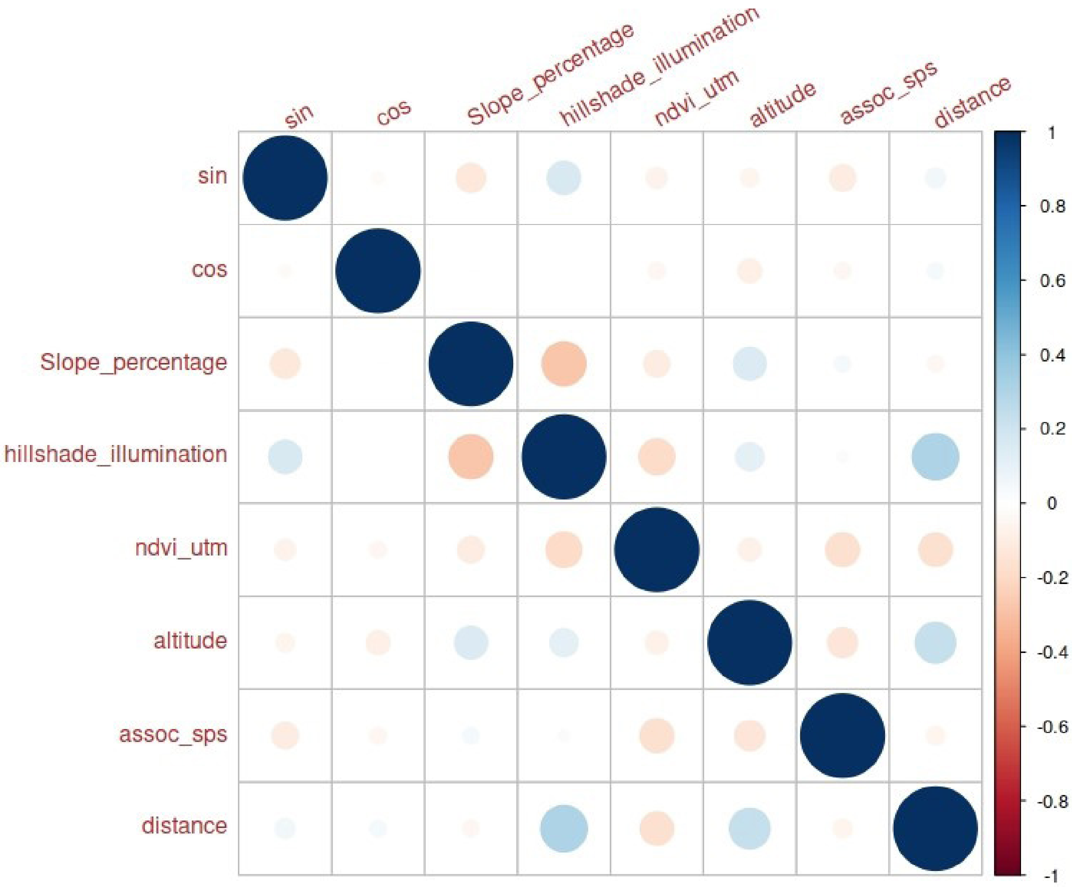


Figure 2. Correlation plots for environmental variables as part of the multidisciplinary test.

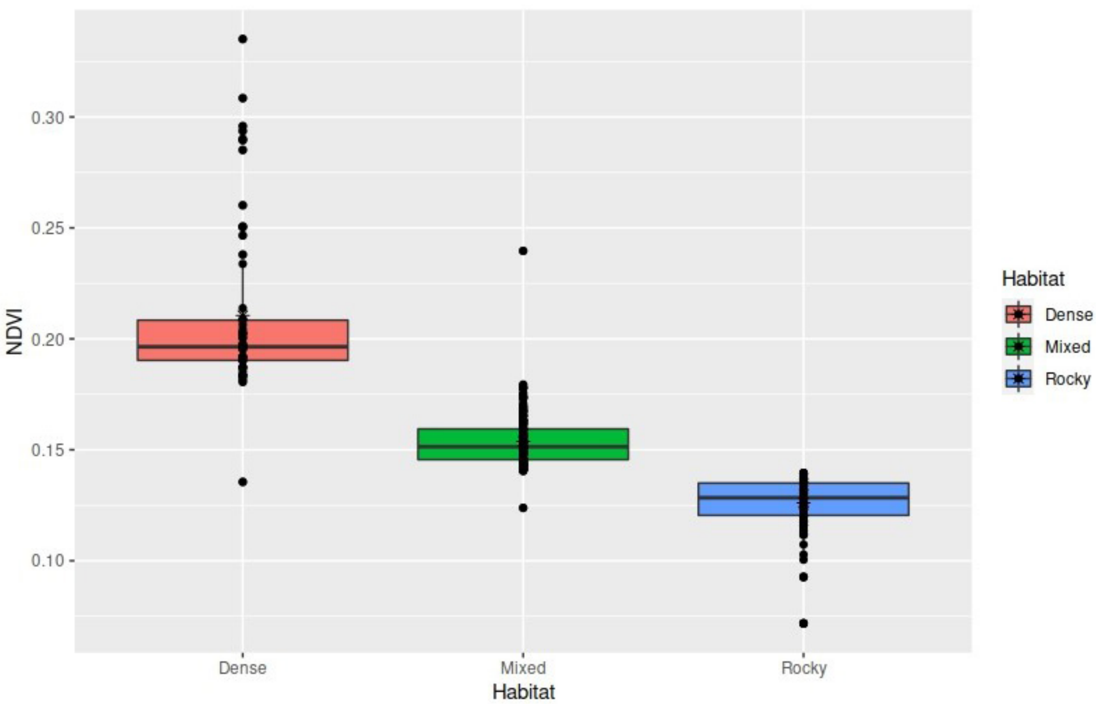


Figure 3. Box plots for comparing the mean NDVI values across the habitat classification in Savandurga Reserve Forest.

vegetation) and three different harvesting intensities (low, medium, high) to identify any variations due to these factors. Since density (D) and population size (N) are related, with N = D x Area, we estimated the density for the sample and used it to compute the total population. We used the formula D(p) = N/A, where D(p) represents population density, N represents the number of stems (population size), and A represents the area. The quadrat and environmental data were analysed using R software version 3.6.3 (R Core Team 2020).

Next, we standardized the densities of *D. hamiltonii* adults, saplings, and seedlings per hectare for all sites in the SRF. We then compared the relative densities of *D. hamiltonii* across habitat types and harvesting intensities. We used the Wilcoxon test to calculate pairwise comparisons between group levels, with corrections for multiple testing. We also plotted population structure curves using the GBH-based size class distribution of *D. hamiltonii* stems. The smallest stems were 0.5 cm which was placed between 0.1 to 3 cm class. We formed 15 size classes ranging 0.1–45 cm with an equal interval of 3 cm and statistically compared the relative densities and size classes using non-parametric ANOVA (Kruskal-Wallis test). Whenever the Kruskal-Wallis test resulted in a significant difference, we performed pairwise Wilcoxon rank sum tests.

To compare the densities and relative densities, we derived four datasets from the *D. hamiltonii* database: (1) entire *D. hamiltonii* stems across SRF; (2) adults; (3) saplings; and (4) seedlings. We attempted a regression analysis to examine the impact of various environmental factors on the distribution and abundance of *D. hamiltonii* in SRF. We initially considered the eight habitat and two categorical variables as predictor variables, and after checking for collinearity among them, we used a final set of nine explanatory variables for regression, excluding habitat types due to high correlation with NDVI.

RESULTS

From the 240 sample plots, total 405 stems of the *D. hamiltonii* species were enumerated from 6000 m^2 (5 x 5 m = 25 m^2 x 240 plots = 6000 m^2). Adults made up the largest portion of them (188 stems, or 46%), followed by seedlings (152 stems, or 37%), and saplings (65 stems, or 16%). Among the 24 grids density ranged from lowest 0.1 ± 0.32/25 m^2 (Mean ± S.D.) to the highest 5.2 ± 2.66/25 m^2 (Mean ± S.D.). The estimated densities of the *D. hamiltonii* per plot (25 m^2) and for each grid were the highest in DBO, KOH, KPN, MPCA, and MST (Table 3), while the grids SFH and JKB had the least densities. The density of the adults was highest (Mean ± S.D.: 313 ± 210 stems/ha, N = 24), followed by the density of the

Table 3. Estimated densities per hectare and per sampled plot (25 m2) for *Decalepis hamiltonii*.

Grids	Density / 25 m^2 (Mean ± S.D)	Density / ha
AAS	1.3 ± 0.95	520
BKM	0.9 ± 1.20	360
DAD	2.4 ± 1.35	960
DBO	2.8 ± 2.30	1120
DGK	1.5 ± 0.71	600
GKM	1.4 ± 0.97	560
HCG	2 ± 2.98	800
ITE	0.8 ± 1.03	320
ITG	1.5 ± 1.65	600
ITM	1.6 ± 1.43	640
JKB	0.5 ± 0.85	200
KOH	2.8 ± 2.39	1120
KPN	3.5 ± 4.62	1400
KPS	1.9 ± 1.97	760
KTK	1.1 ±2.13	440
MPCA	5.2 ± 2.66	2080
MR1	0.8 ± 1.75	320
MR2	0.8 ± 1.03	320
MR3	1.5 ± 1.65	600
MST	2.8 ± 2.86	1120
NK	1.9 ± 2.60	760
SFH	0.1 ± 0.32	40
VBD	0.4 ± 0.52	160
VTK	1 ± 0.67	400

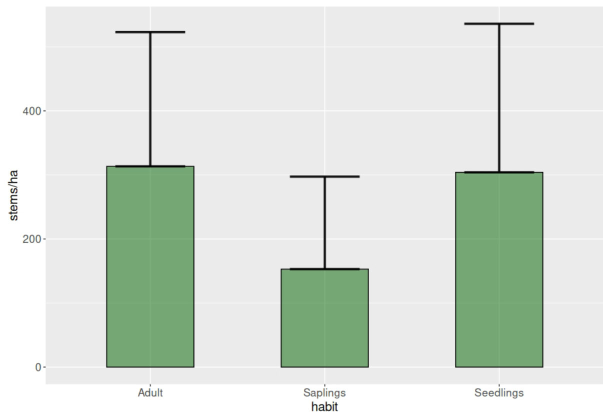


Figure 4. Distribution of the *D. hamiltonii* adult, sapling, and seedling densities per hectare across the Savandurga Reserve Forest.

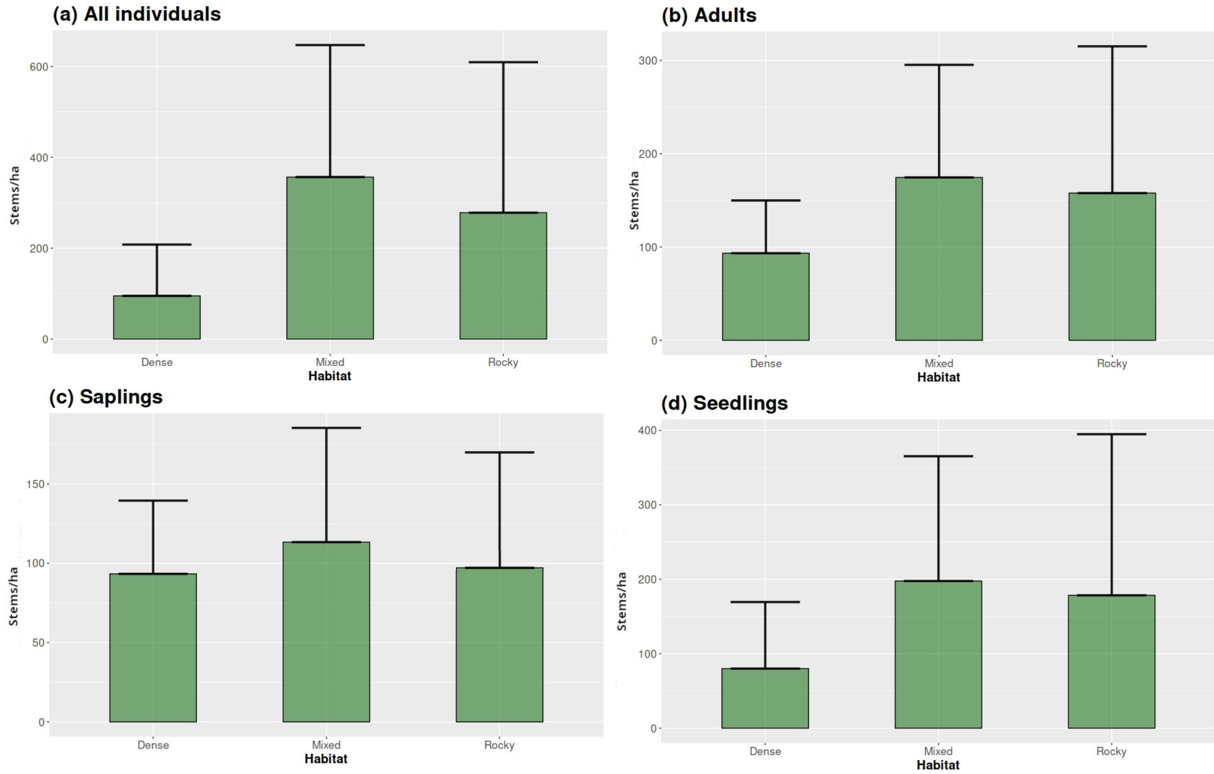


Figure 5. Comparison of the Mean ± S.D. in the *D. hamiltonii* stems from the sites across the three habitat types (dense vegetation, mixed vegetation, rocky outcrops) for: (a)—all the stems | (b)—adults | (c)—saplings | (d)—seedlings.

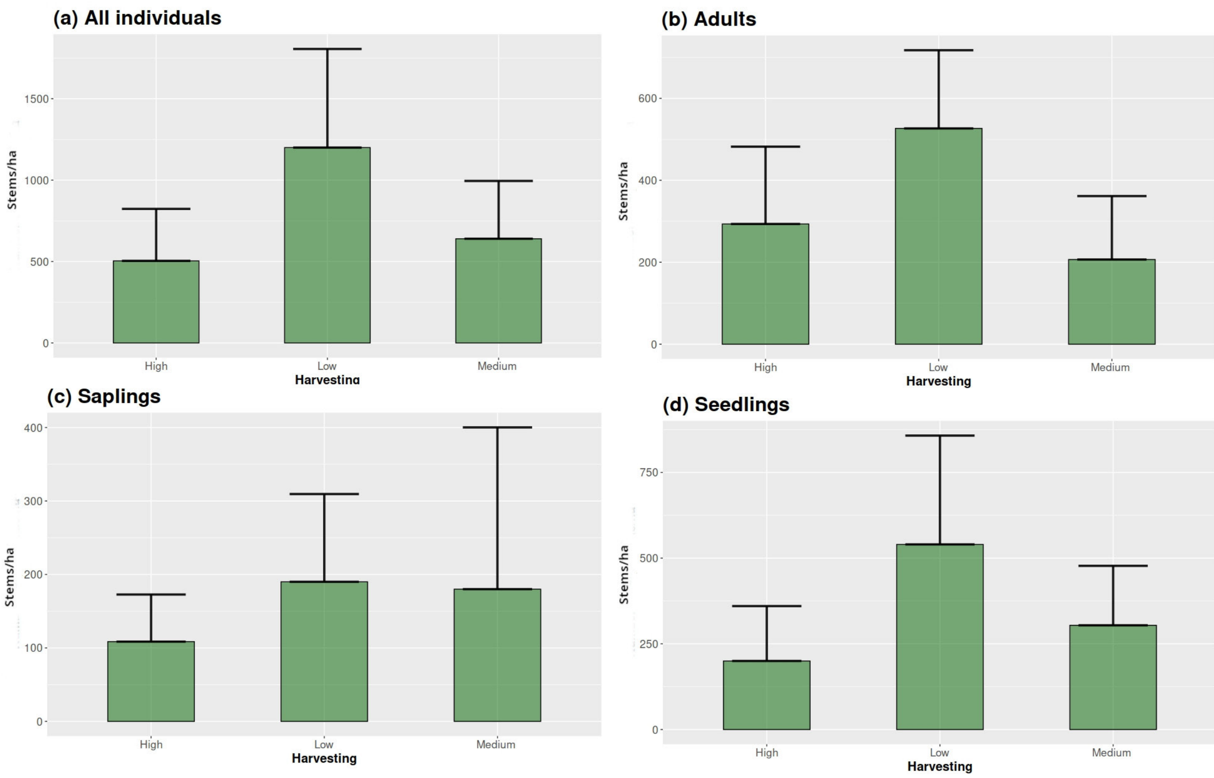


Figure 6. Comparison of the Mean ± S.D in the *D. hamiltonii* stems from the sites across the harvesting regimes (low, medium, high) for: (a)—all the stems | (b)—adults | (c)—saplings | (d)—seedlings.

Table 4. Nonparametric ANOVA results for the comparison of adults, saplings, and seedlings of *Decalepis hamiltonii* compared among sites under different harvesting regimes (high, medium, and low).

Response variable	Harvesting intensity			Kruskal-Wallis ANOVA	*P* value
	High	Medium	Low		
	Mean ± S.D. (N) stems/250 m²	Mean ± S.D. (N) stems/250 m²	Mean ± S.D. (N) stems/250 m²		
Adults	293 ± 188 (15)	206 ± 154 (6)	470 ± 247 (4)	$\chi 2(2,23) = 3.291$	0.19
Saplings	108 ± 64 (7)	180 ± 220 (6)	190 ± 119 (4)	$\chi 2(2,15) = 1.003$	0.6
Seedlings	200 ± 160 (12)	304 ± 77 (5)	540 ± 317 (4)	$\chi 2(2,19) = 5.880$	0.06

Table 5. Multiple linear regression models based on the AIC model selection for (a) total stems, (b) adults, (c) saplings, and (d) seedlings.

Response variable	Predictors	parameter estimate	T	*P*- value	AIC values
All stems	Harvest_high	0.822	1.924	0.056	720.075
	Harvest_medium	1.264	2.803	<0.01	
	Harvest_less	2.585	5.649	<0.0001	
	Associated species	0.038	2.344	<0.05	
Adults	Harvest_high	1.529	13.686	<0.0001	225.13
	Harvest_medium	1.193	8.327	<0.0001	
	Harvest_less	1.682	13.503	<0.0001	
Saplings	NDVI	3.257	1.161	0.2503	241.227
	Altitude	0.001	2.609	<0.05	
Seedlings	Northness	-0.655	-2.006	<0.05	384.043

seedlings (Mean ± S.D. :304 ± 232 stems/ha; N = 20) and density of the saplings (Mean ± S.D.: 153 ± 144 stems/ha, N = 17). Overall mean density (Mean ± S.D.) observed was 675 ± 455 stems/ha in SRF.

When the total number of *D. hamiltonii* individuals at each site was compared, the sites that are subjected to high harvesting had, on average, the fewest individuals (less than ten), with the exception of sites AAS (13 individuals), GKM (14 individuals), KTK (11 individuals), and VTK (10 individuals). The areas that had medium levels of harvesting had a comparatively greater number of plants to begin with (10–20 individuals per site). And the locations that had the fewest plants harvested had more than 20 individuals per site; the site that was protected by the MPCA had the largest number of plants (52 individuals). When compared to the mature plants in the less harvested sites, the medium and highly harvested sites had a much lower number of individuals, with most having fewer than 10 individuals, while the less harvested sites had more than 10 individuals.

When the densities of adults, saplings, and seedlings were compared across different sites in SRF, significant differences were found (Figure 4; Kruskal-Wallis ANOVA: $\chi^2_{(2,21)} = 14.09$; P <0.001). According to the results of the pair wise comparison tests, the sapling densities were substantially lower compared to those of the adults (P <0.001), as well as those of the seedlings (P <0.05). On the other hand, there was no significant difference in the densities of the adults and the seedlings (P = 0.2032).

From the Figure 5a, the densities of the *D. hamiltonii* were significantly less in the dense vegetation (Mean±S.D.: 95 ± 113, N = 16) as compared to the mixed vegetation (Mean±S.D.: 356 ± 290, N = 24) and the rocky outcrops (Mean±S.D.: 278 ± 331, N = 22). This was confirmed using Kruskal-Wallis ANOVA ($\chi^2_{(2,59)} = 13.728$; P <0.01). Furthermore, the pair wise comparison tests revealed that the abundance in the dense vegetation were significantly lower compared to that in the mixed vegetation (P <0.01) and the rocky outcrops (P <0.05). However, there was no differences in the densities of the *D. hamiltonii* in the mixed vegetation and the rocky outcrops (P = 0.22).

When the adult populations were compared across the different types of habitats (Figure 5b), the densities were relatively higher in the mixed vegetation (Mean ± S.D.: 174 ± 120, N = 22) and the rocky outcrops (Mean ± S.D.: 158 ± 157, N = 18) than they were in the dense vegetation (Mean ± S.D.: 93 ± 56, N = 9). However, the

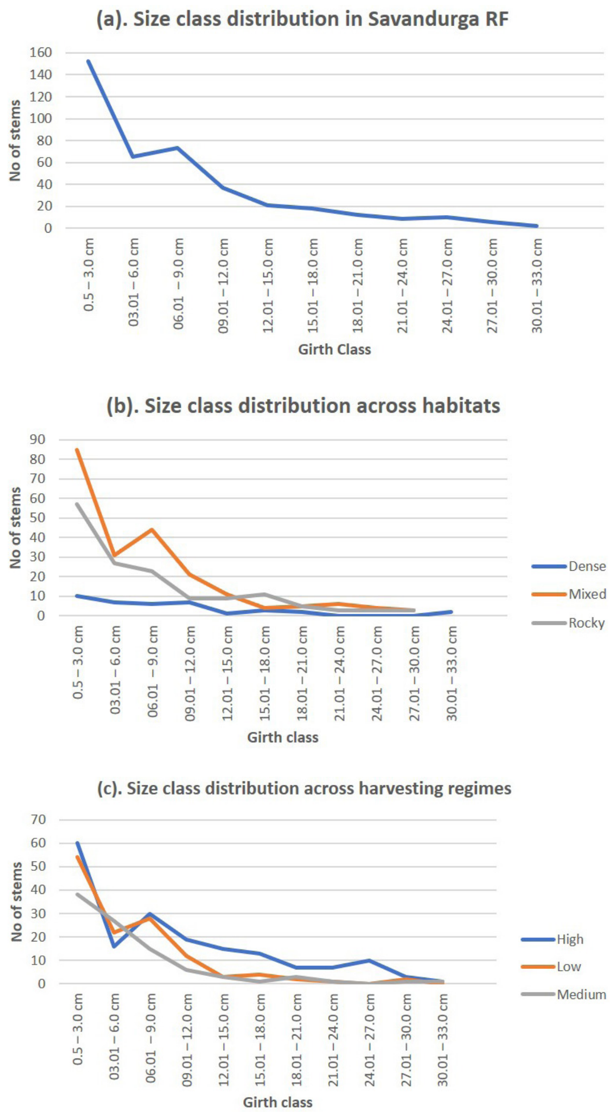


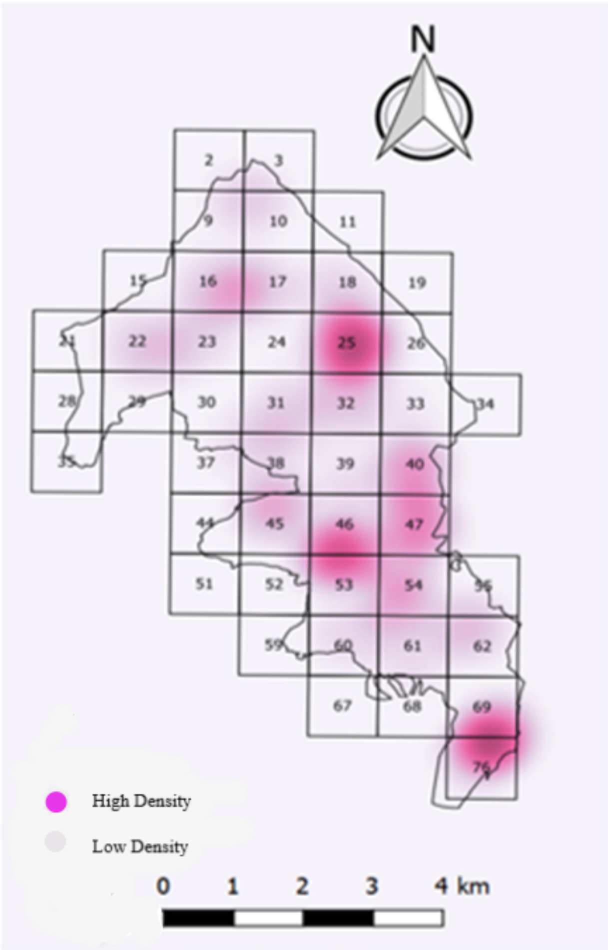
Figure 7. Comparison of the size class distributions of the *D. hamiltonii* stems for: (a)—entire SRF | (b)—across habitat types | (c)—across harvesting regimes.

statistical differences between the populations were not significant (Kruskal-Wallis ANOVA: $\chi^2_{(2,46)}$ = 3.282; P = 0.19). The densities of the saplings were comparable across all three habitat types (Figure 5c; dense vegetation: Mean±S.D.: 93 ± 46, N = 3; mixed vegetation: Mean ± S.D.: 113 ± 72, N = 12; and rocky outcrops: Mean±S.D.: 96 ± 68, N = 9, and the differences between the three habitat types were not statistically significant (Kruskal-Wallis ANOVA: $\chi^2_{(2,21)}$ = 0.032; P = 0.85). In a manner analogous to that of the saplings, the densities of the seedlings did not vary across the three different habitat types (Figure 5d; dense vegetation: Mean ± S.D.: 80 ± 89, N = 5; mixed vegetation: Mean ± S.D.: 197 ± 167, N = 17; and rocky outcrops: Mean±S.D.: 178 ± 216, N = 13, and the differences were not statistically significant (Kruskal-Wallis ANOVA: $\chi^2_{(2,32)}$ = 2.544; P = 0.28).

According to Figure 6a, the densities of *D. hamiltonii* were lower in the sites that were highly harvested (Mean±S.D.: 5483 ± 342, N = 15) and moderately harvested (Mean ± S.D. : 640 ± 554, N = 6) as compared to the sites that had less harvesting which had densities of (Mean ± S.D. : 1280 ± 355, N = 4) The Kruskal-Wallis analysis of variance ($\chi^2_{(2,22)}$ = 8.04; P <0.05) provided evidence in support of this hypothesis. According to the results of the pair wise comparison tests, the mean densities of *D. hamiltonii* were substantially lower in heavily harvested sites in contrast to those in less harvested areas (P <0.01). However, there was no difference in the mean densities of *D. hamiltonii* between highly harvested sites and moderately harvested sites (P = 0.32), nor was there a difference between moderately harvested sites and less harvested sites (P = 0.06). When the densities of adults, saplings, and seedlings were examined across the three harvesting regimes, similar patterns were found; however, the Kruskal-Wallis ANOVA revealed that there were no statistically significant differences (Table 4).

Size class distributions

The size class distribution for the *D. hamiltonii* exhibited close to a typical inverted "J" curve (Figure 7a); however, it can be inferred that the size class distributions for the entire population of *D. hamiltonii* in SRF is unstable due to the lowest densities of the saplings (size class: 3.01–6.0 cm). In a similar manner, when the size class distributions were analyzed across the various habitat types (Figure 7b), it was discovered that the populations are unstable as a result of the decreased abundance of the saplings. Compared to the thick vegetation and the mixed vegetation the rocky outcrops had a greater recruitment into the populations than the dense vegetation. The Kruskal-Walli's analysis of variance revealed very significant differences between the three habitat types ($\chi^2_{(14,42)}$ = 34.576; P <0.01). Furthermore, when the size class distributions were examined among the different harvesting regimes (Figure 7c), it was observed that the populations are unstable due to lower abundance of the saplings. However, the sites subjected to high harvesting pressure had higher recruitment into the populations than compared to that in the sites with moderate and less harvesting pressure. Statistical analysis of size classes reflected high significant differences between the three harvesting regimes (Kruskal-Wallis ANOVA: $\chi^2_{(14,42)}$ = 36.741; P <0.001). On the contrary to our expectations, the sites with higher harvesting pressure had a greater



Grid	Site code	Density/25 m² (Mean ± S.D.)
G31	AAS	1.3 ± 0.95
G18	BKM	0.9 ± 1.20
G40	DAD	2.4 ± 1.35
G47	DBO	2.8 ± 2.30
G32	DGK	1.5 ± 0.71
G17	GKM	1.4 ± 0.97
G53	HCG	2 ± 2.98
G23	ITE	0.8 ± 1.03
G22	ITG	1.5 ± 1.65
G16	ITM	1.6 ± 1.43
G39	JKB	0.5 ± 0.85
G46	KOH	2.8 ± 2.39
G69	KPN	3.5 ± 4.62
G76	KPS	1.9 ± 1.97
G10	KTK	1.1 ±2.13
G25	MPCA	5.2 ± 2.66
G60	MR1	0.8 ± 1.75
G61	MR2	0.8 ± 1.03
G62	MR3	1.5 ± 1.65
G54	MST	2.8 ± 2.86
G45	NK	1.9 ± 2.60
G24	SFH	0.1 ± 0.32
G33	VBD	0.4 ± 0.52
G38	VTK	1 ± 0.67

Figure 8. *D. hamiltonii* population density in SRF for 24 grids with IDs.

number of adults with girth ranging 6–33 cm (Figure 7c).

Influencing variables determining the adult, sapling and seedling distribution

The regression analysis based on AIC model selection indicated that the adult *D. hamiltonii* distribution in the sampled sites of the SRF was determined by harvesting alone with 78% variation explained ($F_{(3,120)}$ = 146.3; P <0.001). Contrary to expectations, the coefficients for the adult plant abundance were more in high and less sites than in moderately harvested sites (Table 5). The sapling distributions in the SRF were mostly determined by the NDVI (2.09% variation explained), a surrogate for habitat type, along with altitude (18.72% variation explained) that explained a total variation of 56.58%. Furthermore, the NDVI and altitude positively correlated with the sapling abundance (Table 5). The seedling distributions in the SRF was determined by the transformed aspect variable–cosine or the northing. The cosine or the northing variable negatively correlated with the seedling abundance suggesting that the densities increased as one travels from north to south in SRF. However, the directional variable explained a mere 4.44% variation observed in the seedling distribution (Table 5).

DISCUSSION

This study serves as the first baseline to assess *D. hamiltonii* population density and size class across habitats and disturbance levels for the entire landscape of SRF, Karnataka, India. The focus on a specific climber species is also fairly unique since most studies of have focused on community-level analysis (Gerwing 2004). Climbers in life forms and root-harvested plants are rarely attempted for research from the perspective of harvesting and its impact on the population is less known (Ticktin 2004; Stanley 2012). Totally, 405 stems were enumerated from the sampled area of 6,000 m² and the density ranged from lowest (Mean ± S.D.: 0.1 ± 0.32/25 m²) to the highest mean density of (Mean ± S.D.:

5.2 ± 2.66/25 m^2) across 24 grids. The overall estimated mean density/ha of *D. hamiltonii* in SRF is (Mean ± S.D.: 675 ± 455 stems/ha) and details for each grid/site is provided in Table 3.

Though the adults are represented in all grids we found that in SFH except for one adult individual none of the other classes was spared as it was a highly disturbed area. Sites such as DGK have the maximum number of adult plants, while others BKM and VBD, are inaccessible peripheral portions of the MPCA having less density. Though, all grids have some kind of disturbances categorized into low, medium, and high levels based on signs of being chopped, uprooted, hanging dead stems, uncovered dug pits, and drying of collected roots, some of these peripheral grids are part of the MPCA which is interior and inaccessible but requires protection for recouping of the population naturally. Seedlings were missing in four grids, which could eventually be the result of harvesting adults, leading to a reduction in fruits or in seed quality which is not germinating well. The second reason is goat herders cutting / pulling the branches with fruits to feed the goat with leaves. This is a matter of concern as it causes great loss by wasting the reproductive effort and material of the plant. Usually, the goat feeds only on the leaves there is no threat to the survival of the plant as the roots are intact.

One would expect that areas of high adult density would also have high sapling and seedling densities since most of the adult plants' have wind-dispersed seeds which place the seeds in open rocky, and dense areas indiscriminately. Grids facing harvest compared with no harvest helps in distinguishing between the varying levels of harvesting intensities and the effects of harvesting on population dynamics (Hall & Bawa 1993). The density map depicts most of the peripheral grids being disturbed and exhibiting unequal patchy density either over-representation or under-representation of size classes and this could have been a result of harvesting largely or due to other kind of disturbances happening over a period of years now affecting the central, interior portions of the forest. Similar patches of disjuncture alternatively, representing areas where adults or seedlings have been preferentially harvested, leaving an overabundance and an under abundance of one size class was observed in *Mondia whitei* harvested for roots in Kakamega forest (McGeoch 2004). It is evident from the study that the highest number of 52 stems were found from the sample plots laid in the MPCA (Grid no 25), with a (Mean ± S.D.: 5.2 ± 2.66/25 m^2). It is worth mentioning that this area had all size classes spread naturally which are not captured in our plots and such population was not observed in any other grids. This is an indication of management effort and a restricted gated area or 'hands off' or 'no harvest area' where the central portion of MPCA is not disturbed, unlike the peripheral grids. The central portion of the MPCA is the only grid with a healthy population representing all size classes. Strict monitoring and regulations are required to support the natural regeneration of the population to support the in situ conservation area as well as throughout the landscape.

Size class distribution exhibits close to a typical inverted "J" curve with lower densities of the saplings (class: 3.01–6.0 cm) compared to seedlings and adults. The abundance of seedlings is an indicator of good regeneration but the low density of the saplings stage poses a future bottleneck (Bitariho & Emmanuel 2019). Reasons for the low density of the sapling class could be due to low recruitment or mortality of the individuals or both. Savandurga RF is a site where sustainable harvesting methods have been trained by the experts and implemented by the community for harvesting *D. hamiltonii* individuals and this could be one of the reasons contributing to the presence of a greater number of adult class (Kinhal & Jagannatha 2006; Kinhal et al. 2006). Unscientific, premature, unregulated root harvesting or uprooting of size classes like saplings do have good yield but may not be able to withstand the intensity of harvest and survive like the adults but rather lead to mortality or delay in their growth progress to reproduction (Image 1b&e). Reduction in sapling class is considered a forewarning as it indicates an unstable population generally observed in tropical forests and reasons could be many factors. One prominent factor to mention is fire which is almost an annual occurrence could also kill the seedlings and saplings (Sukumar et al. 2005). Studies by Parthasarathy (2000), Parren (2003), and Rai et al. (2016) also showed the inverse "J" pattern generally observed in climber communities. Bitariho & Emmanuel (2019) have studied harvested climber populations and found a similar inverted "J" curve pattern in five species whereas other climbers represented different patterns in population structure depending on the intensity of harvest. Similar to our findings in *D. hamiltonii* observations made in perennials like trees for ex *Phyllanthus emblica* population had higher mortality of the sapling size class, as well as *Boswellia serrata* (Ganesan & Setty 2004; Soumya et al. 2019a). These outcomes show similarity in the methods of representing the size class and also representing the negative consequences of the harvested perennials leading to poor representation of size classes, in a dry tropical ecosystem. Contrary to our finding's density of saplings in *C. fenestratum* was positively associated with the adults and exhibited a healthy population but, during the survey they did not find size class above 3.5 cm (Thriveni et al. 2015). In case of climbers like *Mondia whitei* people harvest roots before fruit development and such premature harvesting disturbs the growth of the plant and because of this it is very hard to find adult fruiting plants (McGeoch 2004). As a result of intense stem harvesting in both areas of very disturbed and less disturbed sites there was a prevalence of small diameter sizes in the *Loeseneriella apocynoides* which is typical of a population with many resprouts but very few mature stem (Ndangalasi 2006; Hall and Bawa 1993; Bitariho et al. 2006). The studies mentioned above shows the intensity of harvest on the climber population in *M. whitei* (roots), *L. apocynoides* (stem) and *C. fenestratum* (stem & roots) where only small diameter classes were present but with the absence of adult size classes and very few fruiting individuals. These studies mentioned above and our results, invariable of life form indicate that a species-specific scientific approach unfolds more insights about the population and size classes. Hall & Bawa (1993) emphasize that the method of representing size class distribution is useful to identify the poorly represented size classes and it may differ based on habitats or due to various level of harvesting intensities. Considering the effect of harvesting on different life forms (herbs, shrubs, climbers, trees) the life history (annual, biennial and perennial) or plant parts being harvested (leaf, flower fruits, bark, resin and root) the negative consequence of harvesting is expressed in the process at different life stages. Invariable of the life forms, the plant parts are stored carbon resources for the plants to continue the life cycle, and removal of those parts hampers their growth process.

Harvesting history of the forest is of consideration (Ticktin 2004) because SRF is an area where sustainable harvesting methods for root harvesting of *D. hamiltonii* has been imparted to the community (Kinhal & Jagannatha 2006; Kinhal et al. 2006; Jagannatha & Kinhal 2008). These practices may ensure and support survival of the adult plants after harvest but to what extent the methods are still followed?, how frequently each stem is harvested?, how healthy and productive are the harvested plants?, do the adult plants have their roots intact or lost due to harvest?, are points necessarily to be investigated. Saplings were not found in seven grids and found less in other grids compared to adults and seedlings. This scenario is indicating that the root harvesting is not restricted to only mature adults (>6.1 cm onwards) but being collected from smaller size classes also. This type of harvests may not allow the harvested stems to reach reproductive maturity and eventually recruit (Hall & Bawa 1993). The quantity of root available, for e.g., in a six-month-old plant, i.e., a seedling has minimum 500 g of root below ground. A sapling size class (3–6 cm stem girth) will have, not less than 2–3 kg of roots (minimum). Increased demand and pressure on the collectors, less equipped or unskilled harvesters, plants grown in favorable soil conditions which could be easily harvested are possible options for collecting roots from smaller size class. From the perspective of root harvest and its impact on the growth, survival, duration required to reproduce flower, fruits and potential seeds again are topics for further investigations. Unless monitored, managed and regulated spatially it is difficult to save premature harvest and selective harvest of adults.

Less number of stems is found in the dense vegetation, abundant in mixed vegetation and rocky outcrops. More in areas with higher disturbance which is a characteristic feature of climbers. Density of adults are determined by harvesting alone (78% variation), saplings by NDVI (2.09% variation) a surrogate for habitat type correlating along with altitude (18.72% variation). Seedlings were determined by directional variable (aspect) - 4.44%. (densities increased as one travels from south to north) adult stems had the highest density, followed by seedlings and saplings. The sites with high levels of harvesting had the fewest stems on average, while the protected site had the largest number of plants. The impact of harvesting on the population densities of *D. hamiltonii* was found to be significant, with heavily harvested sites having significantly lower densities compared to less harvested areas.

The densities of *D. hamiltonii* were significantly lower in areas with dense vegetation compared to areas with mixed vegetation and rocky outcrops. Interestingly the dense vegetation had less density but *D. hamiltonii* stems had attained higher diameter like single stems with gbh ≥28 cm to 30 cm. Reason is that some portion of forest fragments have not faced disturbance for a longer period of time and secondly in such dense vegetation these stems are not visible to the human eyes, so in such places the plants have attained higher stem diameters. Likewise, we found stems in undisturbed rocky areas also of gbh ≥20 cm single stems fallen on the rock without host. Similar results have been observed and confirmed in undisturbed, unaffected forests for long periods and also in old growth forests depicting dbh ≥30 cm in climber community studies (Dewalt et al. 2000;

Anbarashan & Parthasarthy 2013).

The destructive root harvesting of *Swertia chirayita* is another example of a habitat-specific species facing similar threats (Pradhan & Badola 2015). Studies have shown that the quality of the microhabitat significantly affects the availability of the *Swertia chirayita* population, with more stems observed in open habitats and on open grassy slopes, possibly due to lower interspecific competition for sunlight, and fewer stems observed in wetland habitats. *Houttuynia cordata* is restricted to specialized moist habitats in Assam (Bhattacharyya & Sarma 2010). Many medicinal plants which are root harvested are habitat-specific for example *Picrorhiza kurroa* (Kutki) grows only in moist rocks and steep slopes at an altitude of 3,500 m (Chandra et al. 2020). *Nardostachys grandiflora* (Accepted name - *Nardostachys jatamansi*) prefers rocky steep areas on the southeast slopes and in alpine grasslands, it is found on southwest facing slopes (Ghimire et al. 2005). In the case of *D. hamiltonii*, it is a wind-dispersed species that can colonize all three habitats in the SRF, but its adaptability to microsite habitat determines its survival as an adult.

Plant density, recruitment and survival rates are found to be more in less harvested areas than high harvest area with decreased densities (Ghimire et al. 2005; Bhattacharyya & Sarma 2010; Chandra et al. 2020). It was observed in *Coscinium fenestratum* population that they survive and regenerate naturally in disturbed habitats compared to undisturbed forest (Kathriarachchi 2004). The larger adults of *D. hamiltonii* were found in dense vegetation and seedlings within the canopy gaps and all classes were found in open areas, rocky outcrops and mixed vegetation in our study. Similarly, *Mondia whitei* also germinates well specifically in disturbed areas and forest gaps, also they are able to survive in all extreme conditions of Kakamega forests (McGeoch et al. 2008).

The mixed vegetation in SRF features an open canopy that allows sunlight to penetrate through exposed rocky areas and gaps in the foliage. *D. hamiltonii* is commonly found in this habitat alongside other plant species such as bamboo and *Sterculia urens*. The species also shows regeneration in the dense vegetation of the forest, particularly in canopy gaps and rock gaps where sunlight can reach. Climbing plants like *D. hamiltonii* often grow on shorter trees such as *Wrightia* spp. (in fact all size classes) and also large trees like *Albizia* spp. Additionally, *Euphorbia antiquorum* which thrives in barren rock fissures and depressions, provides a suitable habitat for *D. hamiltonii for regenerating seeds* by offering protection from grazing and support up to a large adult stage. Rocky outcrops serve as favorable habitats for *D. hamiltonii* as they act as water filters, improving soil moisture. Moreover, the hair-like appendages connected to the seeds aid in wind dispersion, allowing the species to propagate and renew populations in rocky patches.

Apart from cattle grazing, *D. hamiltonii* leaves are extensively browsed by goats of course no damage to the roots. Shepherds also chop down the large climbers with flowers and fruits to feed the goats which is a loss to the population. Similar cases could be found in *Hydrastis canadensis* population, though overharvesting lead to severe decline, browsing of white-tailed deer also was an additional cause (Mulligan & Gorchov 2004). *D. hamiltonii* density is primarily impacted by destructive root harvesting practices. Flat and low-lying regions face higher levels of anthropogenic pressure compared to higher elevations, which results in a decrease in pressure as elevation increases. The reduced recruitment and density are likely due to the prevalent harvesting strategy and the chopping of the climbers that flower and fruit, used for feeding goats. This decrease in recruitment and higher mortality of seedlings and saplings will make it difficult to replace the existing adult population in the future. Although there is a higher number of adult population every other plant has been harvested in previous years, and the adults are preferred by the harvesters due to their potential for producing the highest yield.

The results of this study have clear management implications, primary focus is to mitigate destructive extraction pressure and save the remaining population in SRF by enforcing laws to control harvesting for the entire landscape. The management strategy should prioritize the protection of early life stages (seedlings to saplings stage) to avoid premature harvest and regulate selective harvesting of the adult stems. Goat herders, pulling the fruiting branches to feed the goat should be restricted. It would be worthwhile to protect the adjacent grids surrounding the MPCA also which harbor good density. The area within the MPCA needs protection to support natural regeneration and sustenance of the gene pool. Most of the peripheral grids are disturbed and needs proper planning to restore the species in open and disturbed areas provided protection is ensured (Figure 4. Density Map).

The entire landscape is worth protection as it is one of the best habitats for conserving *D. hamiltonii* population due to the natural design of the topography and supporting associated species. It provides open areas, gap vegetation and rock crevices, slopes, aspect, hillocks which create innumerable micro niches. These micro niches ensure seedling establishment and forms vegetation patches with host species which can provide shelter from seedling to adult stage. Studies deepening the role of these variables will be useful for future studies. These micro niches make this habitat a refuge site for the population to establish, recover and sustain in spite of disturbances.

Our results underscore the necessity of long-term studies to monitor the population at different stages and develop appropriate management plans (Nakazono et al. 2004). The effect of harvesting on different size classes and their response to survival, growth, yield and reproduction necessitates investigation to tease apart the effects and enlighten future research on climbers as well as root harvesting species. All plant species are threatened by changes in temperature, rainfall, disruption of associated species, pests, pathogens, anthropogenic influence, habitat fragmentation, destructive harvesting, which could be the causes to push the populations to extinction. World scientists warning to humanity highlights the fact that medicinal plant species are often harvested unsustainably, when combined with the above pressures the stress level increases and the responses can result in decline in biomass, changes in chemical content affecting the quality and safety of medicinal plants. (Applequist et al. 2020). *D. hamiltonii* is holding a cocktail of medicinal properties and expected to be a potential source for more discoveries to unfold in the future, and so it is of high importance which needs to be conserved.

Harvesting *D. hamiltonii* roots can be one of the reasons which disturbs the host as well as the surrounding associated species because these activities enable gaps and create scope for growth of *Lantana camara* and *Hyptis suaveolens* (Accepted name-: *Mesophaerum suaveolens*) bushes accommodating the area. The post effect of disturbance after roots of *D. hamiltonii* is harvested needs investigation.

Though rocky areas encourage regeneration, long and thick roots, in our study the big size stems were found to be growing very well in undisturbed dense forest and also in loamy soil. This information needs to be shared with the stakeholders to grow/cultivate and reduce the pressure from the wild. It is recommended that future studies focus on identifying similar suitable areas to grow, reintroduce, restore *D. hamiltonii* by using technological tools like Ecological niche modelling. Secondly, monitor the effect of harvest on different size classes.

Encouragement of cultivation locally as well as at large-scale can be provided for the farmers through loans or under the NMPB subsidy schemes. Connecting the product to market will ensure livelihoods and reduce pressure from the wild (Homma et al. 1992). Periodic training on sustainability for harvesters, certification of the raw material and programs to monitor the population involving all the stake holders is essential.

Consequences of root harvested plants are difficult to be traced because the loss is below ground and scope of enquiry is invisible and difficult to gauge the population unless monitored periodically. The results from SRF may serve as an example to encourage more such studies across the distribution range, trigger research on root harvested climber species and compare the evidences across the sites. Such efforts would help in formulation of management plans, assessment of its Red List status and help in sustenance of the remaining endemic population.

The presence of many native species like *Wrightia tinctoria, Albiza amara, Psydrax dicoccos*, and *Euphorbia antiquorum* are potential hosts which supports the growth of *D. hamiltonii* at all stages in the forest. *Wrightia tinctoria* is present in all size classes supporting *D. hamiltonii* abundance both naturally as well as through management efforts. These plants can be used for supporting the climbers while planting or domesticating. Conservation organisations and citizen groups alike must foster a collective responsibility towards preserving this habitat and the species by engaging communities and raising awareness about it. Preserving the habitat is not just a matter of ecological conservation but also a means of securing a sustainable future for both the environment and the communities.
Confidence and capacity building among local people (Rist et al. 2016), citizen science reporting of harvesting/ disturbances, will help the Forest Department to save the population. Field demonstration plots on how *D. hamiltonii* can be grown with interpretation units for surrounding villages, schools and panchayats needs to be encouraged. This effort will be useful to disseminate the value of the resource, habitat and engage community.

CONCLUSION

The high and increasing demand for roots, place undue pressures on the wild population and dynamics of *D. hamiltonii.* The management strategy should prioritize the protection of early life stages (seedlings to saplings stage) to avoid premature harvest, equally regulate selective harvesting of the adult stems and mitigate grazing by strict monitoring and periodic assessment of the population. The impact of root harvest on the reproduction and yield needs to be investigated and monitored on a long-term basis. Intensifying the protection for the MPCA towards the peripheral grids to help natural regeneration and restoring of the population outside the MPCA is highly recommended. Encouragement of local plus large-scale cultivation is inevitable and local citizen science awareness and reporting mechanism of destructive root harvesting will help the forest department to take action and save the remaining population in the wild. It is submitted that the results of this study are based on one site (Savandurga RF) only, hence comparative studies carried out on a regional scale that include both social and ecological analyses will allow to gain better insight into the current population status of *D. hamiltonii*. More collection from the wild and missed conservation actions from the stakeholders at this juncture will lead to depletion of the population in this landscape.

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Appendix 1. Disturbance scoring and conservation implications of Savandurga Reserve Forest (24 sites/grids) with site description.

Grid	Site	Fire	Invasive plants	Collection of fruits, green, etc.	Grazing, chopping	Herbivory	Transport-frequency	Path-ways	People Footfalls	Adventure sports	Distance from villages	Drying of roots	Roots removal	Disturbance score	Dist. code
G10	KTK	1	3	0	0	0	0	1	0	0	1	1	4	11	**High**
G17	GKM	1	2	0	0	0	0	1	1	0	1	1	4	11	**High**
G18	BKM	0	1	0	0	0	0	0	0	0	1	10	4	16	**High**
G23	ITE	0	1	1	1	1	0	1	1	0	3	0	2	11	**High**
G24	SFH	0	3	0	1	1	3	2	2	4	4	0	3	23	**High**
G31	AAS	1	2	1	3	1	3	2	2	4	4	0	3	26	**High**
G33	VBD	0	1	0	0	1	0	0	0	0	3	2	4	11	**High**
G38	VTK	0	3	1	1	1	3	2	2	4	4	0	4	25	**High**
G39	JKB	1	1	0	1	0	0	1	0	0	4	0	4	12	**High**
G60	MR1	1	3	1	1	0	1	1	0	0	4	0	4	16	**High**
G61	MR2	0	1	1	1	1	2	0	0	0	4	0	4	14	**High**
G25	MPCA	0	1	0	0	0	0	0	0	0	0	0	0	1	**Less**
G40	DAD	0	1	0	0	0	0	0	0	0	4	0	0	5	**Less**
G46	KOH	0	1	0	0	0	0	0	0	0	2	0	2	5	**Less**
G47	DBO	0	1	0	1	0	0	1	0	0	2	0	0	5	**Less**
G53	HCG	0	1	0	0	0	1	0	0	0	3	0	0	5	**Less**
G54	MST	0	1	0	0	0	0	0	0	0	4	0	0	5	**Less**
G69	KPN	0	1	0	0	0	0	0	1	0	3	0	0	5	**Less**
G16	ITM	1	2	0	0	0	0	1	1	0	1	0	0	6	**Medium**
G22	ITG	1	1	1	1	0	0	1	0	0	1	0	1	7	**Medium**
G32	DGK	0	1	0	0	0	0	0	0	0	4	0	2	7	**Medium**
G45	NK	0	1	0	0	0	0	1	0	0	4	0	4	10	**Medium**
G62	MR3	0	1	0	0	1	2	0	0	0	3	0	0	7	**Medium**
G76	KPS	0	1	0	1	0	1	0	0	0	3	0	1	7	**Medium**

Criteria for disturbance level calculated for each grid/site level based on field observation.

Site disturbance scores were obtained by assessing all 24 grids/sites which include the following:

1. **Resource removal, roots harvested by different methods–-** uprooted, chopped up to the stem, no of uprooted holes vary–- absent–- 0, partially harvested–- 1, completely harvested, uprooted chopped (>5 ind.), 5–- 10 stems dug in that area–- 3, more than 10 stems harvested–- 4

2. **Accessibility at a Minimum Distance of nearby villages.**–- 500m–- 4, 1000m–- 3, 1500 m- 2, 2000 m- 1.

3. **Pathway–-** Road absent–- 0, Mud Road–- 1, Tar Road–- 2.

4. **People footfalls**–- Absent- 0, interior small worship places visited rarely once in a year by very few families–- 1, regular visit to main temples- 2. The main temples of SRF are visited frequently weekly (rare-frequently).

5. **Adventure habits**–- rock climbing, nature park, trekking. Trekking, birding, boating camps on the other side of the hill i.e., near the Manchanabele waters.

6. **Herbivory observed**–- Porcupines–- 1, Wild boar–- 2.

7. **Fire**–- Low- level fires to clear the weeds.–- observed fire–- yes–- 1, no–- 0.

8. **Grazing** and chopping of *D. hamiltonii* climbers–- Absent–- 0, cattle–- 1, goats–- 2.

9. **Invasive species**–- 1–- less, 2–- medium, 3–- high.

10. **Drying roots**–- absent- 0, evidence of people staying to process the roots–- 5, cooking also–- 10, (high weightage has been given this point).

11. **Collection of other NTFPs or medicinal plant**s–- Bela (*Feronia elephantum*), Soppu (Greens), Genasu (Tubers), medicinal plants–- yes–- 1, no–- 0.

12. **Transport frequency–-** absent–- 0, adventure cycles and two- wheelers- 4, weekend 2 wheelers, & four wheelers–- 3, local autos and transport–- 2, Govt vehicles–- 1.

Overall Disturbance score of each site–Values ranging from 0–- 5 as Less Disturbed, 6–- 10 as Medium Disturbed, and above 10 onwards - Highly Disturbed.

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