Sustainability-based evaluation of bamboo harvest in Pachgaon, Chandrapur, Maharashtra, India

Thesis submitted in partial fulfilment of the requirements of the

BS-MS Dual Degree Program at IISER, Pune

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CERTIFICATE

This is to certify that this dissertation entitled “Sustainability-based evaluation of bamboo harvest in Pachgaon, Chandrapur, Maharashtra, India” towards the partial fulfilment of the BS-MS dual degree programme at the Indian Institute of Science Education and Research, Pune represents research carried out by Rahul Iyer at the Indian Institute of Science Education and Research, Pune under the supervision of Prof. Milind Watve, Professor at the Department of Biology during the academic year 2018-2019.

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DECLARATION

I hereby declare that the matter embodied in the report entitled "Sustainability-based evaluation of bamboo harvest in Pachgaon, Chandrapur, Maharashtra, India" are the results of the investigations carried out by me at the Department of Biology, Indian Institute of Science Education and Research, Pune, under the supervision of Prof. Milind Watve and the same has not been submitted elsewhere for any other degree.

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Abstract

The Gram Sabha of the village of Pachgaon, Chandrapur, owns a big chunk of the forest land nearest to the village, from which they extract a number of products or trade and sustenance, predominantly bamboo. The economy of the entire village depends on an effective Working Plan for the extraction of bamboo based on principles of sustainable harvest. This project was undertaken to evaluate conditions in Pachgaon forest under the Working Plan affecting bamboo growth with the goal of increasing shoot regeneration. The ecology and life history of bamboos called attention to potential factors of shoot recruitment- clump characteristics, abiotic and biotic factors- to be collected as data.The variation in forest density in Pachgaon forest provided a natural experimental setup to understand density and harvest effects. Understanding the effects of density and harvest on shoot recruitment patterns highlighted compensatory growth in high density areas only. Further analysis revealed a differential effect of density and time since harvest on shoot recruitment: a detrimental effect of harvest in lower densities and a compensatory effect in higher densities respectively on shoot recruitment. Additionally, understanding patterns of herbivory led to formulation of ‘Escape Height’, an anti-herbivory quantity.

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Background

In India, tens of millions of people living in and around forests depend on produce from the forests known as Non-Timber Forest Products (NTFPs) for nutrition and trade (Tewari 1992). Extraction of these products runs economies of entire communities around forests. However, the risk of overharvesting in the interest of maximizing immediate profits has proved detrimental in the long run to households that depend on NTFPs for a significant portion of their income. This is particularly problematic in zones of conservation interest because communities would increase the area of harvest over time which would affect the ecosystem in a negative manner. As a solution for conservation interests without conflicting major sources of income of these communities, the conception of sustainable harvest- harvesting sufficient amounts to ensure substantial future regeneration- and its importance has been recognized for decades (Ticktin 2004). Depending on the product in question, the demand for it, its mode and rate of regeneration, its response to various environmental conditions, the method of harvesting, etc., the factors affecting yield can be determined quantitatively and a formulation of maximum sustainable harvest can be done (Ticktin 2004).

Bamboo is India’s biggest NTFP commercially due to its widespread across Indian forests. 136 species across 23 genera are found in all states of India except Kashmir (Source: Forest Survey of India). Major uses include as timber-alternative for building purposes, handcrafting, pulping for the paper industry, and local consumption of new shoots which are edible, while minor uses include medicinal purposes (Maoyi and Banik 1995). An estimate of 7 million hectares of land is occupied by various species of bamboo across the country, with more than 3 million tons per year produced for timber alone (Subramanian 1995). What makes it a very viable option for timber is its rapid biomass accumulation and frequent shoot regeneration. Additionally, there is interest in maintaining the spread of bamboo due to its known properties of soil rejuvenation, soil and water conservation, erosion control, among others (Kleinhenz and Midmore 2001). Their characteristic rapid biomass accumulation is also resulting in a growing interest in their value as significant net carbon sinks and its implications in climate change control (Liese and Kohl 2015). Thus attempting to create a framework of optimizing harvest for long-term sustainability requires an understanding of the species and the factors driving its yield.

Bamboo, aka members of Bambusoideae subfamily under the Poaceae (grass) family, is well known for their cultural and economic significance and is being increasingly recognized for their ecological significance. They are perennial, evergreen, monocotyledonous plants particularly characterized by very rapid growth rates. The 1,500 species across an estimated 119 genera of bamboo currently known are extensively spread across the globe- in all continents except Europe and Antarctica, from 47^{O} S to 50^{O}30' N in latitude and sea level to 4,300 m in altitude (Clark et al 2015). This means they are native to temperate, subtropic and tropic regions, mostly inhabiting mesic to wet forest types though some have adapted to open grasslands and a few specialized habitats (Clark et al 2015). Bamboos are divided into three tribes: temperate woody bamboos or Arundinarieae, tropical woody bamboos or Bambuseae, and herbaceous bamboos or Olyreae. India is primarily home to the tribe Bambuseae, with a few exceptions of Arundinariean species adapted to tropical montane areas. Bambuseae is further classified into Neotropical Woody Bamboos and Paleotropical Woody Bamboos, of which the latter is found here (Clark et al 2015).

The standard bamboo structure consists of, from bottom to top, the belowground rhizome-root system and aerial shoots (also called culms) as shown in Fig. 1. The rhizome-root system is responsible for the structural foundation. Rhizomes facilitate transport of nutrients, growing laterally in the aerated layer of soil, supporting negatively geotropically growing shoots and geotropically growing roots. Rhizomes are of two kinds: leptomorphs or the thin kind, and pachymorphs or the thick kind. Consequently, bamboos are of two forms: monopodial or single shoot bamboos with leptomorph bases, and sympodial or clumping shoot bamboos with pachymorph bases. Roots do not extend to great depths, with over 95% of belowground biomass being found within 70 cm depth from the surface across species (Banik 2015). Shoots are divided into nodes and internodes, with nodes supporting sheathing organs- the dome-shaped sheaths (modified leaves), branches/ buds for branches, and leaves.

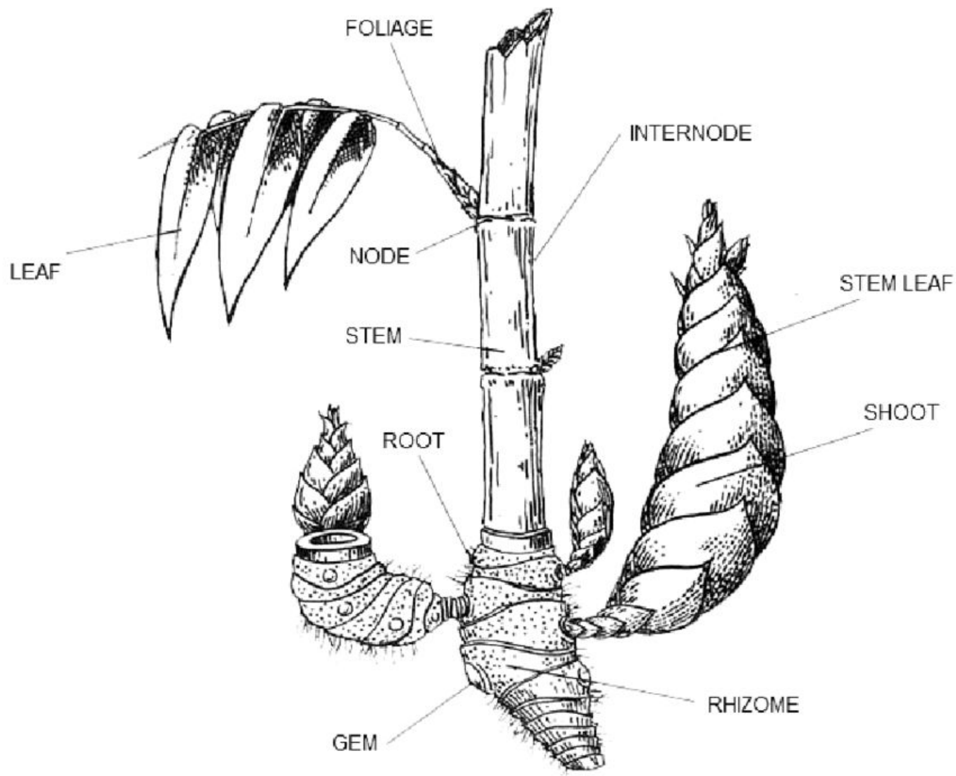

Fig. 1: Schematic of typical structure of bamboo. Source: National Mission on Bamboo Application 2004

Sheaths contain spicules across their surface which play a protective role in the initial stages of shoot growth for shoots and later for branching buds. Branches begin to grow on the main shoot after its full height is reached and supports leaves in addition to those on the main shoot. Leaves are usually linear or lanceolate, thinner than sheaths, and show marked dorsoventrality with glossy ventral side and hairy dorsal side. They are the organs of primary productivity.

The reproduction of bamboo, for most sympodial species, follows a pattern of gregarious flowering with its periodicity spanning decades (Banik 2015, Dwivedi 1988). The emergence and growth of shoots occur every year growing clonally, and the clump thus expands, with annual addition of shoots, between flowering events. Shoot growth is seasonal as it takes place only in the monsoon season, throughout which emergence and complete growth of new shoots takes place. Thus, June to November in India is broadly the growing season for bamboo with early-to-mid season emerging shoots distinctly favoured over late-season emerging shoots. The growth of shoot is set off by the formation of shoot buds on the rhizome which grows into a young conical sheath-covered fresh shoot over 2-3 weeks. At this stage the shoot is edible. When this formation reaches a height of approx. 30-40 cm, shoot growth goes into next gear with an average of 30 cm per day to reach full height in 3-5 weeks. The protective sheath unfurls at this stage and growth occurs between the apex of the cone and nodal plate below. Cell division of internodal meristematic tissue between the plate and the apex until a characteristic internodal length is reached, following which a nodal plate closes right below the apex (Banik 2015). As internodes are formed higher in the shoot, the lower ones lignify to some degree and are no longer edible. The sheaths are retained at the nodes where leaves also begin to form. When full height is reached, as mentioned, branch buds form and elongate into branches. The concentration of nutrients N, P, K, Ca, etc. peak in growing regions during this period, as does nutrient uptake and volume of water absorbed (Shanmughavel and Francis 1996). So at the end of one growing season, new shoots emerge, elongate, lignify, and branch out with leaves carrying out active photosynthesis. Then over the next 3-4 years, sheaths shed, the moisture content of shoots gradually decrease, cell-wall thickness increases, starch content decreases to facilitate the growth of other parts, and waste accumulates due to poor excrement systems. As waste accumulation causes cutoff of water and nutrient supply, the shoot deteriorates and dries off (Kleinhenz and Midmore 2001, Banik 2015).

The flowering event in gregarious type is also marked by clump deaths, so discrete generations are observed (Dwivedi 1988). The growth from seedling to clump is the growth and expansion of rhizomes belowground and shoot formation during growing seasons across years, and can be mapped out in two stages (Kaushal 2016). The first stage includes the formation of rhizome and its development from nutrients in germplasm, followed by the formation of initial shoots which can range from 1-3 (Banik 1988). These shoots are thin and do not grow to great heights, thus shoot diameter and clump size is greatly correlated at this stage. The increase in aboveground biomass is also followed by an increase in primary productivity, although leaf sizes are smaller as they are proportionate to shoot diameter. The nutrients accumulated in these shoots are used for rhizome expansion, literally laying the groundwork for shoot growth for the next growing season. The next few growing seasons see rapidly increasing clump sizes, shoot diameter, and height in the newest shoots, until shoots reach a characteristic diameter specific to the species. The clump gradually enters stage two, as the rate of annual increase in clump size and latest shoots' height reduces. shoot height and diameter are indicators of clump biomass, and clump size is expected to be by extension (Kaushal 2016). Soil conditions- soil nutrient and water availability- are critical factors for growth, although compared to dicots, the critical level for bamboo is lower (Tripathi and Singh 1994). Each year, new shoots that have completed formation act as primary reserves for clump growth, with contribution to growth reducing as they age. 1st year shoot leaves are known to be the most photosynthetically efficient, while 2nd year shoots are known to carry the most foliage. The current leading theory in shoot distribution is that new shoots emerge at a minimum distance from 1st and 2nd year shoots to minimize transport energetics (Qiu et al 1992). In any case, the emergence of new shoots is not strictly peripheral and can occur anywhere throughout the clump. Thus, over years the density and distribution of shoots itself hampers the growth of new shoots, as has been extensively demonstrated (Chaturvedi 1988, Prasad 1988). As clumps do not have too much starch storage facility, growth is heavily dependent on factors limiting photosynthesis: air temperature, rainfall, and sunlight. However, bamboos are understory plants in most forests as seedling growth is hampered by sunlight (Chaturvedi 1988).

Pachgaon (Gondpipri taluka) is a village in the Chandrapur district of Maharashtra, adjoining the Forest Reserve of Chandrapur. In 2012, the Gram Sabha of Pachgaon bought sections of the forest closest to the village, undertaking the responsibility to ensure its protection, so as to reap benefits of timber and non-timber forest products, under the Forest Rights Act, 2006. Among the NFTPs, extraction of bamboo (spp. *Dendrocalamus strictus*) contributes to a huge portion of the economy of every household, to the extent that they have formulated a 'Working Plan' for year-round harvesting, towards which every member of the village contributes.

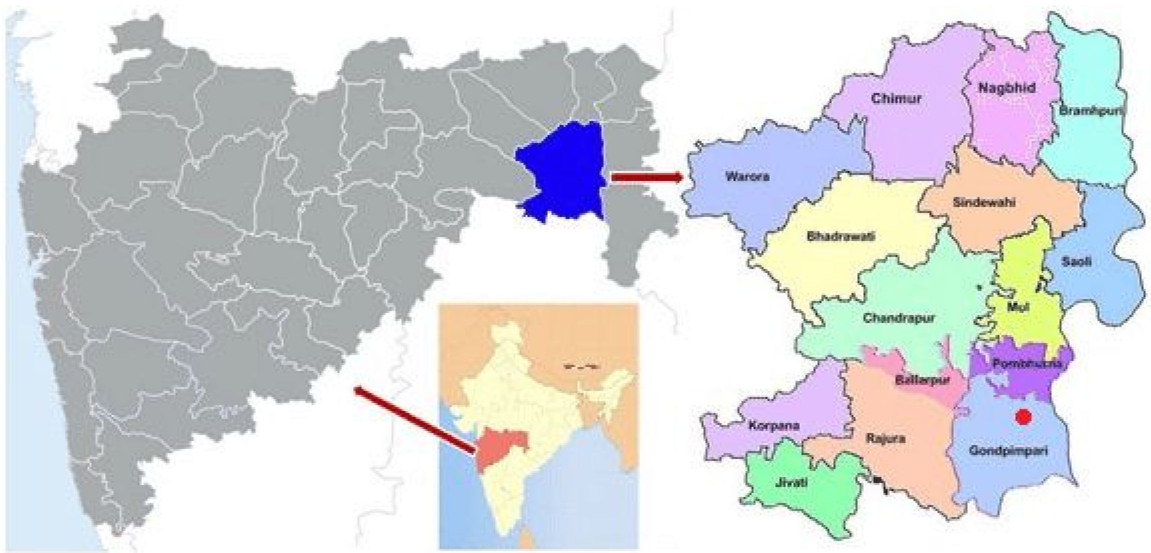

Fig. 2: Location of Pachgaon (red circle) in India.

Objectives

The basic tenet of sustainable harvest is to ensure net growth of harvested part in the long-term, which depends on the nature of growth of harvested part and the growing conditions therewith, as well as the effect of harvest on the growth (Ticktin, 2004). Based on the broad objective of evaluating the sustainability of bamboo harvest, the objectives now become the following:

- Identifying variables that could affect recruitment and growth of new shoots and collecting data for the same
- Studying the effects of harvest in the recruitment of new shoots
- Understanding the variation in clump characteristics, environmental factors, and biotic factors, and their respective roles in recruitment of new shoots
- Translating results into implementable measures in forest management

Methodology

The species: *Dendrocalamus strictus* is the most common species of Bamboo in India found, occupying around 53% of them (Kaushal et al. 2016). Mostly found in dry, deciduous forests, its spread ranges from Arunachal Pradesh to Kerala and Rajasthan to Bengal, across rainforests and savannahs. A sympodial variety of bamboo, identification keys include mature shoot height of 8-20 m, 30-45 cm internodal height, 6-10 cm diameter with thick walls. Shoot sheaths are deciduous with a characteristic dark brown shade. Shoots were identified by age as 1, 2 and 3 years based on the hue of green on the shoot, which progressively darkens, and the presence of shoot sheaths and leaves, primarily done by assisting villagers who were experienced in this regard. Although new shoots are commonly extracted for consumption across India, residents of Pachgaon extract mature shoots only for village construction utility and selling purposes.

The site: Pachgaon Jungle (19.680^{O}-19.705^{O} N, 79.509^{O}-79.535^{O} E, elevation range 107-139 ft) spanning 1006.413 ha is adjacent to Pachgaon village, Chandrapur dist., Maharashtra, India. Forests in this area are dry and deciduous. Day air temperatures fall between 38^{O}C-45^{O}C during summer and 25^{O}C-30^{O}C during winter. Rainfall usually spans between 1100 mm and 1350 mm, with monsoon humidity of around 66%.

The rules of the People's Plan coincides with recommendations known in Forest Management circles for a few decades, outlined in Prasad (1988) among others, and they are stated below:

- Shoots younger than 3 years of age shall not be cut.
- Shoots will be cut at a height of ~30 cm from the ground.
- Harvesting will take place year round except during the growing season.
- A felling cycle of 3 years will be employed (3-6 years recommended).
- No fires should be caused by the residents, and natural fires should be curbed as much as possible.
- Grazing should be minimized in bamboo heavy areas during the growing season.

Permission to carry out the study was granted by Pachgaon Gram Sabha in May, as long as harvest under the Working Plan was not disrupted. This determined the period of data collection and to an extent also the variables to be collected.

Harvesting takes place across the forest (Fig. 3) in a 3-year cycle across 3 sections of the forest, so each year harvesting is carried out in one of these sections. The growing season is June to November, during which harvesting does not take place. Towards the end of each growing season, time and resources are devoted to preparing smooth routes (thin roads where all vegetation has been cleared) along the boundaries of each section or *tapu*, as seen in Fig. 3, to ease transportation of harvested bamboos during harvest. Data could not be collected during the harvest period and was collected from mid-July to end-of-September of 2018.

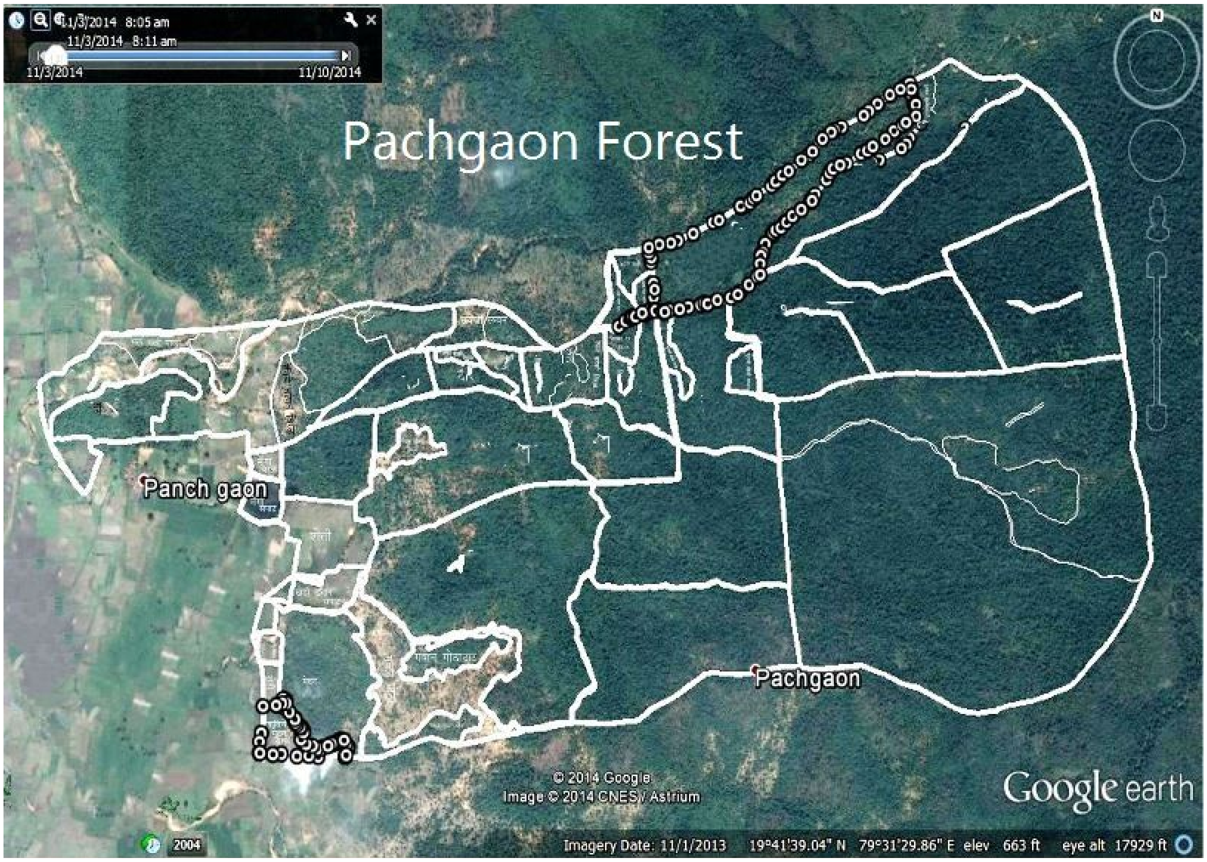

Fig 3: Site map - Pachgaon forest. Source: Gram Sabha, Pachgaon.

As visible on the site map, there is a gradient of forest density increasing from left (sites closest to the village) to right. A census was done in 2014 of all the vegetation across the entire forest, and based on that sections are classified as high density, medium density and low density. However, this census data proved inaccessible to be able to determine the quantitative basis for this classification. Since 2012, certain areas were declared to be 'no harvest' zones, where grazing and NTFP extraction was banned (areas in open circles in Fig. 3). Plots were selected for data collection based on density and harvest cycle as summarized in Table 1.

Harvest cycle status	Density		
	Low	Medium	High
2017-2018 (-1)	-	1 (60 clumps)	1 (60 clumps)
2016-2017 (-2)	1 (60 clumps)	1 (60 clumps)	1 (59 clumps)
2015-2016 (-3)	1 (57 clumps)	1 (60 clumps)	1 (60 clumps)
Unharvested (U)	1 (60 clumps)	1 (60 clumps)	1 (60 clumps)

Table 1: Selection of plots based on harvest cycle status and density type.

Note: -1, -2, -3 will hereby refer to the groups of clumps harvested the year before this study, two years before this study, and three years before this study, respectively. U will represent the group of unharvested clumps.

Variables of study: Taking into account the nature of growing cycle and under aforementioned constraints of non-invasive approach, the variables determined to most affect shoot recruitment were:

a) Clump characteristics related to growth and biomass:

1. Age-based distribution of shoots: Based on age from status of sheaths/leaves and hue of shoot, 1 year old shoots, 2 year old shoots, 3 year old shoots, and dry (3+ year old) shoots were counted in the first phase of data collection (see below). During the second phase, number of new shoots per clump also joined this data. This is one estimate of clump biomass, and due to differential productivity of shoots based on their age this could also inform us of ideal shoot age distributions.

2. Clump size: These are estimators of biomass and, to a lesser degree, clump age. Three metrics of this was collected:

Clump circumference: The basal circumference of each clump was collected by tape.

Clump width: Since clump basal shape varied from circular to elliptical, the basal width of each clump was also collected in case it affects shoot recruitment differently from clump circumference. This was also measured by tape.

Clump height: For this the height of a one year old shoot in each clump was estimated. The method of estimation was trigonometric, where the estimate and the formula to calculate actual shoot height is described in Fig. 4.

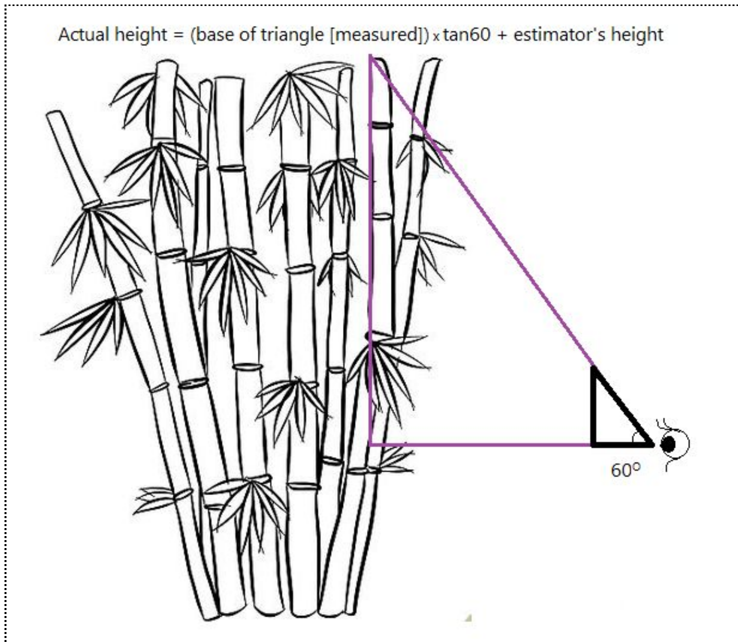

Fig. 4: Method of height estimation. Black triangle represents the instrument used, while the purple triangle is it's projection onto the clump.

3. Growth rate of new shoots: In the second phase of data collection, the growth of all new shoots was monitored in 4-5 day intervals for a month. This was done only in high and medium density plots.

b) Environmental factors affecting photosynthesis and growth:

4. Sunlight: To measure sunlight availability to clumps, a semi-quantitative measure of canopy closure was collected. A score of 1-5 (1=scarce lateral sunlight, 5=complete exposure to sunlight) was given based on the Clark-Clark method shown in Fig. 5 (Clark and Clark 1992).

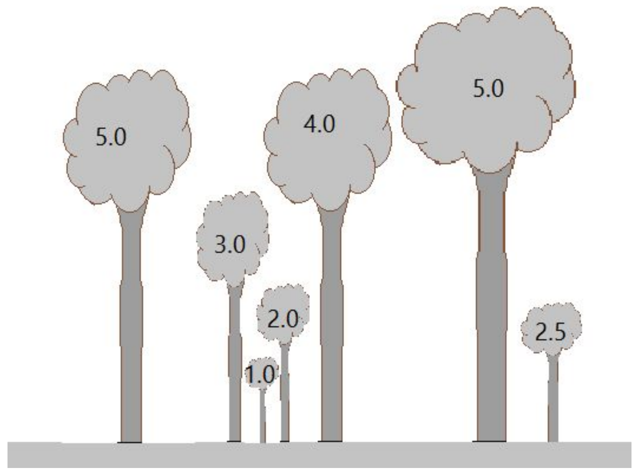

Fig. 5: The Clark Clark method of canopy closure estimation. 5 represents complete exposure from all sides and 1 represents complete closure from all sides.

5. Disturbance: The disturbance due to the harvest regime happens mostly along the routes between sections in Fig. 3. So distance from routes was thought to be the best measure of disturbance to explore its effect on new shoots. A GIS based approach was used, with each clump position being recorded and all routes being tracked on GPS files.

6. Water availability: Apart from the near uniform water availability during the growing season, any non-uniform access to water would cause variation in year-round productivity and, in turn, in shoot recruitment. The only measurable proxy for this was the distance from surface water. This was again measured on GPS files with positions of clumps and closest flowing water routes being recorded.

7. Soil properties: Soil properties are a major aspect of growing conditions. Soil from each site was collected for analysis of pH, Electrolyte Conductivity, Organic Carbon content, $CaCO_3$ content, N content, P content, K content, Micronutrients, Bulk density, Water holding capacity, Hydraulic conductivity, and Texture. Analysis was carried out in the College of Agriculture, Pune.

c. Biotic factors:

8. Shoots previously harvested: Under rule 2 of the People's Plan, there were remnants of previous harvest which could be counted for each clump. This was collected per clump to test whether this measure of the effect of harvest affected shoot recruitment.

9. Herbivory: Boars, monkeys, and a few insects consume edible bamboo prior to lignification. During the second phase of data collection, the number of shoots eaten in each clump, our measure of herbivory, was noted to check the effects of density and harvest on the extent of herbivory.

Throughout data collection period, I was assisted by members of the village. These members accompanied me to the forest, helped with measurements, informed me about their harvest regime, and provided information about observed patterns (based on their traditional knowledge) in bamboo growth, all of which was invaluable to the process. Data collection was carried out in two phases. During the first phase, the data of all clump-related variables that wouldn't change during growing season was documented between July 15th and August 10th based on availability of said village members. The second phase took place between August 26th and September 29th, during which data regarding shoot recruitment, growth of new shoots, and herbivory was monitored for high and medium density plots. For this, an initial round of measurement involved tagging new shoots over 2 weeks, and for the rest of the period, 2 out of the 8 plots were visited each day and emergence of new shoots, the increment in height, and herbivory was collected. When under 2 m, height was measured by tape, and above that it was measured by the method outlined in Fig. 4. While all data collected in the second phase was not collected for the entire growing period, but rather for a 1 month period, it is believed to represent the peak of the growing season. Also, because late emerging shoots are known to be unsuccessful in growth, shoot recruitment values will be accurate in most cases. Along with this, soil sample from each plot was also collected (variable 9) for analysis.

Tools and techniques: For data collection, apart from simple tools like measuring tape and height estimator- a 30-60-90 triangle made using sticks, the only other tool used was the GPS Essentials app © (MacLeod 2015) for tracking routes and recording clump positions and surface water locations in GPS files. QGIS 3.4 was used to extract distance data per clump for water availability and disturbance. The soil analysis of the collected soil samples was outsourced to the SLA dept. in College of Agriculture, Pune.

Data analysis began with initial exploration of the effects of harvest and density on clump characteristics, to shed light on the significance of the available variation in the two factors and the degree of their effect on present clump characteristics, and possibly clump expansion. Descriptive statistics and two-way ANOVAs with density and harvest factors were done for clump size, but only the former for shoot age distribution which contains an additional dimension of shoot ages. Next, the effect of density and harvest cycle status on herbivory was examined to see if these factors also affected agents of herbivory, again using two-way ANOVAs. Following this, the question of whether recently harvested clumps show any differences in clump growth compared to other clumps, and how this response varies with density was asked. For this, shoot recruitment and clump growth for different density and harvest cycle status were compared using two-way ANOVAs. All two-way ANOVAs were carried out on Statistica 8, and were followed up by an Unequal N HSD test when necessary. A note of clarification: exploring the effect of harvest is essentially comparing clumps in harvested sites against those in unharvested sites (i.e two groups), whereas the effect of harvest cycle status refers to when the clump last experienced harvest which is in four groups (-1, -2, -3, U). Plots were generated using Matplotlib (Hunter, 2007). With this done, shoot recruitment was correlated with other variables using Type II linear regressions since in each case both variables are measured. This was done on R 3.5.1 using the R package lmodel2 (Legendre and Legendre, 2012), and the recommendations therein suggested the use of Ranged Major Axis method of Type II regression. The regression coefficient changes accordingly and confidence intervals for slopes were set at 95%. A multiple comparison correction was applied when testing significance.

Results and Discussion

A. Effects of Density and Harvest on Clump Characteristics:

a. Shoot age distribution: Fig. 6 shows mean shoot count of each shoot age for clumps in each density- harvest combination. Shoot recruitment here is the number of surviving new shoots. The simplest perceivable pattern is the greater count of 3 year and dry shoots in unharvested regions compared to harvested regions of the same density, which can be easily explained by the Working Plan's first rule. There is also a decline in shoot count with decreasing order of age, and the degree of decline is greater as density decreases. This either suggests that clump expansion is near saturation, or possibly brings into question the accuracy of the morphological keys used to distinguish shoots by age. It is possible that shoot lifespan, which is a function of waste accumulation in shoots, could vary with density thus giving higher number of '3 year old shoots' which might actually be 3+ year old shoots depending on lifespan in low densities. In any case, given that mean shoot recruitments seem comparable, more standing biomass is needed in clumps for shoot recruitment for low density sites than others.

b. Clump Size: Fig. 7 shows mean clump sizes for a) circumference, b) width, and c) height for each density-harvest combination. The similarity in mean and standard error patterns in circumference and width suggests that most clumps have a similar ellipticity so either one measure of lateral clump size is sufficient. Additionally, despite the two-way ANOVA showing a density x harvest interaction effect in both cases, there is no clear pattern along the gradients. In the case of height, however, there is a clear

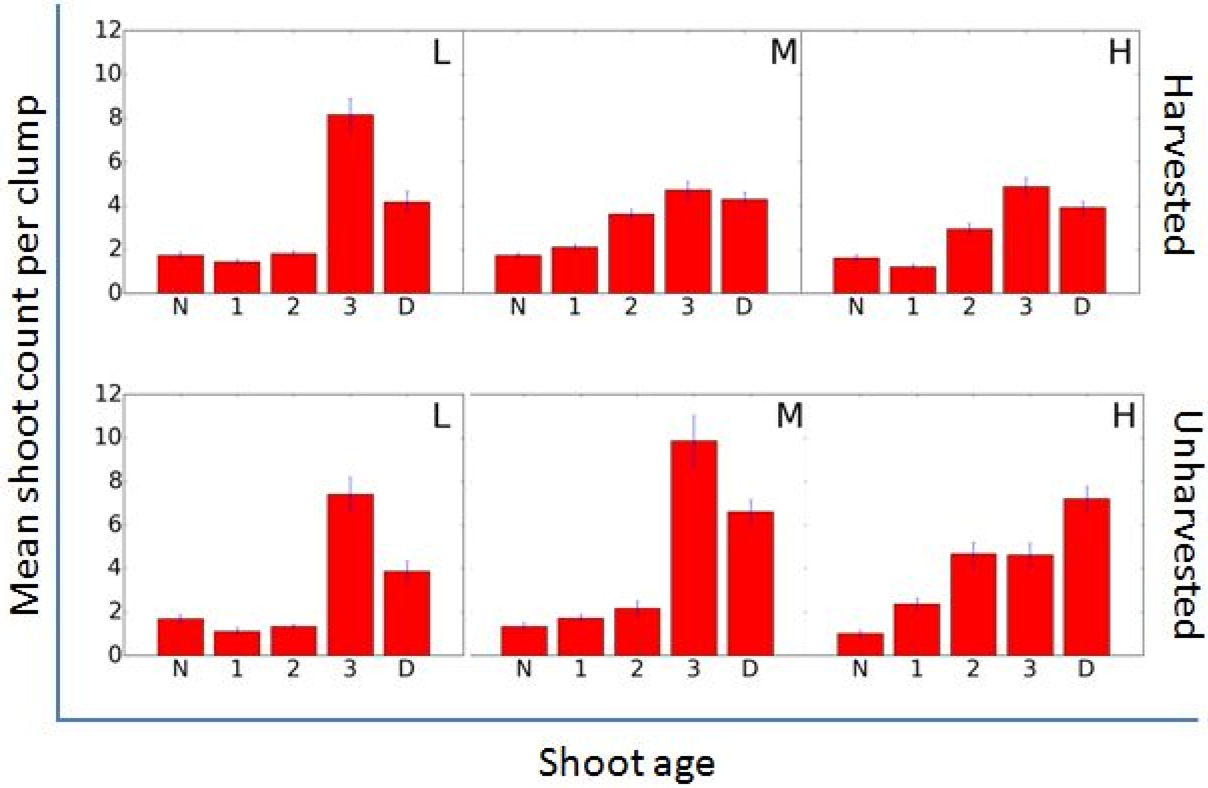

Fig. 6: Mean shoot count per clump for each shoot age for harvested (upper) and unharvested (lower) sites. L, M and H refers to low, medium, and high density, respectively. N refers to new shoots, 1-3 refer to the respective shoot ages, and D refers to dry shoots. n = 117 for low density harvested sites, 180 for other harvested sites, and 60 for all unharvested sites. Error bars represent SEMs.

density-based effect. So clumps of similar lateral sizes have taller shoots in high density regions. A possible explanation is that canopy height dictates height of new shoot, but if this is true the insignificant differences in means of shoot recruitment across densities suggests that there is no trade-off in biomass partitioning.

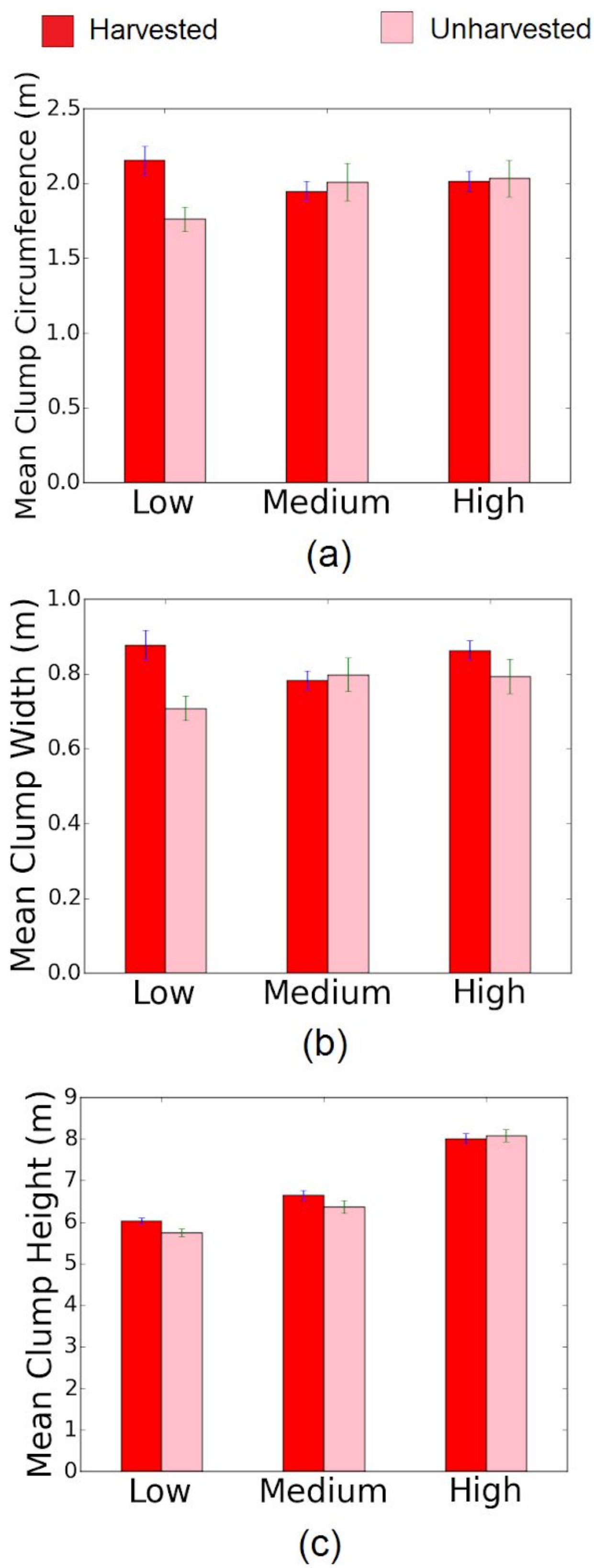
Harvested
Unharvested
Mean Clump Circumference (m)
2.5
2.0
1.5
1.0
0.5
0.0
Low
Medium
High
(a)
Mean Clump Width (m)
1.0
0.8
0.6
0.4
0.2
0.0
Low
Medium
High
(b)
Mean Clump Height (m)
9
8
7
6
5
4
3
2
1
0
Low
Medium
High
(c)

Fig. 7 (prev. page): Mean clump sizes for low, medium, and high densities. For each case, n = 117 for low density harvested sites, 180 for other harvested sites, and 60 for all unharvested sites. (a) shows clump circumference means, (b) shows clump width, (c) shows clump height. Error bars represent SEMs.

Effect	Effects significance (p-values) on clump size		
	Circumference	Width	Height
Density	NS	NS	**
Harvest	NS	NS	NS
Density x Harvest	**	**	NS

Table 2: ANOVA results for effects of Density and Harvest on Clump sizes. ** implies $p<0.05$, NS = not significant.

B. Effects of Density and Harvest Cycles on Herbivory:

Fig. 8 shows mean count of eaten shoots within the data collection period against harvest cycle status across densities. An Unequal N HSD post hoc (Table 3) shows that few means of consecutive harvest cycle statuses (-1 to -2, -2 to -3, etc.) are significantly different from one another. Although in almost all cases, for the same harvest cycle status, the means of medium and high density sites are significantly different. So clumps in high density are more susceptible to herbivory. However, compared to harvested regions, unharvested regions have far less human disturbance so herbivory is expected to be higher here than in harvested regions, which is seen in the medium density U site. However, the same is not seen in high density sites.

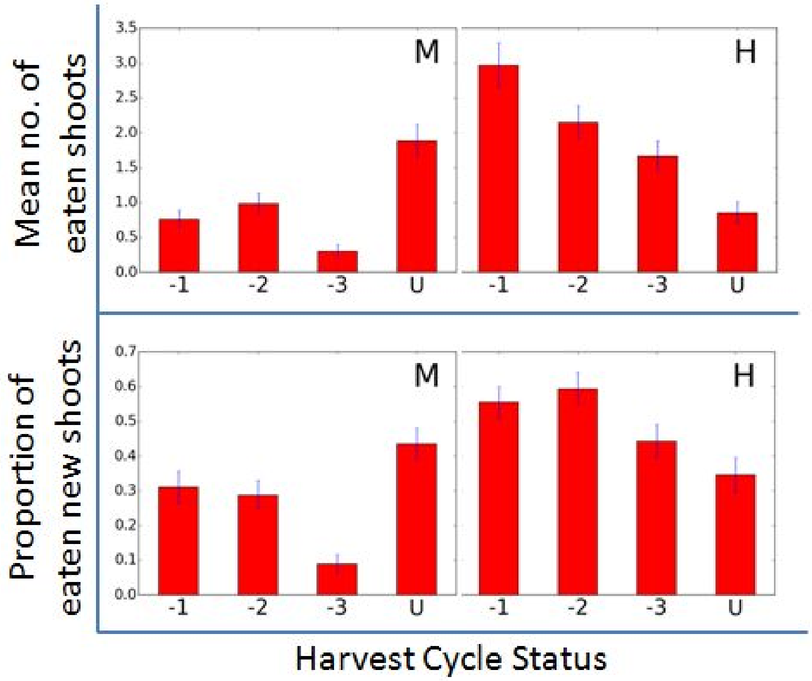

Fig. 8: Mean herbivory per clump (upper) and mean relative herbivory [no. of eaten new shoots/no.of emerged shoots] (lower) for all harvest cycle status. M and H refers to medium and high density respectively. n ~ 60 in each case. Error bars represent SEMs.

(D,H)	(H,-3)	(M,-3)	(H,-2)	(H,-2)	(H,-1)	(M,-1)	(H,U)	(M,U)
(H,-3)		**	NS	NS	**	**	NS	NS
(M,-3)	-		**	NS	**	NS	NS	**
(H,-2)	-	-		**	NS	**	**	NS
(M,-2)	-	-	-		**	NS	NS	**
(H,-1)	-	-	-	-		**	**	**
(M,-1)	-	-	-	-	-		NS	**
(H,U)	-	-	-	-	-	-		**
(M,U)	-	-	-	-	-	-	-	

Table 3: ANOVA Unequal N HSD post hoc results for effects of Density and Harvest on herbivory. All density-harvest combinations are compared with each other. ** implies p<0.05, NS = not significant.

Escape height- An alternative anti-herbivory formulation was explored with the following idea. Given an understanding of shoot growth within a growing season, it was reasoned that herbivory might be based on shoot availability, so when the shoot reaches a possible height, it might be inaccessible for consumption. Fig. 9 shows a distribution of the proportion of new shoots eaten at a given height to all shoots crossing that height. Within the first 0.5 m of emerging, around 25% of all emerging shoots recorded were eaten. Any shoot that reaches 3 m has a less than 1% chance of being eaten, so one can think of this as an Escape Height from herbivory. This could be the lignification of lower parts of the shoot, or could even be spatial inaccessibility for the herbivores.

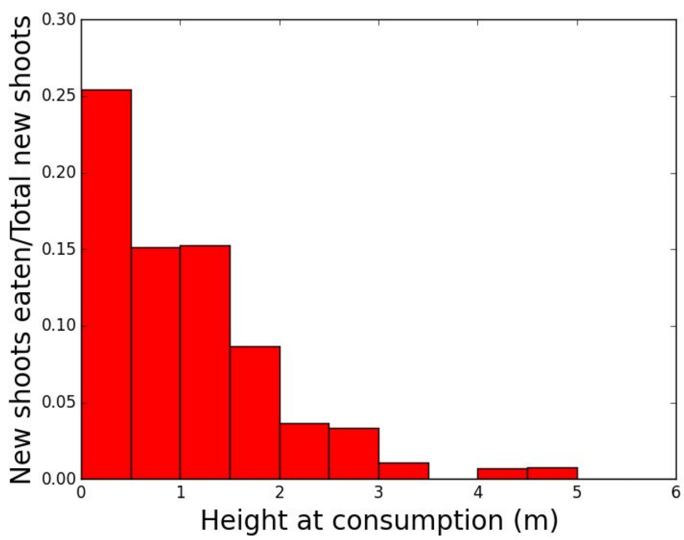

Fig. 9: Proportion of shoots eaten across heights reached by shoots. Height intervals in increments of 0.5 m.

C. Effects of Density and Harvest Cycles on Shoot Recruitment:

Fig. 10(a) shows mean count of shoot recruitment as total new shoots emerged per clump and Fig. 10(b) shows mean shoot growth rate per day, across each density-harvest cycle combination. For shoot recruitment, significant differences can be seen across densities, harvest cycle status, as well as an interaction effect. An Unequal N HSD post hoc test (table 4) reveals that the high density -1 mean is significantly higher above other means. This was not seen in shoot growth rate. So in high density sites, there is an increase in the number of new shoots in the growing season of the year following harvest. This implies a compensatory clump growth as a response to harvest in high density sites alone, and no significant differences in medium density sites.

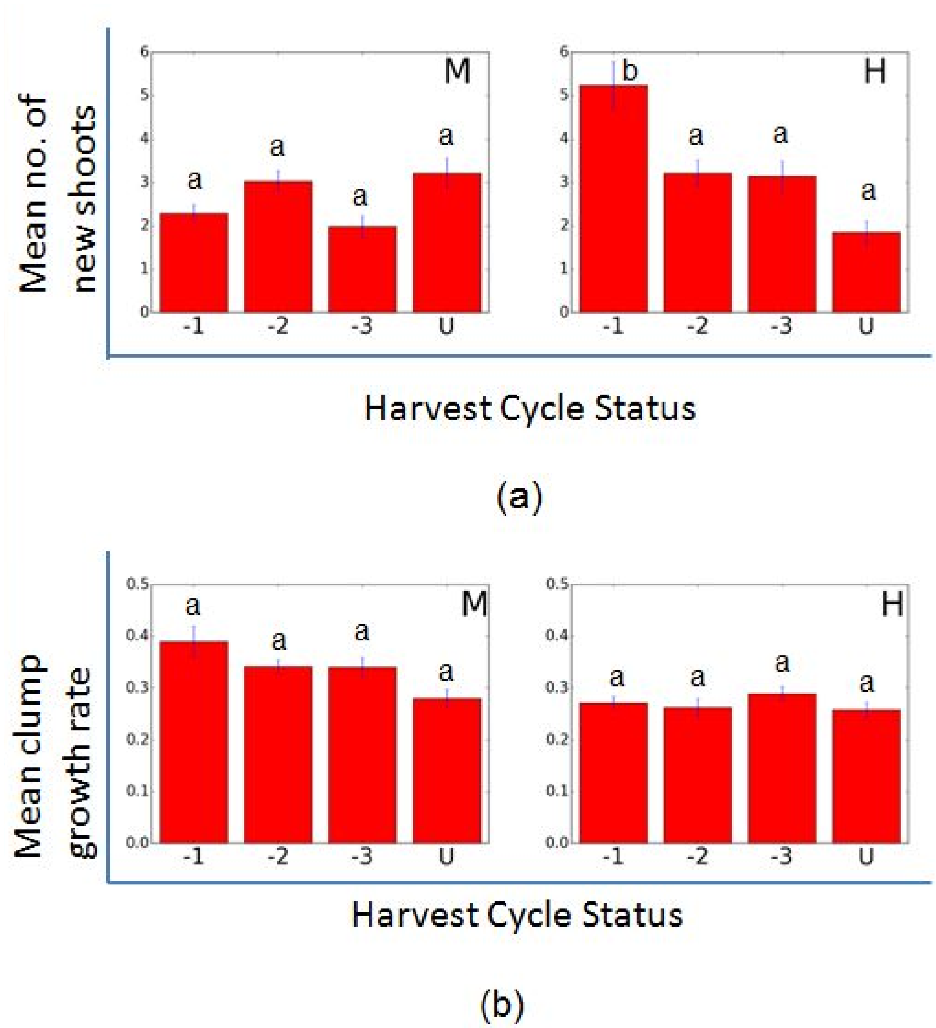

Fig. 10: (a) Mean shoot recruitment per clump and (b) mean growth rate (lower) for all harvest cycle status. M and H refers to medium and high density respectively. n ~ 60 in each case. Error bars represent SEMs. Post hoc results are synbolized based on table 4.

(D,H)	(H,-3)	(M,-3)	(H,-2)	(H,-2)	(H,-1)	(M,-1)	(H,U)	(M,U)
(H,-3)		NS	NS	NS	**	NS	NS	NS
(M,-3)	-		NS	NS	**	NS	NS	NS
(H,-2)	-	-		NS	**	NS	NS	NS
(M,-2)	-	-	-		**	NS	NS	NS
(H,-1)	-	-	-	-		**	**	**
(M,-1)	-	-	-	-	-		NS	NS
(H,U)	-	-	-	-	-	-		NS
(M,U)	-	-	-	-	-	-	-	

Table 4: ANOVA Unequal N HSD post hoc results for effects of Density and Harvest on shoot recruitment. All density-harvest combinations are compared with each other. ** implies $p<0.05$, NS = not significant.

D. Shoot recruitment correlates:

Since there are density and harvest cycle status based effects in shoot recruitment, regressions of other variables on shoot recruitment were done for each combination. Tables 5-10 describes regression parameters of type II regressions of these variables on shoot recruitment.

a. Clump size: Table 5 and table 6 describe regression parameters of clump circumference and clump height respectively with shoot recruitment. Clump circumference correlates well with shoot recruitment in all density-harvest cycle combinations as expected. The slope of regressions in high density plots for -1 site is higher than the others, which gives a quantitative estimate of compensatory growth based on existing biomass. What is of note here, though, is that the slopes of regressions in high densities decreases with increase in temporal proximity to harvest, and those of low densities show the opposite trend, illustrated in Fig. 11. Clump height also correlates well with shoot recruitment in all density-harvest cycle combinations bar two: (M,-1) and (D,-2). This, given that height varies across densities, seems arbitrary.

Circ.	**Low density**				**Medium density**				**High density**			
	n	p	r	m	n	p	r	m	n	p	r	m
-1					60	**	0.66	1.71	59	**	0.68	2.34
-2	60	**	0.64	1.47	60	**	0.63	1.82	60	**	0.52	2.08
-3	57	**	0.73	1.58	59	**	0.7	2.13	59	**	0.73	1.44
U	60	**	0.65	2.70	60	**	0.7	1.56	60	**	0.55	1.30

Table 5: RMA regression parameters for circumference vs. shoot recruitment. n - sample size, r - correlation coeff., m- slope. ** implies p<0.05/11, NS = not significant.

Height	**Low density**				**Medium density**				**High density**			
	n	p	r	m	n	p	r	m	n	p	r	m
-1					60	**	0.66	1.71	59	**	0.68	2.34
-2	60	**	0.64	1.47	60	**	0.63	1.82	60	**	0.52	2.08
-3	57	**	0.73	1.58	59	**	0.7	2.13	59	**	0.73	1.44
U	60	**	0.65	2.70	60	**	0.7	1.56	60	**	0.55	1.30

Table 6: RMA regression parameters for height vs. shoot recruitment. n - sample size, r - correlation coeff., m- slope. ** implies p<0.05/11, NS = not significant.

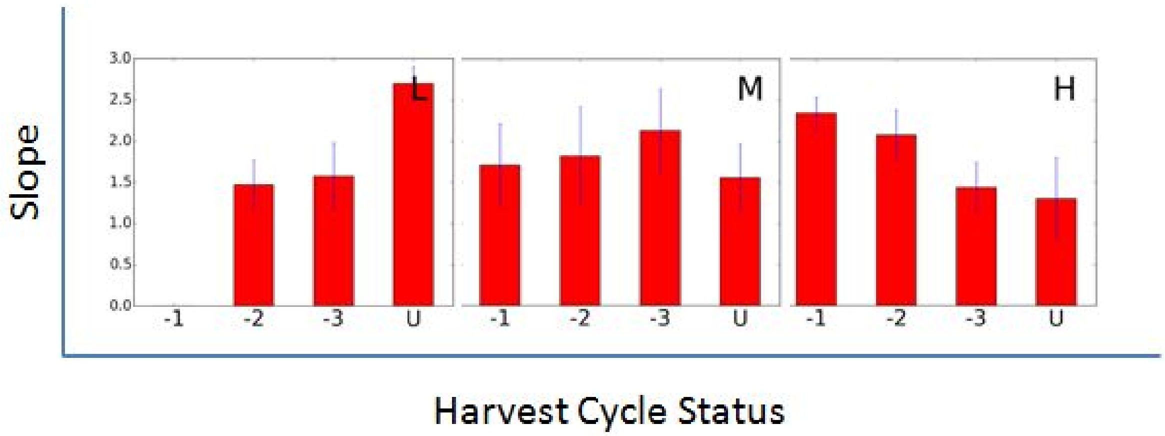

Fig. 11: Slopes of circumference vs shoot recruitment across harvest cycle status, across density. L, M and H refers to low, medium, and high density, respectively. n ~ 60 in each case. Error bars represent 90% (5,95) confidence interval of slopes.

b. Environmental factors: Tables 7, 8 and 9 describe regression parameters for sunlight, water availability and disturbance respectively. Water availability and disturbance do not seem to have any effect on shoot recruitment. This is likely because the proxies of water availability and disturbance used here, distance from surface water and distance from routes respectively, do not effectively capture these quantities. Light, however, correlates well with shoot recruitment in most cases. Oddly, light shows weak correlations in two of the high density sites, whereas light is expected to be a limiting factor in these sites. Soil properties' regression parameters with site means of shoot recruitment are summarized in table 10. None of them showed significant correlations with shoot recruitment, although they are important factors for bamboo growth. The variation in samples might not be enough to cause great variation in shoot growth across sites.

Height	Low density				Medium density				High density			
	n	p	r	m	n	p	r	m	n	p	r	m
-1					60	**	0.547	3.18	59	**	0.47	10.7
-2	60	**	0.55	2.48	60	NS	0.23	7.12	59	NS	0.24	6.34
-3	57	**	0.38	3.76	59	**	0.4	7.09	59	**	0.56	2.85
U	60	**	0.6	2.09	60	NS	0.36	4.69	60	NS	0.34	4.21

Table 7: RMA regression parameters for sunlight vs. shoot recruitment. n - sample size, r - correlation coeff., m- slope. ** implies p<0.05/11, NS = not significant.

Height	Low density				Medium density				High density			
	n	p	r	m	n	p	r	m	n	p	r	m
-1					59	NS	-0.07	-3.05	54	NS	0.25	0.67
-2	60	NS	0.14	0.72	60	NS	-0.02	-8.13	59	NS	-0.09	-1.15
-3	56	NS	-0.26	-0.68	59	NS	0.05	0.16				
U	57	NS	-0.16	-0.05	51	NS	-0.07	-2.4	60	NS	-0.31	-0.04

Table 8: RMA regression parameters for water availability vs. shoot recruitment. n - sample size, r - correlation coeff., m- slope. ** implies p<0.05/11, NS = not significant.

Height	Low density			Medium density			High density		
	n	p	r	n	p	r	n	p	r
-1				59	NS	0.03	54	NS	-0.14
-2	60	NS	-0.16	60	NS	-0.04	59	NS	-0.07
-3	56	**	-0.45	59	NS	-0.03			
U	57	NS	0.16	51	NS	0.03	60	NS	-0.2

Table 9: RMA regression parameters for disturbance vs. shoot recruitment. n - sample size, r - correlation coeff., m- slope. ** implies p<0.05/11, NS = not significant.

Soil properties	Units	p	r
pH		NS	-0.45
Electrolyte Conductivity	dS/m	NS	0.66
Organic Carbon	%	NS	-0.21
$CaCO_3$	%	NS	0.45
N	kgh/a	NS	0.03
P	kgh/a	**	-0.01
K	kgh/a	NS	-0.60
Fe	ppm	NS	0.68
Mn	ppm	NS	0.10
Zn	ppm	NS	0.19
Cu	ppm	NS	-0.06
Bulk density	g/cm^3	NS	0.28
Water holding capacity	%	NS	0.58
Hydraulic conductivity	cm/hr	NS	0.48

Table 10: Linear regression parameters of plot soil properties with mean site shoot recruitment.

Conclusions and future directions:

To the end of sustainable bamboo growth under a harvest regime, this study has the following suggestions that could lead to an increase in long term harvest gains-

1. Anti-herbivory measures: The formulation of escape height for *D. strictus* that has been done here could be used as the basis for a cost-benefit analysis for protective measures around clumps. The sample here suggests that even a 1 m long structure could would effectively result in a 20% increase in number of new shoots. This profit can be weighed against the investment in protecting clumps, particularly those in high density sites.

2. Density-based modification of harvest practices: On the basis of compensatory growth seen in high density patches here, period of harvest cycle should be reduced in high density plots to check whether the same compensatory growth is still seen. It might turn out to be quite profitable if high density plots are harvested every year instead of every three years. In the case of low density plots, where harvest has a negative impact for shoot recruitment and the three-year cycle might not be optimal. The quantitative differences in shoot recruitment across harvest cycle status for low density can be used to model clump expansion in low density conditions to determine an optimal harvest cycle period, though this could not be done here.

An additional recommendation from this study that might amend our understanding of clump expansion in *D. strictus*: studying accuracy of morphological keys for shoot age across densities. That might help answer if rates of biological processes involved in clump expansion are independent of density, which is an assumption in Traditional Ecological Knowledge currently and was an assumption for this study.

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