

1 **Phytolith analysis reveals the intensity of past land use change in the Western Ghats biodiversity**  
2 **hotspot**

3 Sandra Nogué<sup>1,2\*</sup>, Katie Whicher<sup>1</sup>, Ambroise G Baker<sup>1,3</sup>, Shonil A Bhagwat<sup>1,4</sup>, Kathy J Willis<sup>1,5,6</sup>

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5 <sup>1</sup>*Long-Term Ecology Laboratory, Biodiversity Institute, Department of Zoology, University of Oxford,*  
6 *Oxford, United Kingdom.*

7 <sup>2</sup>*Geography and Environment, University of Southampton, Highfield, Southampton SO17 1BJ, UK*

8 <sup>3</sup>*Environmental Change Research Centre, Department of Geography, University College London,*  
9 *London, United Kingdom.*

10 <sup>4</sup>*Department of Geography, The Open University, Walton Hall, Milton Keynes, United Kingdom.*

11 <sup>5</sup>*Department of Biology, University of Bergen, Bergen, Norway*

12 <sup>6</sup>*Royal Botanical Gardens, Kew, Richmond, Surrey, United Kingdom.*

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17 **Corresponding author:** *Geography and Environment, University of Southampton, Highfield,*  
18 *Southampton SO17 1BJ, UK. Sandra Nogué, [s.nogue-bosch@soton.ac.uk](mailto:s.nogue-bosch@soton.ac.uk)*

19 *Tel:*

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25 **Abstract**

26 This paper presents a study of phytoliths (opal silica bodies from plants) from sediment sequences  
27 obtained from two tropical forest patches in the Western Ghats of India: a sacred grove (sequence  
28 covers last 550 cal years BP) and a forest patch in a plantation (sequence covers last 7500 cal years  
29 BP). The sites are located at mid-elevation (c. 650- 1400 m above sea level) in a mosaic landscape  
30 showing anthropogenic open habitats as well as some evergreen forests. The aim of this paper is to  
31 evaluate the landscape composition of grassland and forest over time in the region, grassland being  
32 invariably shaped by anthropogenic activities, particularly fire for cultivation. We identified and  
33 classified phytoliths into 34 morphotypes from five taxonomic groups: Poaceae (grasses),  
34 Cyperaceae (sedges), Arecaceae (palms), Pteridopsida (ferns) and woody dicotyledons (broad-leaved  
35 trees and shrubs). We also calculated the humidity-aridity index (Iph). First, our results show that  
36 grasses are the most represented phytolith types in both sites, followed by broad-leaved trees and  
37 shrubs, palms, sedges, and ferns. Second, the highly variable climatic index Iph over the last 1000  
38 years suggest that changes in phytolith percentage (e.g. broad-leaved trees) might be caused by  
39 human agro-pastoral activities, such as clearing through fires and irrigation. Prior to these human  
40 activities, the phytolith signal for early Holocene climate is congruent with the existing literature.  
41 Finally, this study compares new phytolith results with previous pollen data from the same sites. We  
42 find good agreement between these two botanical proxies throughout, thus validating our findings.  
43 We provide important evidence regarding the history of environmental change due to  
44 anthropogenic activities in the Western Ghats. This has important implications because it provides  
45 insights into how tropical forest will respond to increased intensity of human activities.

46 **Keywords:** land-use change, local dynamics, Holocene, Phytoliths, tropical forest, Western Ghats

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## 49 **1. Introduction**

50 Recent palaeoecological studies in the Western Ghats of India have analysed fossil pollen grains and  
51 charcoal time-series to show the importance of grassland-forest dynamics in a human modified  
52 landscape (Bhagwat et al., 2012; Bhagwat et al., 2014). However, it is desirable to consolidate these  
53 findings with an independent line of evidence and with an improved taxonomic identity of grasses  
54 (Poaceae) and broad-leaved trees to better understand the dynamics of the whole system.

55 The origin of mid-elevation (c. 650- 1400 m a.s.l) grasslands vegetation mosaics in the Western Ghats  
56 remains controversial because the date of initial forest removal for agricultural purposes is  
57 unattested. It is believed to be around 6000 and 3500 cal years BP (Caratini et al., 1994) but earlier  
58 agricultural activities might have existed in the region throughout the Holocene (Caratini et al., 1994;  
59 Chandran, 1997). It remains difficult to ascertain using pollen studies alone (e.g. Bhagwat et al. 2012,  
60 2014) whether the grassland-forest dynamics are solely induced by human activities. . Therefore,  
61 using phytolith as a proxy here we consolidate the understanding of landscape dynamics in the mid-  
62 elevation forest-grassland mosaics of the Western Ghats of India.

63 Except for a few cultivated grass species corresponding with cereal grains, the identification of  
64 grasses in temporal sediment sequences has always been a challenge in palaeoecology due to the  
65 limitations in identifying fossil pollen grains at sub-family level (Fearn, 1998). However, grasses are  
66 excellent environmental indicators (Ghosh et al., 2011) and they also give information on dominant  
67 photosynthetic pathways (C3 or C4 grasses) that can be directly interpreted in terms of  
68 environmental and climatic conditions (Edwards et al., 2010; Gu et al., 2008; Strömberg, 2011).

69 Phytoliths, the opaline silica bodies precipitated in or between cells of plant tissues, form a useful  
70 proxy because provide additional information about changes in grass diversity over time that pollen  
71 grains alone do not. This information can provide further insights into whether the presence of  
72 grassland in landscape mosaics is due to human activities, environmental causes or purely climatic  
73 factors.

74 Phytoliths, provide robust information about identification of grasses often to subfamily level  
75 (Piperno, 2006). For example, phytoliths have been successfully applied in palaeoecology and  
76 archaeology to understand the consequences of slash-and-burn agricultures on vegetation (Piperno,  
77 1989), to reconstruct humidity, temperature, and aridity (e.g Bremond et al., 2005, 2008), and to  
78 understanding diet and past plant uses (e.g Harvey and Fuller, 2005; Saul et al., 2013). Moreover,  
79 one of the main advantages of using phytoliths in multiproxy studies lies in their size, rate of  
80 transport, and resistance to fire and changes in pH (e.g. Harvey and Fuller, 2005; Aleman et al., 2014;  
81 Cabanes et al., 2015). This is particular useful when studying disturbed ecosystems such as the  
82 human-dominated landscape of the Western Ghats (Ranganathan et al., 2008).

83 The aim of this paper is to improve our understanding of the landscape composition of grassland and  
84 forest over time at mid-elevation evergreen forests in the Western Ghats of India using the analysis  
85 of phytolith assemblages. The key question we are interested in answering is: what impact does the  
86 increased intensity of human activities have on the Western Ghats landscape?

87 Our objectives are:

88 -Analyse the phytolith record for two cores from mid-elevation forest patches in the  
89 Western Ghats region.

90 -Compare this phytolith record with previously published pollen record from the same cores  
91 in order to improve our understanding of grass diversity and abundance over time.

92 -Discuss the nature and magnitude of anthropogenic and climatic vegetation changes on the  
93 basis of the phytolith and pollen record at local scale and regional scale.

94 An accurate knowledge of forest-grassland dynamics in the region will improve our understanding of  
95 human activities in the past, which has important implications because it provides insights into how  
96 the tropical forest will respond to increased intensity of human activities in the future.

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98 **2. Regional setting**

99 The Western Ghats of India was amongst ten regions in the world to be first identified as tropical  
100 forest 'hotspots' by Norman Myers in 1988 (Myers et al., 2000). The study site was located in the  
101 southwestern part of Kodagu district, Karnataka state in Southern India. The landscape in the study  
102 sites is comprised of paddy cultivation in low-lying valleys, agroforestry systems on hill slopes, and  
103 tropical forest patches. Among the forest patches, some are considered sacred groves, which are an  
104 example of community-based conservation. In this phytolith study we extracted two sedimentary  
105 cores from small wet forest hollow on the forest patch at the Bopaiah plantation (BOP, 12° 9' 14"N,  
106 75° 42' 47.002"E) and on the Mythadi sacred grove site (MY, 12° 13' 13" N, 75° 47' 31" E), at 910  
107 and 879 m a.s.l, respectively. BOP was a 172 cm sedimentary core extracted from a relatively flat  
108 foothill forest patch in a coffee (*Coffea arabica var. robusta*) and betelnut palm (*Areca catechu*)  
109 plantation. The MY sedimentary core was 44 cm in length and extracted from a sacred grove within  
110 the same region (Fig. 1).

111

112 The vegetation of Western Ghats is divided into three major types (Daniels et al., 1995; Roy et al.,  
113 2015): 1) Tropical evergreen forest that can potentially cover 64 750 km<sup>2</sup>, 2) Tropical evergreen  
114 forest that occurs adjoining with tropical evergreen and form a transition between evergreen forest  
115 and moist deciduous forest, and 3) Tropical dry deciduous forests. Our study site falls in the mid  
116 elevations (650- 1400 m a.s.l.) of the tropical evergreen forest dominated by *Cullenia*  
117 (*Bombacaceae*), *Palaquium* (*Sapotaceae*), *Aglaia* (*Meliaceae*), *Mallotus* and *Drypetes*  
118 (*Euphorbiaceae*). Trees from *Dipeterocarpaceae* (*Hopea*), *Elaeocarpaceae*, *Flacourtiaceae*,  
119 *Myristicaceae*, and *Myrtaceae* are also well represented (Pascal 1988, Ganesh et al., 1996). Also in  
120 the study site there are several "natural" palm species e.g. *Corypha umbraculifera* together with  
121 betelnut palms located in plantations (Kulkarni and Mulani, 2004).

122 Most research on grasses in the grasslands of the Western Ghats has occurred in high-elevation  
123 forests (1500 m a.s.l.)(e.g. Das et al., 2015).This is also the case with the review paper by Thomas

124 and Palmer (2007). They found that the montane grasslands and adjacent evergreen tropical forests  
125 form a distinctive vegetation mosaic dominated by *Eulalia phaeothrix* and *Dicanthium polyptychum*  
126 (*Panicoideae*). In mid-elevation the grass communities as far as the authors know, there are only a  
127 few inventories. For example, Annaselvan and Parthasarathy (1999) found that in Varagaliar (600 m  
128 a.s.l south of the study sites described in the present paper) of the 155 species of the understory, 65  
129 are herbs (22.8%), 17 climbers (0.5%), 13 ferns (4.8%), 8 grasses (6.1%), and 4 sedges (0.4%). In  
130 particular, the authors found 8 species of Poaceae e.g. *Paspalum conjugatum* (*Panicoideae*). In  
131 Karnataka, there is evidence of the presence of Arundinoideae (*Elytrophorus spicatus*),  
132 Bambusoideae (*Dendrocalamus strictus*, *Bambusa arundinacea*), Chloridoideae (*Chloris barbata*,  
133 *Cynodon dactylon*), Panicoideae (*Cenototheca lappacea*, *Oplismenus compositus*) (e.g. Prasad, 1985;  
134 Surrey and Everett, 2000). According to the ecology of Pooideae grasses it is unlikely that they occur  
135 in the environments of our study sites (Surrey and Everett, 2000). This subfamily is present in the  
136 Nilgiri Hills at higher elevation and in open grasslands, not under the forest canopy (Singh 2003).  
137  
138 Finally, the Western Ghats receives rain from the southwest monsoon. The average annual rainfall in  
139 the evergreen forests ranges from 3500-7500 mm. The climate is generally warm and humid with  
140 maximum temperature of 30°C and minimum of 0°C in high elevations (Pascal 1982). More details  
141 on the coring site can be found in Bhagwat et al. (2012) and Bhagwat et al. (2014).

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### 143 **3. Material and Methods**

#### 144 **3.1 Phytolith extraction, identification, and classification**

145 From BOP site we analysed 19 samples covering 168 cm, and for MY, 9 samples over 36 cm.

146 Phytolith isolation from the core BOP and MY was carried out following Piperno (1989) protocol.

147 The process includes: carbonate removal, deflocculation, oxidation, and gravity separation with a

148 heavy liquid. After drying, phytoliths were embedded in Canada balsam and transferred to slides for  
149 microscopic observation.

150 Phytoliths were identified throughout the sedimentary sequence for MY, however several levels in  
151 BOP had very low number of diagnostic phytoliths and so had to be excluded from our analysis.  
152 Counts ranged from 200 to 300 taxonomically significant phytolith per sample. The identification  
153 was carried out following relevant literature (Gu et al., 2008; Pearsall, 2013; Piperno, 1989; Piperno,  
154 1998; Runge, 1999). Analyses were performed on relative counts (percentages). The phytoliths were  
155 divided into morphotypes. BOP site contained 34 distinct morphotypes from 5 broad taxonomic  
156 groups; and MY site, 27 distinct morphotypes from 5 groups. The broad taxonomic groups were  
157 grasses (Poaceae) sedges (Cyperaceae), ferns (Pteridopsida), palms (Arecaceae), and broad-leaved  
158 trees (woody dicotyledons) (Fig. 2, Table, 1).

159 In the absence of a phytolith reference collection from modern vegetation at the coring sites, we  
160 followed the most relevant literature and interpreted our phytolith morphotypes as described in  
161 Table 1. In particular, we based our classification on Gu et al. (2008), another phytolith investigation  
162 from dipterocarp evergreen forest in Asia. The attribution of some of our morphotypes to *Poaceae*  
163 subfamilies such as Panicoideae remains tentative because a thorough investigation of all grass  
164 species growing at the study sites and of their phytoliths was beyond the scope of this paper. The  
165 approach we followed has been successful for many other palaeoecological phytolith studies in the  
166 past (see e.g. literature review in Piperno, 2006). Only the correct classification of phytoliths into  
167 indicator of grasses and forest was critical in this study. It was not affected by the imperfect  
168 knowledge of phytoliths produced by local flora because the distinction between our 5 broad  
169 taxonomic groups is a very robust one that can be applied across the world. The phytolith  
170 assemblages are compared with pollen time series from Bhagwat et al 2012 and Bhagwat et al 2014  
171 (SI).

172

### 173 **3.3 Humidity-aridity index**

174 Some authors propose the use of phytolith indices to reconstruct changes in vegetation and climate,  
175 and previous studies have demonstrated that such indices have significant potential as climatic  
176 indicators for sedimentary palaeoenvironmental interpretation (Parker et al., 2004, Bremond 2005,  
177 2008). To interpret the phytolith assemblage we used the humidity-aridity index (Iph), determined  
178 by the relative percentages of C4 plants in the grass assemblage. The Iph index relies on the  
179 proportion of saddle phytoliths produced by Chloridoideae grasses. Because of the lack of modern  
180 phytolith reference collection and because saddles can be produced by Bambusoideae (oblong  
181 concave saddle or collapsed saddle), Arundinoideae (trapeziform saddle), as well as Chloridoideae  
182 (square saddle) grasses in the region (Gu et al., 2008) (Table 1), the index should be interpreted with  
183 caution. Iph is calculated by the ratio of Chloridoideae: Chloridoideae + Panicoideae phytoliths. A  
184 high Iph value indicates a dominance of chloridoideae grasses, suggesting xeric (warm-dry)  
185 conditions, while a low Iph value indicates warm and humid conditions.

186 In addition, we calculated Cyperaceae percentages relative to the whole assemblage (sum of  
187 identifiable phytolith) as this family of plant is considered to be a reliable indicator for wet local  
188 conditions.

### 189 **3.4 Geochronology**

190 In this paper we used detail on C<sup>14</sup> dates from Bhagwat et al 2012 and Bhagwat et al 2014. We  
191 established the chronology of the two sediment sequences by obtaining radiocarbon dates on each.  
192 Samples were measured at the Oxford Radiocarbon Accelerator Unit and 14CHRONO Centre at  
193 Queens University Belfast. Radiocarbon ages were calibrated using the IntCal13 dataset (Reimer et  
194 al., 2013) to years before present (cal. years BP). For example, BOP at 164 cm was 6491 cal years BP.  
195 (OxA-16465) and My at 44 cm was 912 cal years BP (OxA-16771). Note that for MY we analysed the



196 first 36 cm with an estimated date of 550 cal years BP. Age-depth relationships were established  
197 using Clam (Blaauw, 2010).

## 198 **4. Results**

### 199 **4.1 7000 years of phytolith assemblage**

200 Grasses (45-68%) and broad-leaved trees and shrubs (8-30%) dominated the assemblage (Fig. 2).  
201 From broad-leaved trees and shrubs category, globular granulate phytoliths were the best  
202 represented in both sites (Fig. 1 and 2 in SI). Within the grass phytolith, bilobate morphotypes (peaks  
203 of 15%, poss. subfamily Panicoideae), oblong concave saddles (peaks of 20%, poss. subfamily  
204 Bambusoideae) and rondels (peaks of 20%) were the best represented. Palm (peaks of 12%), and  
205 fern phytoliths (peaks of 7%) were visible throughout both cores.

206 For the forest patch in the plantation (BOP) in particular, oblong concave saddle (poss. subfamily  
207 Bambusoideae), trapezoid saddles (poss. subfamily Arundinoideae), square saddles (poss. subfamily  
208 Chloridoideae), and rondel morphotypes showed low percentages (maximum of 15%). During this  
209 period there was also a general decrease in broad-leaved trees and shrubs (from 20% to 5%) most  
210 noticeable in numbers of globular granulate phytoliths counted. This decrease in broad-leaved trees  
211 and shrubs was followed by a decrease in ferns (from 8% to 5%), palms (from 12% to 5%), and an  
212 increase in Cyperaceae (from 8% to 12%) during the period of time covering the last 3000 to 1000  
213 years ago. For this site, the number of palm phytoliths recorded reached their peak at the top of the  
214 core (15%). Grasses selected in figure 2b showed a general decrease of grasses morphotypes 3000  
215 years ago, followed by an increase until 1000 years ago (Fig. 2).

216 As for the sacred site MY: grasses, Cyperaceae, ferns, broad-leaved trees, and palms were observed  
217 throughout the core. Grasses remained constant for the period 600 to 200 cal years BP. Then while,  
218 square saddles (poss. subfamily Chloridoideae), trapezoid saddles (poss. subfamily Arundinoideae)  
219 morphotypes increased; quadra-lobate (poss. subfamily Panicoideae) and oblong concave saddle

220 (poss, subfamily Bambusoideae) morphotypes, decreased. Broad-leaved trees and palms increased  
221 for the last 150 years while grasses decreased. Cyperaceae and ferns remained highly variable  
222 throughout the core.

223 Finally, as can be seen in figure 4, there is an excellent agreement between grass pollen and  
224 phytoliths over time. Both time-series followed the same trend but with higher percentage values  
225 for phytoliths than for pollen grains (Bhagwat et al., 2012; Bhagwat et al., 2014). In BOP site there is  
226 a general increase of grasses two marked peaks at 4500 and 200 cal BP. In the case of the temporal  
227 trends there is an increase towards the present in pollen percentages from 10% to 40% (with a peak  
228 of 45%) and for phytoliths from 45% to 55% (with a peak of 70%). In the MY site, there is a general  
229 decrease in grasses. The pollen data set showed a decrease from 45 % to 10% with a peak 300 years  
230 ago of 40%. The phytolith data displayed a plateau of 60% with a slight increase from 550 to 300 cal  
231 BP. During the last 100 years phytoliths decreased to 40%.

#### 232 **4.2 Cyperaceae and Humidity-aridity index**

233 BOP humidity-aridity index displayed the following trends: during the oldest period covering 7500 to  
234 6000 cal BP the Iph index displayed the lowest values recorded, dropping from 0.19 to 0.07 (Fig. 3),  
235 suggesting high humidity. The first Iph value above 0.3 (indicative of aridity) is recorded at  
236 approximately 5800 to 4400 cal years BP. This was complemented by a relatively low percentage of  
237 Cyperaceae, an indicator of humidity. Finally, during the last 1000 years Iph displayed high  
238 fluctuation. There continues to be a general increase in Iph values, with an alternation of arid and  
239 humid periods.

240 Humidity-aridity index in the core MY was as follows: during the older period (approximately 550 to  
241 200 cal BP) Iph values remained between 0.25 and 0.12, suggesting humidity. A general decrease in  
242 the abundance of *Cyperaceae* is also observed (Fig. 2). Iph values in this part of the core remain  
243 systematically low, until approximately 150 cal years BP, where a value of 0.31 is observed. This

244 period is also characterised by a sample where no Cyperaceae were present, suggesting punctual  
245 arid conditions.

## 246 **5. Discussion**

247 We start by highlighting the main local changes observed over the last 1000 years. We will end with  
248 a final section comparing our results with regional climatic trends, with emphasis on the earlier  
249 periods covered in our phytolith study. When possible we will refer to the taxonomic origin of each  
250 phytolith morphotype (table 1).

### 251 **5.1 Phytoliths and local human activities in a forest patch in a coffee plantation (3500 cal years to 252 present)**

253 Research has shown that agricultural landscapes were established over 3000 years before present in  
254 the Western Ghats (Ranganathan et al., 2008). The so-called megalithic period, between 3000 and  
255 1000 years ago saw the Western Ghats be subjected to agro-pastoralism, and shifting cultivation.  
256 Shifting cultivation includes felling of trees and clearing of lands prior to the sowing of seeds  
257 (Saravanan, 2008). For example, the pollen record suggests cultivation began in the area  
258 surrounding BOP at around 3000 cal years BP, with high levels of pollen of cultivated taxa being  
259 detected at this time (Bhagwat et al., 2012). Moreover, according to Bhagwat et al. (2012) the local-  
260 scale fires start around 3500 cal years ago with a sharp peak between 2000 and 1500 years ago. This  
261 fact together with the fossil pollen data suggests agriculture and other human impacts have been an  
262 important driver of vegetation change during the last 3500 years (Fig. 4). Although we cannot  
263 exclude climatic changes from our interpretation it has also been suggested that present climate was  
264 established in the region 2200 years ago (Caratini *et al.* 1994; Giriraj *et al.* 2008; Bhagwat *et al.*,  
265 2012). We therefore, suggest that the decrease during the last 2000 years in broad-leaved trees in  
266 the phytolith record may have some relation to this agricultural activity and not to climate change.

267 Also important is the slight increase seen at the very top of the core in broad-leaved trees phytoliths.  
268 The slight increase is interesting, as cultivators of betelnut palm and coffee are known to shade their  
269 crops with taller surrounding trees (Bhagwat et al., 2005). This fact is also supported by the palm  
270 spherical echinate phytolith morphotype, which show a steady increase throughout the last 1000  
271 years, with a peak of 16% at the top of the core (Fig. 2). This modern peak in palm phytolith  
272 coincides with the current land use at the site i.e. cultivation of coffee and betelnut palm.

273 As anthropological research by Neilson et al (2008) shows, coffee has been cultivated in the Western  
274 Ghats for centuries, possibly since the 16th century. In addition, this region was also affected by an  
275 increase in the spice trade and extraction of ship wood (Chandran, 1997). As a result, large amounts  
276 of wood and timber were exported from South India during 792-1882 AD (Saravanan, 2008). The  
277 establishment of plantation crops and the beginning of state forestry management may have  
278 resulted in new land management in the area (Chandran, 1997). In this context, and for the last 2000  
279 years the highly variability of lph may be attributed, as well, to the disturbances caused by humans,  
280 such as clearing through fires and irrigation mechanisms that might have changed the soil water  
281 balance. Although we can not rule out a decrease in water availability due to a weakening of  
282 precipitation (but see Caratini 1994, Kodandapani et al. 2004), it is reasonable to assume that  
283 increasing levels of disturbance might have been accompanied by variations in soil moisture (Daniels  
284 et al., 1995).

## 285 **5.2 Phytoliths and local human activities in a sacred grove (3500 cal years BP to present)**

286 The MY sedimentary sequence comes from a sacred grove, and thus has been protected from  
287 cultivation and maintained by the local community (Bhagwat et al., 2005; Bhagwat et al., 2014). The  
288 vegetation we see today consists of evergreen forest (Bhagwat et al., 2005). Recent palaeoecological  
289 reconstruction indicated a transition from non-forest open landscape to tree-covered landscape at  
290 MY site suggesting that the establishment of the sacred groves may have occurred possibly around  
291 400 cal years BP (Bhagwat et al., 2014). Since then, a change in vegetation is observed with an

292 increase of broad-leaved trees and a decrease in grasses. Our phytolith results confirm the pollen  
293 data obtained in this palaeoecological study (Fig. 2, Fig. 4). However our new phytolith data set  
294 provides some minor differences. For example, we show that grasses decrease at around 200 cal  
295 year BP, while this trend started around 400 years ago according to the pollen record (Fig. 4).  
296 Bambusoideae and Panicoideae are the first grasses to decrease followed by an increase in broad-  
297 leaved trees for the last 120 years (Fig. 2 and Fig. 4). The delayed increase in broad-leaved trees  
298 phytoliths (200 years after evergreen forest pollen grains increased) might suggest a forest recovery  
299 at landscape level, with tree pollen from nearby forest blown to the coring site, followed by a local  
300 forest recovery during the last century.

301 These results suggest a good development of canopy cover modifying the microclimate and soil  
302 moisture due to increased shading of the forest floor (Fig.2 table 1). During this period then, the  
303 local community would have prevented the site from human disturbances such as intensive timber  
304 harvesting (Chandran, 1997), and instead used the site as an important source of non-timber  
305 products (Brown et al., 2006).

### 306 **5.3 Phytoliths in the regional context (7500 to 3500 cal years BP)**

307 Although the aim of this paper is to focus on the local ecological and climatic conditions, the lph  
308 index calculated compares well with regional patterns during the period of time between 7500 and  
309 3500 cal years BP.

310 Multi-proxy palaeo-reconstructions of monsoon intensity in India have identified a range of arid and  
311 humid periods for the last 10,000 years. For example, research by Rajagopalan et al. (1997) in the  
312 Nilgiri hills, Western Ghats, found a moist period peaking between 10000 - 5000 cal BP, as a result of  
313 higher annual precipitation in Southern Asia. Also in Southern India, (Veena et al., 2014) found warm  
314 and dry climatic conditions between 6200 and 420 cal BP, but with short and intense wet phases.  
315 These wet events resulted from the strengthening of the monsoon causing rising water levels. These

316 climatic changes were inferred by changes in pollen composition, i.e. increase in evergreen forest  
317 pollen types, increase in mangrove, and decrease in grasses. Therefore, our phytolith data might add  
318 some information to these regional arid and wet events.

319 First, in the oldest section of the BOP sedimentary sequence (from 7500 to 6000 cal years BP) the  
320 lph displayed the lowest values (0.19 - 0.07) (Fig.3), suggesting high humidity. This is reflected in the  
321 increase in: *Cyperaceae* and *Panicoideae* phytoliths. This wet phase, would have favoured the  
322 expansion of forests within the Western Ghats, producing the high levels of soil moisture needed by  
323 trees to remain sufficiently hydrated to perform photosynthesis (Kramer, 1969). This is reflected in  
324 the peak abundance of globular granulate phytoliths in this period (18.81%). Relatively high  
325 percentages of *Bambusoideae* and *Arundinoideae* grasses are also observed indicating a densely  
326 forested environment. Thus, the dominance of phytoliths of broad-leaved trees and shrubs and low  
327 lph (<0.3) values correlate well with the regional records of the time. This also concurs with other  
328 research demonstrating high annual precipitation during the early to mid-Holocene in southern Asia  
329 (Tiwari et al., 2010).

330 Finally, an arid period at 3500 has been recorded from different sedimentary cores across India. For  
331 example a drastic reduction in humidity from 3500 cal years BP has been found in a marine core off  
332 the coast of Western India using  $\delta^{13}C$  values and marine microfossils (Caratini et al., 1994). This arid  
333 phase is also suggested by e.g. (Prasad et al., 2007) in Gujarat (eastern part of India) and (Phadtare,  
334 2000) in the Himalayas. Within this period, our lph show a general increase in values. This suggests  
335 as well, an arid and warm period. This agreement is further supported by the extremely low values  
336 of fern and *Cyperaceae* phytoliths around this time, both groups being strongly linked to high  
337 moisture environments.

## 338 **6. Conclusions**

339 One of the main questions we were interested in this study was: what impact does the increased  
340 intensity of human activities have on the Western Ghats landscape? The results obtained here  
341 suggest that phytoliths analysis has great potential for the indication of local dynamics of  
342 human/environmental relationships:

343 1) The highly variable of lph for the last 1000 years may be attributed, to the disturbances caused by  
344 humans, such as clearing through fires and irrigation.

345 2) We have seen that Panicoideae phytolith are the most abundant grasses in both sites, followed by  
346 those originating from Bambusoideae, Chloridoideae, and Arundinoideae.

347 3) We can only provide limited information about crop composition. We know that the current crop  
348 production in our sites is limited to coffee and betelnut plantations. In agreement with this, we have  
349 not found any cereal phytolith at any time period. In addition, our record indicates an increase in  
350 palm phytolith in the last 100 years, likely to reflect the establishment of Betelnut plantation.

351 4) The long-term vegetation trends presented here on the basis of in two cores, with differing  
352 temporal resolutions might provide conservationists with valuable data for quantifying the impacts  
353 of land-use on human dominated landscapes in tropical regions.

354 Finally, our phytoliths trends concur with the pollen data (Bhagwat et al., 2012; Bhagwat et al.,  
355 2014). Such concurrence between different proxies is important when dealing with records from the  
356 past.

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361 collection.

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507 **Figure captions**

508 **Figure 1.** Map of India showing the distribution of the Western Ghats and the location of the two  
509 study sites. Map from figure b is from GlobCover ([http://due.esrin.esa.int/page\\_globcover.php](http://due.esrin.esa.int/page_globcover.php)) and  
510 it illustrated land cover types and the location of the two study sites.

511 **Figure 2.** A) Percentage of phytolith grasses, ferns, palms, and broad-leaved trees for the two sites.  
512 B) Selection of percentage of phytolith morphotypes.

513 **Figure 3.** Trend of the humidity-aridity index (Iph) over time for both sites.

514 **Figure 4.** Comparison between the % of fossil grass pollen grains (Bhagwat et al., 2012; Bhagwat  
515 et al., 2014) and phytoliths over time.

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527 **Table 1** Description of phytolith morphotypes, ecological interpretation and climatic index used.

528 Information from Gu et al., 2007; Piperno, 2006.

Phytolith morphotype	Taxonomic origin	English name	Ecological interpretation
Polihedrons with conical projection (<40 µm)	Cyperaceae	Sedges	Wet habitats, high soil moisture.
Spherical echinate (< 30 µm)	Areaceae (=Palmae)	Palms	Plantations and forested environments. Warm and humid regions
Elongate undulating, prism sinuate	Pteridopsida	Ferns	Shady habitats
Globular with granulate surface	woody dicotyledons	Broad-leaved trees/shrubs	Forest habitats
Trapezoid saddle (<15 µm)	Poaceae (poss. Arundinoideae)	Grasses	Mostly C3 Grass from warm regions.
Collapsed saddle (<20 µm)	Poaceae (poss. Bambusoideae)	Grasses	Mostly C3 grasses in warm and humid regions.
Oblong concave saddle	Poaceae (poss. Bambusoideae)	Grasses	Mostly C3 grasses in warm and humid regions.
Square saddle (<15 µm)	Poaceae (poss. Chloridoideae)	Grasses	Mostly C4 grasses in warm, arid to semi-arid regions with low soil moisture.
Bilobate (<25 µm)	Poaceae (poss. Panicoideae)	Grasses	Mostly C4 grasses in warm an humid regions. Tropical regions with high soil moisture.
Quadra-lobate (<15 µm)	Poaceae (poss. Panicoideae or Chloridoideae)	Grasses	Grasses in warm regions
Trapeziform polylobates (<30 µm)	Poaceae	Grasses	
Rondel (<15 µm)	Poaceae	Grasses	

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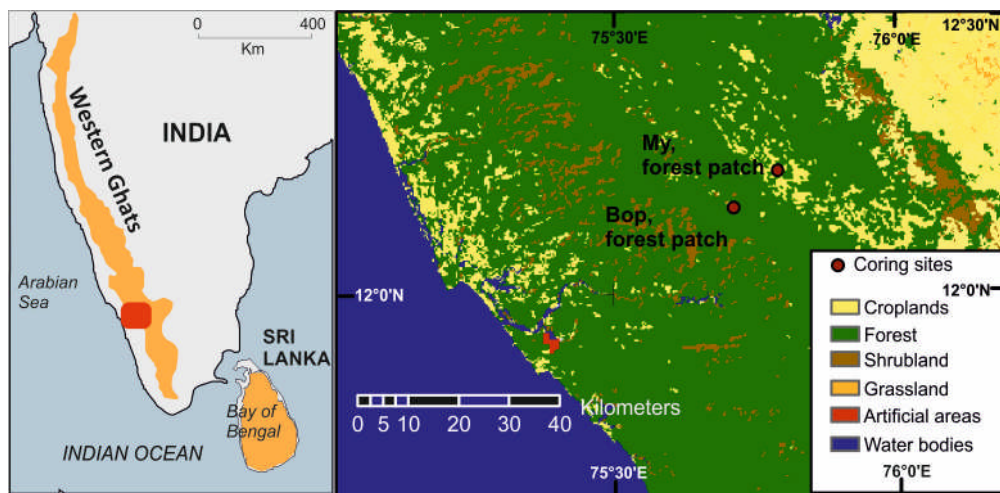
Figure 1

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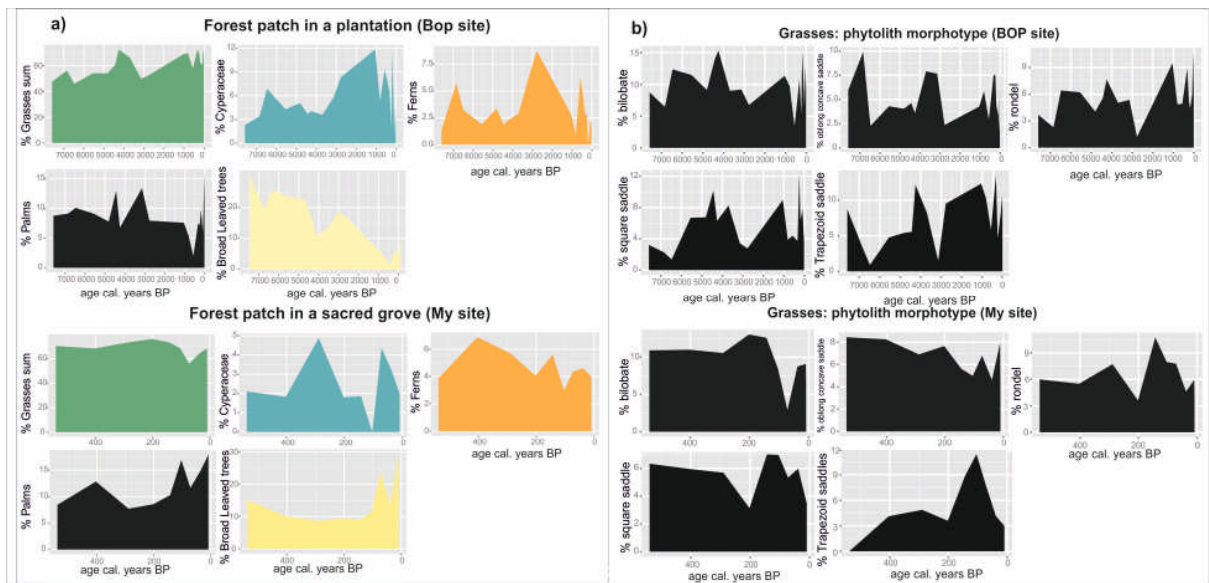
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Figure 2

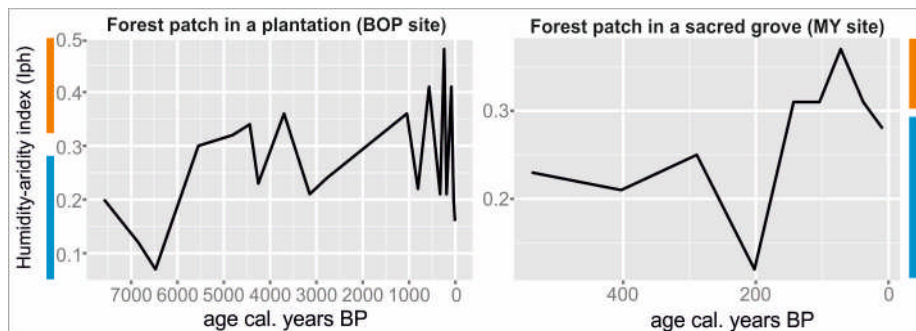


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Figure 3

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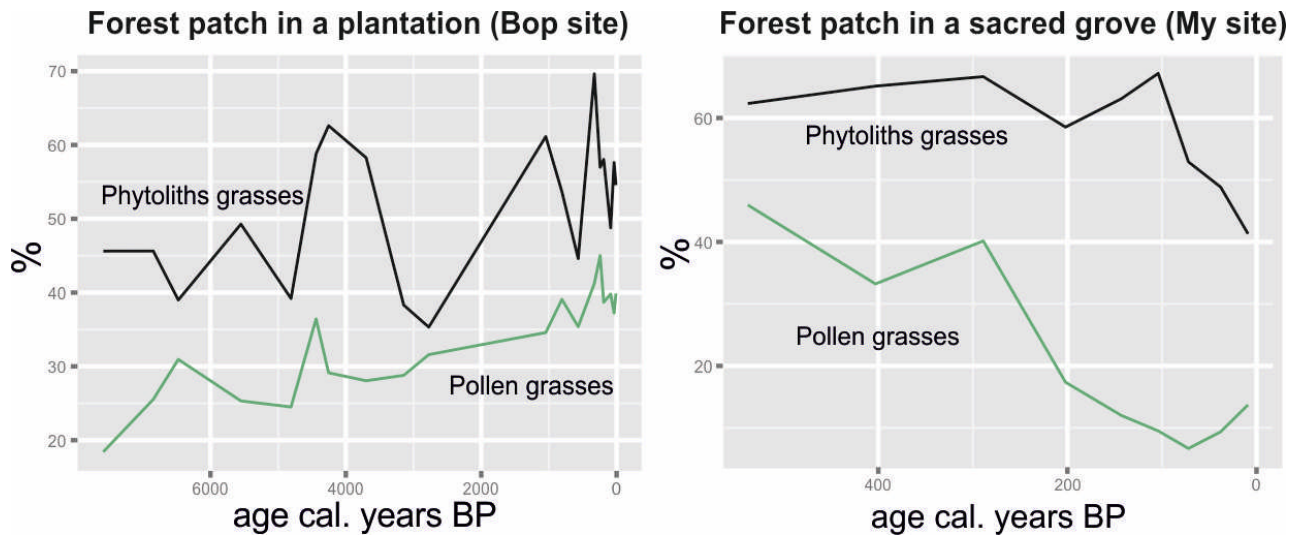
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Figure 4

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