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

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Abstract

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

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

1. Introduction

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

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

Except for a few cultivated grass species corresponding with cereal grains, the identification of grasses in temporal sediment sequences has always been a challenge in palaeoecology due to the limitations in identifying fossil pollen grains at sub-family level (Fearn, 1998). However, grasses are excellent environmental indicators (Ghosh et al., 2011) and they also give information on dominant photosynthetic pathways (C3 or C4 grasses) that can be directly interpreted in terms of environmental and climatic conditions (Edwards et al., 2010; Gu et al., 2008; Strömberg, 2011). Phytoliths, the opaline silica bodies precipitated in or between cells of plant tissues, form a useful proxy because provide additional information about changes in grass diversity over time that pollen grains alone do not. This information can provide further insights into whether the presence of grassland in landscape mosaics is due to human activities, environmental causes or purely climatic factors.

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

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

Our objectives are:

- -Analyse the phytolith record for two cores from mid-elevation forest patches in the Western Ghats region.
- -Compare this phytolith record with previously published pollen record from the same cores in order to improve our understanding of grass diversity and abundance over time.
- -Discuss the nature and magnitude of anthropogenic and climatic vegetation changes on the basis of the phytolith and pollen record at local scale and regional scale.

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

2. Regional setting

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

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

Most research on grasses in the grasslands of the Western Ghats has occurred in high-elevation forests (1500 m a.s.l.)(e.g. Das et al., 2015).This is also the case with the review paper by Thomas and Palmer (2007). They found that the montane grasslands and adjacent evergreen tropical forests form a distinctive vegetation mosaic dominated by *Eulalia phaeothrix* and *Dicanthium polyptychum* (*Panicoideae*). In mid-elevation the grass communities as far as the authors know, there are only a few inventories. For example, Annaselvan and Parthasarathy (1999) found that in Varagaliar (600 m a.s.l south of the study sites described in the present paper) of the 155 species of the understory, 65 are herbs (22.8%), 17 climbers (0.5%), 13 ferns (4.8%), 8 grasses (6.1%), and 4 sedges (0.4%). In particular, the authors found 8 species of Poacaeae e.g. *Paspalum conjugatum* (Panicoideae). In Karnataka, there is evidence of the presence of Arundinoideae (*Elytrophorus spicatus*), Bambusoideae (*Dendrocalamus strictus, Bambusa arundinacea*), Chloridpoideae (*Chloris barbata, Cynodon dactylon*), Panicoideae (*Cenototheca lappacea*, *Oplismenus compositus*) (e.g. Prasad, 1985; Surrey and Everett, 2000). According to the ecology of Pooideae grasses it is unlikely that they occur in the environments of our study sites (Surrey and Everett, 2000). This subfamily is present in the Nilgiri Hills at higher elevation and in open grasslands, not under the forest canopy (Singh 2003).

Finally, the Western Ghats receives rain from the southwest monsoon. The average annual rainfall in the evergreen forests ranges from 3500-7500 mm. The climate is generally warm and humid with maximum temperature of 30ºC and minimum of 0ºC in high elevations (Pascal 1982). More details on the coring site can be found in Bhagwat et al. (2012) and Bhagwat et al. (2014).

3. Material and Methods

3.1 Phytolith extraction, identification, and classification

From BOP site we analysed 19 samples covering 168 cm, and for MY, 9 samples over 36 cm. Phytolith isolation from the core BOP and MY was carried out following Pipernos (1989) protocol. The process includes: carbonate removal, deflocculation, oxidation, and gravity separation with a heavy liquid. After drying, phytoliths were embedded in Canada balsam and transferred to slides for microscopic observation.

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

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

3.3 Humidity-aridity index

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

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

3.4 Geochronology

In this paper we used detail on C^{14} dates from Bhagwat et al 2012 and Bhagwat et al 2014. We established the chronology of the two sediment sequences by obtaining radiocarbon dates on each. Samples were measured at the Oxford Radiocarbon Accelerator Unit and 14CHRONO Centre at Queens University Belfast. Radiocarbon ages where calibrated using the IntCal13 dataset (Reimer *et al.*, 2013) to years before present (cal. years BP). For example, BOP at 164 cm was 6491 cal years BP. (OxA-16465) and My at 44 cm was 912 cal years BP (OxA-16771). Note that for MY we analysed the first 36 cm with an estimated date of 550 cal years BP. Age-depth relationships where established using Clam (Blaauw, 2010).

4. Results

4.1 7000 years of phytolith assemblage

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

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

As for the sacred site MY: grasses, Cyperaceae, ferns, broad-leaved trees, and palms were observed throughout the core. Grasses remained constant for the period 600 to 200 cal years BP. Then while, square saddles (poss. subfamily Chloridoideae), trapezoid saddles (poss. subfamily Arundinoideae) morphotypes increased; quadra-lobate (poss. subfamily Panicoideae) and oblong concave saddle (poss, subfamily Bambusoideae) morphotypes, decreased. Broad-leaved trees and palms increased for the last 150 years while grasses decreased. Cyperaceae and ferns remained highly variable throughout the core.

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

4.2 Cyperaceae and Humidity-aridity index

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

Humidity-aridity index in the core MY was as follows: during the older period (approximately 550 to 200 cal BP) Iph values remained between 0.25 and 0.12, suggesting humidity. A general decrease in the abundance of *Cyperaceae* is also observed (Fig. 2). Iph values in this part of the core remain systematically low, until approximately 150 cal years BP, where a value of 0.31 is observed. This period is also characterised by a sample where no Cyperaceae were present, suggesting punctual arid conditions.

5. Discussion

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

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

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

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

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

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

The MY sedimentary sequence comes from a sacred grove, and thus has been protected from cultivation and maintained by the local community (Bhagwat et al., 2005; Bhagwat et al., 2014). The vegetation we see today consists of evergreen forest (Bhagwat et al., 2005). Recent palaeoecological reconstruction indicated a transition from non-forest open landscape to tree-covered landscape at MY site suggesting that the establishment of the sacred groves may have occurred possibly around 400 cal years BP (Bhagwat et al., 2014). Since then, a change in vegetation is observed with an increase of broad-leaved trees and a decrease in grasses. Our phytolith results confirm the pollen data obtained in this palaeoecological study (Fig. 2, Fig. 4). However our new phytolith data set provides some minor differences. For example, we show that grasses decrease at around 200 cal year BP, while this trend started around 400 years ago according to the pollen record (Fig. 4). Bambusoideae and Panicoideae are the first grasses to decrease followed by an increase in broad-leaved trees for the last 120 years (Fig. 2 and Fig. 4). The delayed increase in broad-leaved trees phytoliths (200 years after evergreen forest pollen grains increased) might suggest a forest recovery at landscape level, with tree pollen from nearby forest blown to the coring site, followed by a local forest recovery during the last century.

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

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

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

Multi-proxy palaeo-reconstructions of monsoon intensity in India have identified a range of arid and humid periods for the last 10,000 years. For example, research by Rajagopalan et al. (1997) in the Nilgiri hills, Western Ghats, found a moist period peaking between 10000 - 5000 cal BP, as a result of higher annual precipitation in Southern Asia. Also in Southern India, (Veena et al., 2014) found warm and dry climatic conditions between 6200 and 420 cal BP, but with short and intense wet phases. These wet events resulted from the strengthening of the monsoon causing rising water levels. These climatic changes were inferred by changes in pollen composition, i.e. increase in evergreen forest pollen types, increase in mangrove, and decrease in grasses. Therefore, our phytolith data might add some information to these regional arid and wet events.

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

Finally, an arid period at 3500 has been recorded from different sedimentary cores across India. For example a drastic reduction in humidity from 3500 cal years BP has been found in a marine core off the coast of Western India using δ13C values and marine microfossils (Caratini et al., 1994). This arid phase is also suggested by e.g. (Prasad et al., 2007) in Gujarat (eastern part of India) and (Phadtare, 2000) in the Himalayas. Within this period, our Iph show a general increase in values. This suggests as well, an arid and warm period. This agreement is further supported by the extremely low values of fern and *Cyperaceae* phytoliths around this time, both groups being strongly linked to high moisture environments.

6. Conclusions

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

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

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

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

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

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

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References

Aleman J C., Canal-Subitani S., Favier C., Bremond L., 2014. Influence of the local environment on lacustrine sedimentary phytolith records. Palaeogeography, Palaeoclimatology, Palaeoecology 414, 273-283.

Alexandre, A., Meunier, J.-D., Lézine, A.-M., Vincens, A., Schwartz, D., 1997. Phytoliths: indicators of grassland dynamics during the late Holocene in intertropical Africa. Palaeogeography, Palaeoclimatology, Palaeoecology 136, 213-229.

Annaselvam, J., Parthasarathy, N., 1999. Inventories of understory plants in a tropical evergreen forest in the Anamalais, Western Ghats, India. Ecotropica 5, 197-211.

Barboni, D., Bonnefille, R., Alexandre, A., Meunier, J.D., 1999. Phytoliths as paleoenvironmental indicators, West Side Middle Awash Valley, Ethiopia. Palaeogeography, Palaeoclimatology, Palaeoecology 152, 87-100.

Bhagwat, S.A., Kushalappa, C.G., Williams, P.H., Brown, N.D., 2005. A Landscape Approach to Biodiversity Conservation of Sacred Groves in the Western Ghats of India. Conservation Biology 19, 1853-1862.

Bhagwat, S.A., Nogué, S., Willis, K.J., 2012. Resilience of an ancient tropical forest landscape to 7500years of environmental change. Biological Conservation 153, 108-117.

Bhagwat, S.A., Nogué, S., Willis, K.J., 2014. Cultural drivers of reforestation in tropical forest groves of the Western Ghats of India. Forest Ecology and Management 329, 393-400.

Biodiversity Information System. Indian Institute of Remote Sensing. http://bis.iirs.gov.in (last accessed 20th November 2015).

Bremond, L., Alexandre, A., Hély, C., Guiot, J., 2005. A phytolith index as a proxy of tree cover density in tropical areas: calibration with Leaf Area Index along a forest–savanna transect in southeastern Cameroon. Global and Planetary Change 45, 277-293.

Bremond, L., Alexandre, A., Wooller, M.J., Hely, C., Williamson, D., Schafer, P.A., Majule, A., Guiot, J., 2008. Phytolith indices as proxies of grass subfamilies on East African tropical mountains. Global and Planetary Change 61, 209-224.

Brown, N., Bhagwat, S., Watkinson, S., 2006. Macrofungal diversity in fragmented and disturbed forests of the Western Ghats of India. Journal of Applied Ecology 43, 11-17.

Cabanes, D., Shahack-Gross, R., 2015. Understanding Fossil Phytolith Preservation: The Role of Partial Dissolution in Paleoecology and Archaeology. PLoS ONE DOI: 10.1371/journal.pone.0125532

Caratini, C., Bentaleb, I., Fontugne, M., Morzadec-Kerfourn, M.T., Pascal, J.P., Tissot, C., 1994. A less humid climate since ca. 3500 yr B.P. from marine cores off Karwar, western India. Palaeogeography, Palaeoclimatology, Palaeoecology 109, 371-384.

Chandran, M.D., 1997. On the ecological history of the Western Ghats. Current Science.

Das, A., Nagendra, A., Anand, M., Bunyan, M., 2015. Topographic and Bioclimatic Determinants of the Occurrence of Forest and Grassland in Tropical Montane Forest-Grassland Mosaics of the Western Ghats, India. PLoS One. 2015; 10(6): e0130566.

Daniels, R.J.R., Gadgil, M., Joshi, N.V., 1995. Impact of Human Extraction on Tropical Humid Forests in the Western Ghats Uttara Kannada, South India. Journal of Applied Ecology 32, 866-874.

Edwards, E.J., Osborne, C.P., Strömberg, C.A., Smith, S.A., 2010. The origins of C4 grasslands: integrating evolutionary and ecosystem science. science 328, 587-591.

Fearn, M.L., 1998. Phytoliths in sediment as indicators of grass pollen source. Review of Palaeobotany and Palynology 103, 75-81.

Ganesh, T., Ganesan, R., Soubadra Devy, M., Davida, P., Bawa, KS., (1996). An assessment of plant biodiversity at a mid elevation evergreen forest of Kalakad Mundanthurai Tiger Reserve, Western Ghats, India. Current Science 71, 379-392.

Ghosh, R., Naskar, M., Bera, S., 2011. Phytolith assemblages of grasses from the Sunderbans, India and their implications for the reconstruction of deltaic environments. Palaeoegeography, Palaeoeclimatology, Palaeoecology 311, 93-102.

Gu, Y., Pearsall, D.M., Xie, S., Yu, J., 2008. Vegetation and fire history of a Chinese site in southern tropical Xishuangbanna derived from phytolith and charcoal records from Holocene sediments. Journal of Biogeography 35, 325-341.

Harvey, E.L., Fuller, D.Q., 2005. Investigating crop processing using phytolith analysis: the example of rice and millets. Journal of Archaeological Science 32, 739-752.

Kramer, P.J., 1969. Plant and soil water relationships: a modern synthesis. Plant and soil water relationships: a modern synthesis. New York: McGraw-Hill, New York, USA.

Kulkarni, AR., Mulani, RM., 2004. Indigenous palms of India. Current Science 86, 1598-1603.

Lo Seen, D., Ramesh, B., Nair, K., Martin, M., Arrouays, D., Bourgeon, G., 2010. Soil carbon stocks, deforestation and land-cover changes in the Western Ghats biodiversity hotspot (India). Global Change Biology 16, 1777-1792.

Messager, E., Lordkipanidze, D., Delhon, C., Ferring, C., 2010. Palaeoecological implications of the Lower Pleistocene phytolith record from the Dmanisi Site (Georgia). Palaeogeography, Palaeoclimatology, Palaeoecology 288, 1-13.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B., Kent, J., 2000. Biodiversity hotspots for conservation priorities. Nature 403, 853-858.

Neilson, J., 2008. Environmental Governance in the Coffee Forests of Kodagu, South India. Transforming Cultures eJournal, 3(1), 185-195.

Parker, A.G., Eckersley, L., Smith, M.M., Goudie, A.S., Stokes, S., Ward, S., White, K., Hodson, M.J., 2004. Holocene vegetation dynamics in the northeastern Rub' al-Khali desert, Arabian Peninsula: a phytolith, pollen and carbon isotope study. Journal of Quaternary Science 19, 665-676.

Pascal, JP., 1982. Bioclimates of the Western Ghats. Institute Française de Pondichery, Travaux de la Section Scientifique et Technique.

Pascal, jp., 1988. Explanatory Booklet on the Forest Map of South India. Sheets: Belgaum- Dharwar-Panaji, Shimoga, Mercara-Mysore. Institut Français de Pondichery, Travaux de la Section Scientifique et Technique.

Pearsall, D.M., 2013. Paleoethnobotany: a handbook of procedures. Academic Press.

Phadtare, N.R., 2000. Sharp Decrease in Summer Monsoon Strength 4000–3500 cal yr B.P. in the Central Higher Himalaya of India Based on Pollen Evidence from Alpine Peat. Quaternary Research 53, 122-129.

Piperno, D.R., 1989. The occurrence of phytoliths in the reproductive structures of selected tropical angiosperms and their significance in tropical paleoecology, paleoethnobotany and systematics. Review of Palaeobotany and Palynology 61, 147-173.

Piperno, D.R., 1998. Opal phytoliths in Southeast Asian flora.

Piperno, D.R., 2006. Phytoliths: a comprehensive guide for archaeologists and paleoecologists. Altamira Press, Oxford.

Prasad, V., 1985. Impact of grazing, fire and extraction on the bamboo (Dendrocalamus strictus and Bambusa arundinacea populations of Karnataka. Agriculture, Ecosystems & Environment 14, 1-14.

Prasad, V., Phartiyal, B., Sharma, A., 2007. Evidence of enhanced winter precipitation and the prevalence of a cool and dry climate during the mid to late Holocene in mainland Gujarat, India. The Holocene 17, 889-896.

Rajagopalan, G., Sukumar, R., Ramesh, B., Pant, R.K., 1997. Late Quaternary vegetational and climatic changes from tropical peats in southern India – An extended record up to 40,000 years BP. Current Science 73, 60-63.

Ranganathan, J., Daniels, R.J.R., Chandran, M.D.S., Ehrlich, P.R., Daily, G.C., 2008. Sustaining biodiversity in ancient tropical countryside. Proceedings of the National Academy of Sciences 105, 17852-17854.

Roy, PS., Behera, MD., Murthy, MSR ., Roy, A., Singh, S., Kushwaha, SPS ., Jha, CS., Sudhakar, S., Joshi, PK., Reddy, Ch, Gupta, S., Pujar, G., Dutt, CBS., Srivastava, VK., Porwal, MC., Tripathi, P., Singh, JS., Chitale, V., Skidmore, AK., Rajshekhar, G., Kushwaha, D., Saran, S., Giriraj, A., Padalia, H., Kale, M., Nandy, S., Jeganathan, S., Singh, CP., Chandrashekhar, MB., Pattanaik, C., Singh, DK., Devagiri, GM., Talukdar, G., Panigrahy, R.K., Singh, H., Sharma, JR., Haridasan, K., Trivedi, S., Singh, KP., Kannan, L., Daniel, M., Misra, MK., Niphadkar, M., Nagbhatla, N., Prasad, N., Tripathi, OP., Rama, P., Chandra Prasad, M., Dash, P., Qureshi, Q., Tripathi, SK., Ramesh, BR., Gowda, B., Tomar, S., Romshoo, S., Giriraj, S., Ravan, SA., Behera, SQ., Paul, S., Das, AK., Ranganath, BK., Singh, TP., Sahu, TR., Shankar, U., Menon, ARR., Srivastava, G., Sharma, S., Mohapatra, UB., Peddi, A., Rashid, H., Irfan Salroo, Hari Krishna, P PK Hajra, AO Vergheese, Shafique Matin, Swapnil A Chaudhary, Sonali Ghosh, Udaya Lakshmi, Deepshikha Rawat, Kalpana Ambastha, P Kalpana, BSS Devi, Balakrishna Gowda, KC Sharma, Prashant Mukharjee, Ajay Sharma, Priya Davidar, RR Venkata Raju, SS Ketewa, Shashi Kant, Vatsavaya S Raju, BP Uniyal, Bijan Debnath, DK Rout, Rajesh Thapa, Shijo Joseph, Pradeep Chhetri, Ramchandran, R., 2015. New vegetation type map of India prepared using satellite remote sensing: Comparison with global vegetation maps and utilities. International Journal of Applied Earth Observation and Geoinformation 39, 142-159.

Kodandapani, N., Cochrane, MA., Sukumar, R., 2004. Conservation threat of increasing fire frequencies in the Western Ghats, India. Conservation Biology 18, 1553-1561.

Runge, F., 1999. The opal phytolith inventory of soils in central Africa —quantities, shapes, classification, and spectra. Review of Palaeobotany and Palynology 107, 23-53.

Saravanan, V., 2008. Economic exploitation of forest resources in south India during the pre-Forest Act colonial era, 1793-1882. International Forestry Review 10, 65-73.

Saul, H., Madella, M., Fischer, A., Glykou, A., Hartz, S., Craig, O.E., 2013. Phytoliths in Pottery Reveal the Use of Spice in European Prehistoric Cuisine. PLoS ONE 8, e70583.

Singh, J N., 2003. Grasses and their hydro-edaphic characteristics in the grassland habitat of Nilgiris Biosphere Reserve, Tamil Nadu. Bulletin of the Botanical Survey of India 45, 143-164.

Strömberg, C.A., 2011. Evolution of grasses and grassland ecosystems. Annual Review of Earth and Planetary Sciences 39, 517-544.

Surrey, SWL., Everet, J., (2000) Grasses: Systematics and Evolution. CSIRO Publishing. Australia.

Thomas, SM., Palmer, MW., 2007. The montane grasslands of the Western Ghats, India: Community ecology and conservation. Community Ecology 8, 67-73.

Tiwari, M., Ramesh, R., Bhushan, R., Sheshshayee, M.S., Somayajulu, B.L.K., Jull, A.J.T., Burr, G.S., 2010. Did the Indo-Asian summer monsoon decrease during the Holocene following insolation? Journal of Quaternary Science 25, 1179-1188.

Twiss, P.C., Suess, E., Smith, R.M., 1969. Morphological classification of grass phytoliths. Soil Science Society of America Journal 33, 109-115.

Veena, M., Achyuthan, H., Eastoe, C., Farooqui, A., 2014. A multi-proxy reconstruction of monsoon variability in the late Holocene, South India. Quaternary International 325, 63-73.

Figure captions

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

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

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

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

Table 1 Description of phytolith morphotypes, ecological interpretation and climatic index used. 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)	Arecaceae (=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	

Figure 1

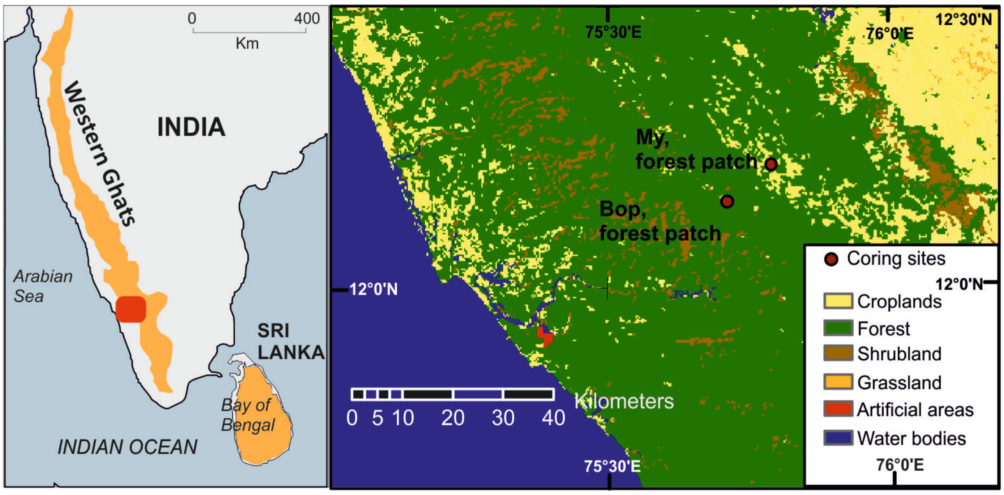

0
400
Km
Western Ghats
INDIA
Arabian Sea
SRI LANKA
Bay of Bengal
INDIAN OCEAN
75°30'E
76°0'E
12°30'N
My, forest patch
Bop, forest patch
12°0'N
0 5 10 20 30 40
Kilometers
75°30'E
Coring sites
12°0'N
Croplands
Forest
Shrubland
Grassland
Artificial areas
Water bodies
76°0'E

Figure 2

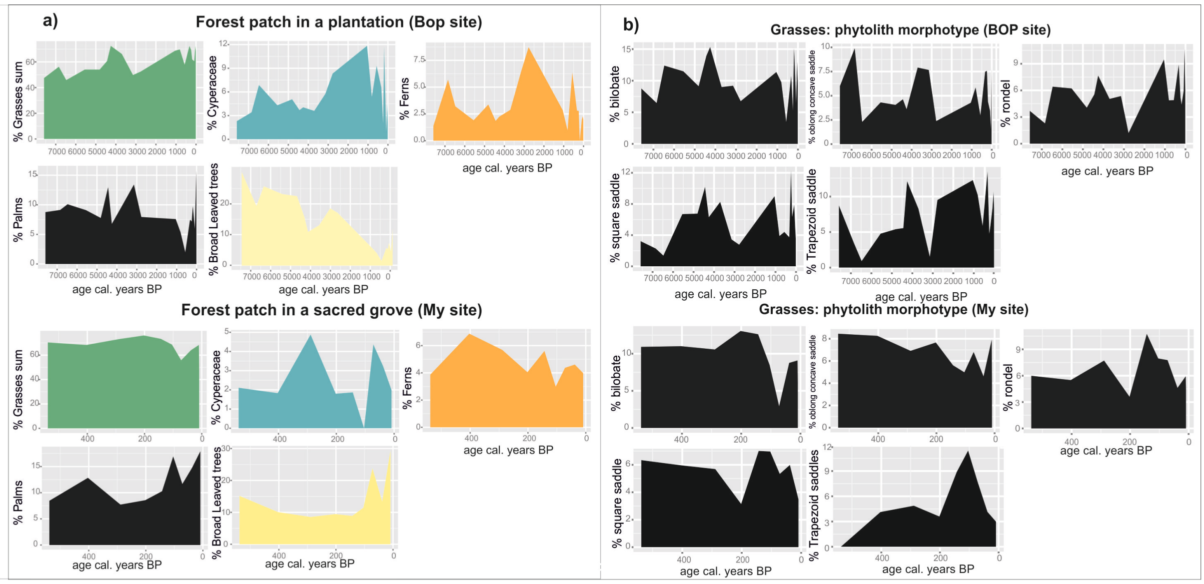
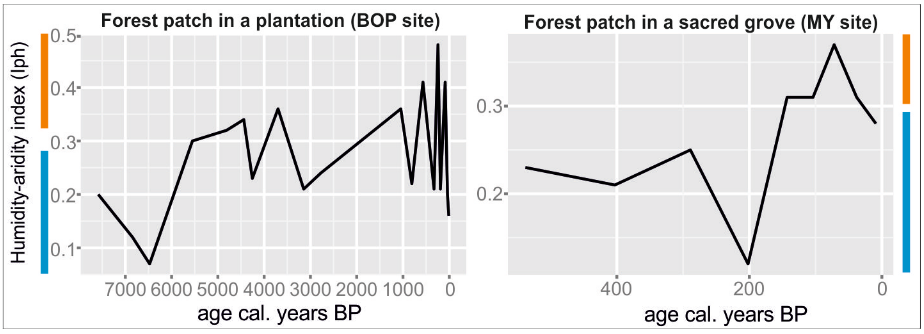
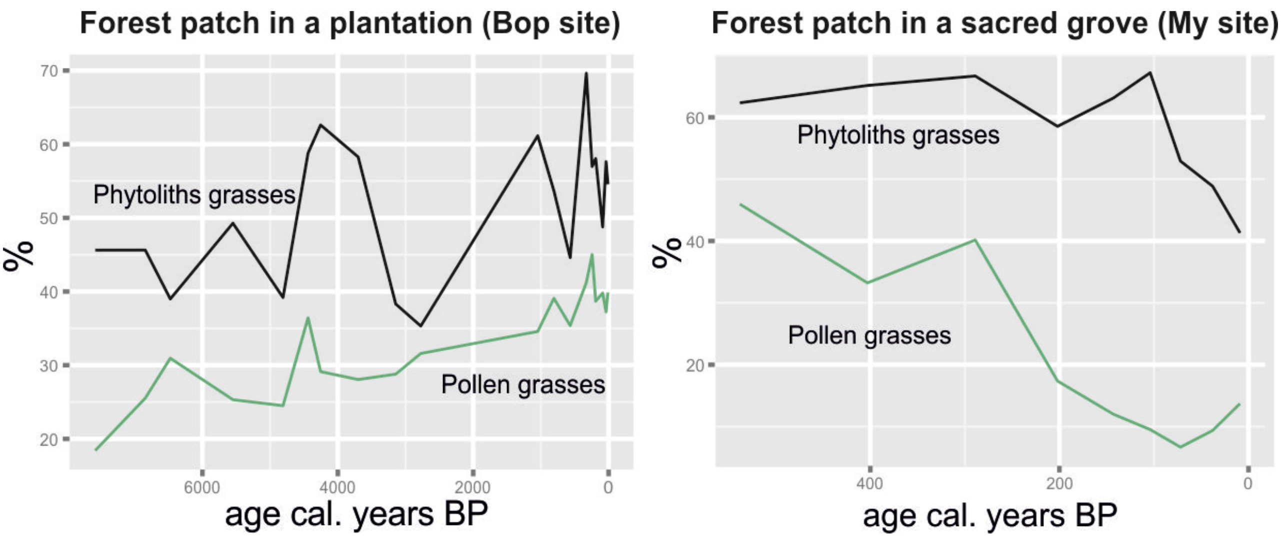

a)
Forest patch in a plantation (Bop site)
% Grasses sum
% Cyperaceae
% Ferns
% Palms
% Broad Leaved trees
age cal. years BP
Forest patch in a sacred grove (My site)
b)
Grasses: phytolith morphotype (BOP site)
% bilobate
% oblong concave saddle
% rondel
% square saddle
% Trapezoid saddle
Grasses: phytolith morphotype (My site)
% Trapezoid saddles

Figure 3



Forest patch in a plantation (BOP site)
Forest patch in a sacred grove (MY site)
Humidity-aridity index (Iph)
0.5
0.4
0.3
0.2
0.1
7000 6000 5000 4000 3000 2000 1000 0
age cal. years BP
0.3
0.2
400
200
0
age cal. years BP

Figure 4


Forest patch in a plantation (Bop site)
Phytoliths grasses
Pollen grasses
%
70
60
50
40
30
20
6000
4000
2000
0
age cal. years BP
Forest patch in a sacred grove (My site)
Phytoliths grasses
Pollen grasses
%
60
40
20
400
200
0
age cal. years BP