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Vegetation, land cover and land use changes of the last 200 years in the Eastern Ghats (southern India) inferred from pollen analysis of sediments from a rain-fed tank and remote sensing

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ABSTRACT

A 98 cm core from *Potapuram Cheruvu*, a rain-fed tank in the Nallamalai Hills of south India, has been palynologically analyzed to study the changes in vegetation and climate of the recent past. This run-off harvesting reservoir, chosen on the basis of remote sensing analysis and field surveys, is not linked with any major river. Its water level is the lowest in the summer, for two to three months, during which time the sampling was carried out. The site, lying south of the "core monsoon zone", gets most of its rains from the south-west monsoon. Palynological studies yielded 75 pollen taxa with "dryness", "wetness", and "human-impact" markers. The ecological attributes of the plant species assigned to the pollen taxa provide an indirect link to specific environments (wetter/drier) that supported the land cover. The analyzed core revealed the vegetation history around the site during the past two centuries through pollen analyses supported by remote sensing. Even during this short period, distinct fluctuations in the vegetation assemblages were observed. Remote sensing indicates that the forest cover did not change significantly during the past ~30 years. During this period there was also a change in the area covered by scrub and agriculture. Taken together and linked to the variations of the individual forest tree markers, this leads to the following story: a definitely drier period between ca. AD 1798 and AD 1846 and a definitely wetter one between ca. AD 1876 and AD 1920. The results from the RS and GIS show that while there was almost no change in the forest cover of the *Potapuram Cheruvu* watershed between 1973 and 2005, taking into account the tank's seasonality by analyzing the wet and dry seasons, there was a notable decrease in the forest cover between 1924 and 1973.

1. Introduction

Palynological analyses of Quaternary sediments in terrestrial sites traditionally involve sampling and analyzing deposits from natural lakes, peats, and fluvio-lacustrine archives (Wright, 1980; Vasanthy, 1988; Sutra et al., 1997; Kumaran et al., 2013). In the tropical south Indian context, undisturbed natural lakes are almost non-existent and the peats are restricted to some highlands abutting the Western Ghats (Nilgiris, Palnis and Anamalais), leaving a huge data gap in the drier Deccan plateau, a large part of which is in the rain shadow of the Indian monsoon. Very few attempts have been made (Morrison, 1993; Bauer and Morrison, 2008; Stephen, 2010) to analyze the sediments from the organically poorer non-system tanks or rainfed reservoirs, that occur in multitudes throughout the south Indian landscape (Gunnell and Anupama, 2003; Gunnell et al., 2007). The present work, a part of a larger research programme on modern pollen rain and paleovegetation studies in south India, aims to fill this gap by studying the sediments of one such non-system tank from the Nallamalai hills of south India, for paleoecological reconstruction, with pollen as the main proxy, supported by remote sensing (RS).

Although the existence of such tanks in peninsular India has been long known, they have remained practically unexplored as sediment repositories. Reasons for this include skepticism regarding their "pristine", "undisturbed", or at least "minimally disturbed" status. Several of these tanks have closely been linked to human habitations for at least a century, and have been found in Survey of India topographical maps dating to the early 20th century. The undulating terrain offers the possibilities for several small "natural" inundation channels. These channels may have been made into non-system tanks by erecting a barrier (bund). Stone

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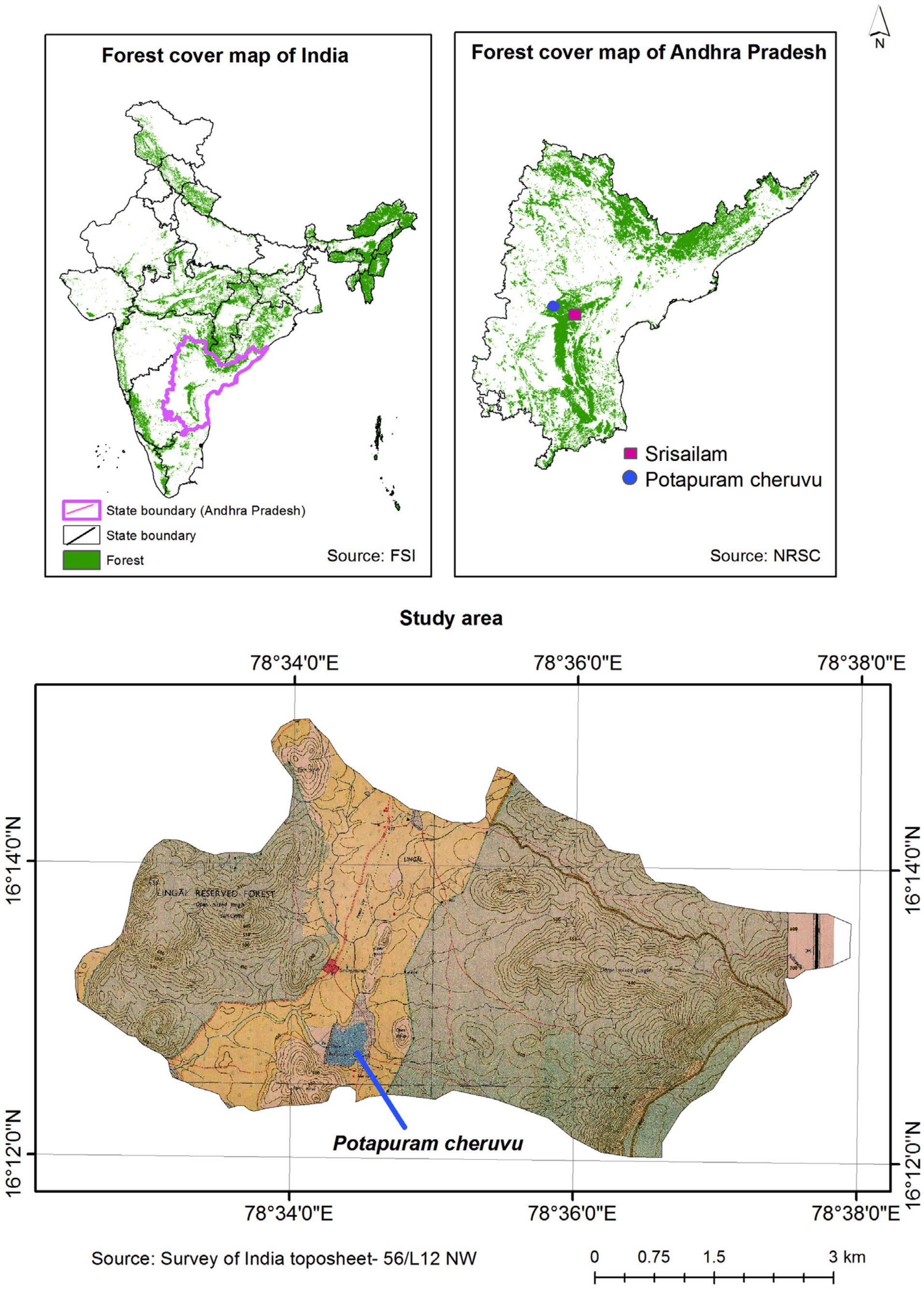

Fig. 1. Study area, locating the coring site *Potapuram Cheruvu*.

inscriptions (epigraphical records) often found in the site are used to date the construction of this bund, which indirectly provides an estimate on the chronology of the tank.

These tanks date to AD 450–500 (Subbarayalu, 2012), although sources from ancient Tamil literature take the date further back (Srinivasan, 1991). The sediment record is likely to be much older. Finer changes over even short periods of the last few centuries are efficiently captured in the sediment records of these tanks. One important advantage of analyzing such non-system water bodies, not linked with major rivers, is that the organic inputs to the tank, including pollen grains, probably originate mainly from within a relatively short distance, which should allow reconstruction of the local vegetation more precisely. Topographic maps of the area clearly show that no major river or stream feeds the tank and even during the monsoons it is fed only by runoff from the slopes. The available instrumental records of rainfall of the station close to the site – Achampet, Mahabubnagar district, Andhra Pradesh, and RS imageries of the tank and its watershed during the past three decades facilitate an easier correlation of the inferred vegetation with climate and land use.

2. Materials and methods

2.1. Site selection and regional setting

The short-listing of potential sites and the final selection were made based on a combination of remote sensing and field surveys of the selected areas. Based on an initial RS analysis of imageries of the Eastern Ghats over thirty years and verifying the toposheets of 1920s, system tanks were eliminated and non-system tanks, not linked to any major river, were short-listed (Anupama et al., 2008). After field visits and surveys of several of these tanks and their catchments, Potapuram Cheruvu (16°12′46″ N; 78°34′12″ E) was chosen as a potential site for collection of a sediment core.

Potapuram Cheruvu is a non-system tank or rain-fed reservoir located in the Nallamalai Hills in the central part of the state of Andhra Pradesh, south India (Figs. 1 and 2). The water (and sediment) catchment for this tank mainly depends on the run-off from the nearby Achampet plateau and surrounding slopes that consist of deciduous forests. Scrubs, thickets, and clearings are present on the lower slopes and in the foothills. Recent plantations and some small clearings for grazing/agriculture were visible around the bund during the field surveys. The water level variation in the tank is distinctly seasonal (Fig. 2).

The topographic map of the tank (Fig. 1) shows that this run-off harvesting reservoir is purely rain-fed and is not linked with any major or minor rivers. The tank never dries out completely, although its water level is the lowest in the summer for two to three months. The site, south of the "core monsoon zone" (Sinha et al., 2007), gets most of its rains from the southwest monsoon, though there is a smaller but significant contribution from the retreating monsoon as well (graph in Fig. 2).

2.2. Core collection, subsampling and laboratory analysis

A Russian corer was used to collect the soft sediments from the partially dried tank bed. The core collected measured 98 cm and was subsampled at 2 cm intervals. The core presented a uniform appearance in terms of colour and texture and comprised organically poor sandy clay. Core sampling was done in June 2005.

Twenty-three subsamples from the core were dried at 40 °C and then prepared and analysed for their pollen content. Laboratory procedure followed the standard protocols (Faegri et al., 1989; Moore et al., 1991) as illustrated in Fig. 4. We found removal of microdebris <5 μm useful (Stephen et al., 2008). The final residues were dried and then mounted with pure glycerin on a glass slide, covered with a 22 mm square cover slip and sealed with DPX mountant. The mounted slides were observed under a light microscope (Wild) using a 50× objective and the pollen contents were enumerated. The Thanikaimoni reference collection of pollen slides at the French Institute of Pondicherry and the standard regional pollen floras (Huang, 1972; Vasanthy, 1976; Nayar, 1990; Tissot et al., 1994) formed the basis of microscopic identification. The pollen taxa were identified and recorded (Fig. 5).

Around 500 pollen were counted for each of the twenty-three samples analyzed. In addition to conventional pollen percentages, volumetric measurements of the sediment and residue were made to obtain quantitative measures of Pollen Per Gram of sediment (PPG) or pollen concentrations. This measure may be cautiously used as an indirect indicator of pollen influx or accumulation rate because the core studied is a short one, with no dramatic changes in its layers in terms of sediment composition (sandy clay). TILIA® was used to plot a diagram of pollen percentages and CONISS (Grimm, 1987) to implement the cluster analysis on the pollen percentages. SoS (sum of squares) was chosen as the measure of dissimilarity for the clustering. A diagram of pollen concentrations (PPG) was also plotted separately.

Due to the poor organic content, PPG provided a basis for selecting the three samples sent for AMS radiocarbon dating to Beta

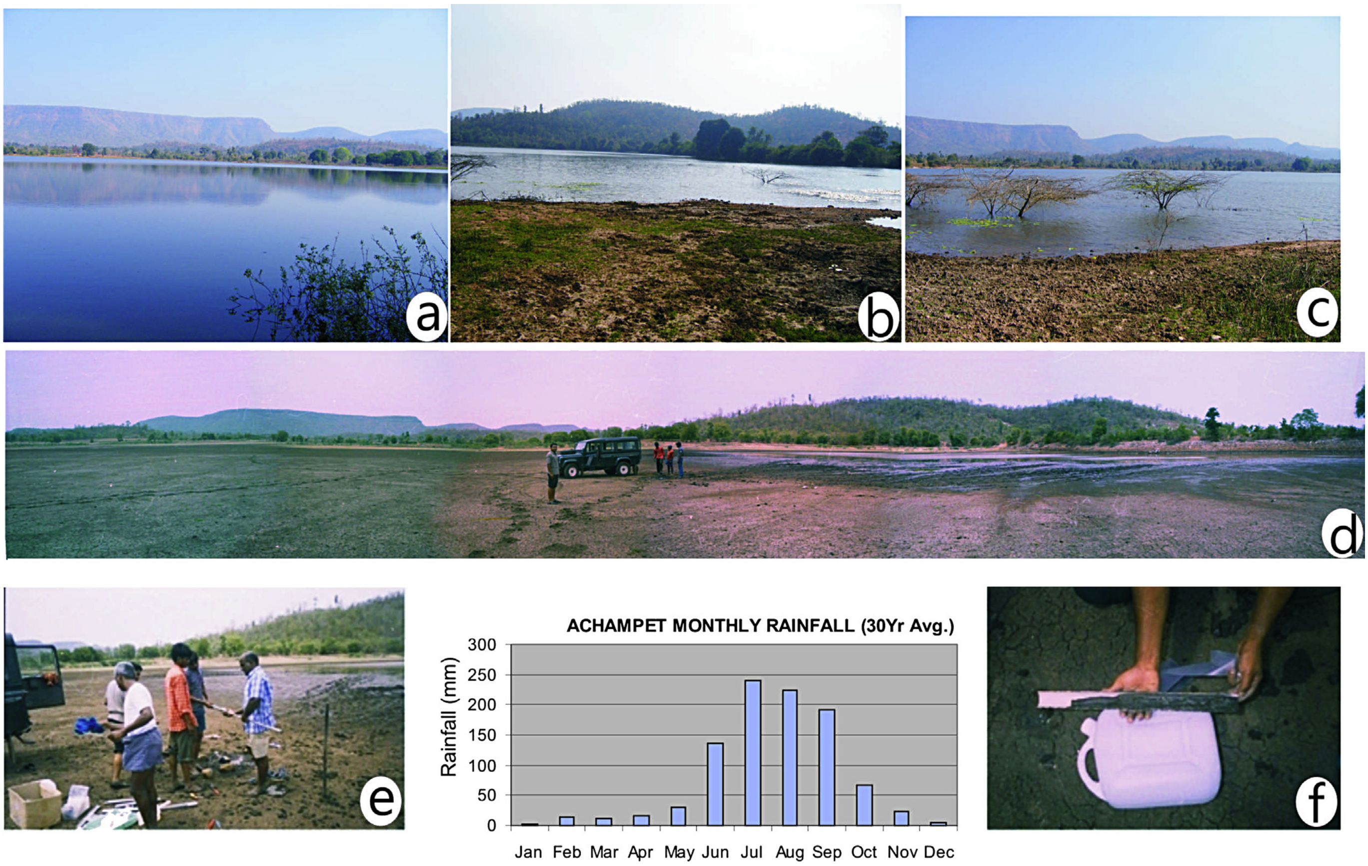

Fig. 2. *Potapuram Cheruvu*: a–c: Views of the site during wet season. d: Panoramic view of the site at the time of sample collection during dry season. e: Coring in progress. f: Core section immediately after collection (a–e: background showing the tank's water catchments comprising deciduous forests on the slopes, scrubs, thickets and clearings in the foothills). Graph shows the available 30 year average instrumental record of rainfall from the station close to the site – Achampet, Mahabubnagar district, Andhra Pradesh.

Analytic Labs, USA (Table 1). The measured and conventional ages are reported in BP and the 2 sigma calibrated dates in Cal AD along with $^{13}C/^{12}C$ ratios (Table 1; INTCAL 04, Talma and Vogel, 1993). Although the intercepts of the radiocarbon ages with the calibration curve were provided in the report from Beta Analytic, these were not used (Telford et al., 2004). Instead, the CLAM programme (current version 2.2; Blaauw, 2010) in R (current version 3.0.1; R Development Core Team, 2013) was used to calibrate (Stuiver and Reimer, 1993; Reimer et al., 2004a,b; Bronk Ramsey, 2013; Hua et al., 2013; Reimer et al., 2013) and plot a simple, linear age depth model (Fig. 6). The calendar scale is in cal BP by default though the equivalents in BC/AD are also shown for convenience. This chronology is based on the assumption that the surface corresponds to AD 2005 (date of coring) and the highest probabilities of the calibrated dates are ca. AD 1770 for the lowest date and ca. AD 1850 for the middle date.

In this study, the remote sensing and pollen data cover periods of different lengths and have different time resolutions. The relevant climate data available were instrumental records and reports of significant famines at the regional level of the presidency of Madras (Raman, 2009). The instrumental record of variations is rainfall at the station close to the site, Achampet, from the IMD (India Meteorological Division, Pune) database. The monthly rainfall variation (graph in Fig. 2) is averaged over thirty non-continuous years (1933–1986 with a major hiatus between 1950 and 1975). One novelty of the methodology employed here is an attempt to use both RS and GIS and pollen analyses to understand vegetation changes post-1925.

3. Results

The analyzed core revealed the vegetation history of the site during the past two hundred years through pollen analyses supported by remote sensing. Even during this short period, distinct fluctuations in the vegetation assemblages were observed, which is of specific interest especially in the context of the results from the RS indicating that the forest cover did not change significantly.

Table 1
AMS radiocarbon dates from bulk sediments measured at Beta Analytic labs, USA. The measured and conventional ages are reported in BP and the 2 sigma calibrated dates in Cal AD along with $^{13}C/^{12}C$ ratios (INTCAL 04, Talma and Vogel, 1993).

Sample depth (cm)	Beta number	Measured age	$^{13}C/^{12}C$	Conventional age	2 Sigma calibration
10–12	231096	105.1 ± 0.3 pMC	−22.3‰	104.5 ± 0.3 pMC	Modern – the material was living within the last 50 years
62–64	231097	40 ± 40 BP	−21.5‰	100 ± 40 BP	Cal AD 1670–1770 (Cal BP 280–180)/Cal AD 1800–1940 (Cal BP 150–10)/Cal AD 1950–1960 (Cal BP 0–0)
96–98	231098	90 ± 40 BP	−21.0‰	160 ± 40 BP	Cal AD 1660–1960 (Cal BP 290–0)

2.3. Remote sensing

Remote sensing and GIS were used to understand the changes in land use in the study area, trying to go back as far as records exist – both satellite images and old topographical maps. The Survey of India topographical map (Toposheet id: NE44/13) of 1924 was downloaded from Berkeley digital website: U.S. Army Map Service, 1:250,000 scale from the Perry Castaneda map collection (http://www.lib.utexas.edu/maps/ams/india/ last accessed 15 July 2013). Given the size of the study area, this is a rather coarse-scale map, but this was the only source for land cover data prior to 1973. Indian Remote Sensing (IRS) P6 (Resourcesat-1) LISS–III (Linear Imaging Self Scanner) was procured from National Remote Sensing Centre's Data Centre (NDC) with a spatial resolution of 23.5 m. Both dry (18th February 2005) and wet seasons' (4th Nov. 2005) satellite data of LISS–III (2005) were taken for study, which was geometrically rectified with an average of less than one pixel accuracy using ERDAS Imagine 9.0 image processing software. Ortho-rectified Landsat MSS (Multi Spectral Scanner) data of 27th February 1973, which was resampled to 57 m spatial resolution, was downloaded from Global Land Cover Facility website (Koeln et al., 1999). Ground truth was undertaken to get acquainted with the general patterns of land cover types of the area. Preparation of vegetation and land cover map (Fig. 3 and Table 2) was accomplished through visual interpretation of multi-temporal satellite images based on image elements including size, shape, pattern, association, tone, and textural variations within a given scene.

Table 2
Remote sensing and GIS details.

Land cover class	1924		Feb. 1973		Feb. 2005		Nov. 2005	
	Area (ha)	% of area	Area (ha)	% of area	Area (ha)	% of area	Area (ha)	% of area
Forest	2875.7	98.9	2228.3	76.6	2228.3	76.6	2228.3	76.6
Wetland	32.1	1.1	28.6	1.0	29.0	1.0	47.7	1.6
Sub total	2907.7	100.0	2256.9	77.6	2257.3	77.6	2276.0	78.3
Scrub	0.0	0.0	70.3	2.4	70.3	2.4	70.3	2.4
Agriculture	0.0	0.0	580.6	20.0	580.2	20.0	561.5	19.3
Sub total	0.0	0.0	650.8	22.4	650.4	22.4	631.7	21.7
Grand total	2908	100	2908	100	2907.7	100	2908	100

3.1. Chronology

The linear age depth model (Fig. 6) established using the available dates from this 98 cm core, dates the bottom of the sequence to ca. AD 1772, 60 cm to ca. AD 1875, and 40 cm to ca. AD 1920. The CLAM software (that helped generate this model) also allowed to find for each depth, "the weighted average or midpoint of the calendar ages from the age-depth models themselves; these latter estimates being based on all dates together as well as on the applied model" (http://chrono.qub.ac.uk/blaauw/wiggles/). The age depth model established also helped estimate ages for all depths in a sequence by extrapolation. Some are shown alongside the depths in the pollen diagrams (Figs. 7 and 8). Thus, AD 1935 corresponds approximately to the upper ∼32 cm of the core.

3.2. RS and GIS

The forested steep slopes of the Achampet plateau, the mid-elevation Srisailam forests and those in the plains to the west of the plateau contribute to the pollen inputs of *Potapuram Cheruvu*. Visual inference that the site, nestled in the interiors of the Lingal Reserve Forest, seemed minimally disturbed or even undisturbed was validated by RS assessment that the forest cover in the *Potapuram Cheruvu* watershed did not change much during the period 1973–2005 (Fig. 2).

Surveys during ground truth showed that at present the vegetation is typically dry deciduous, the forest formation mainly consisting of characteristic trees *Anogeissus latifolia*, *Terminalia alata*, *Cassine glauca*, *Hardwickia binata*, *Pterocarpus marsupium*, *Lagerstroemia parviflora*, *Ixora arborea*, *Ziziphus* spp, and shrub *Grewia hirsuta*. Patches of dry-evergreen forests with *Memecylon umbellatum* are also present in these slopes. The plains and the foothills consist of scrub forests with their characteristic shrubs and thorny shorter trees and lianas.

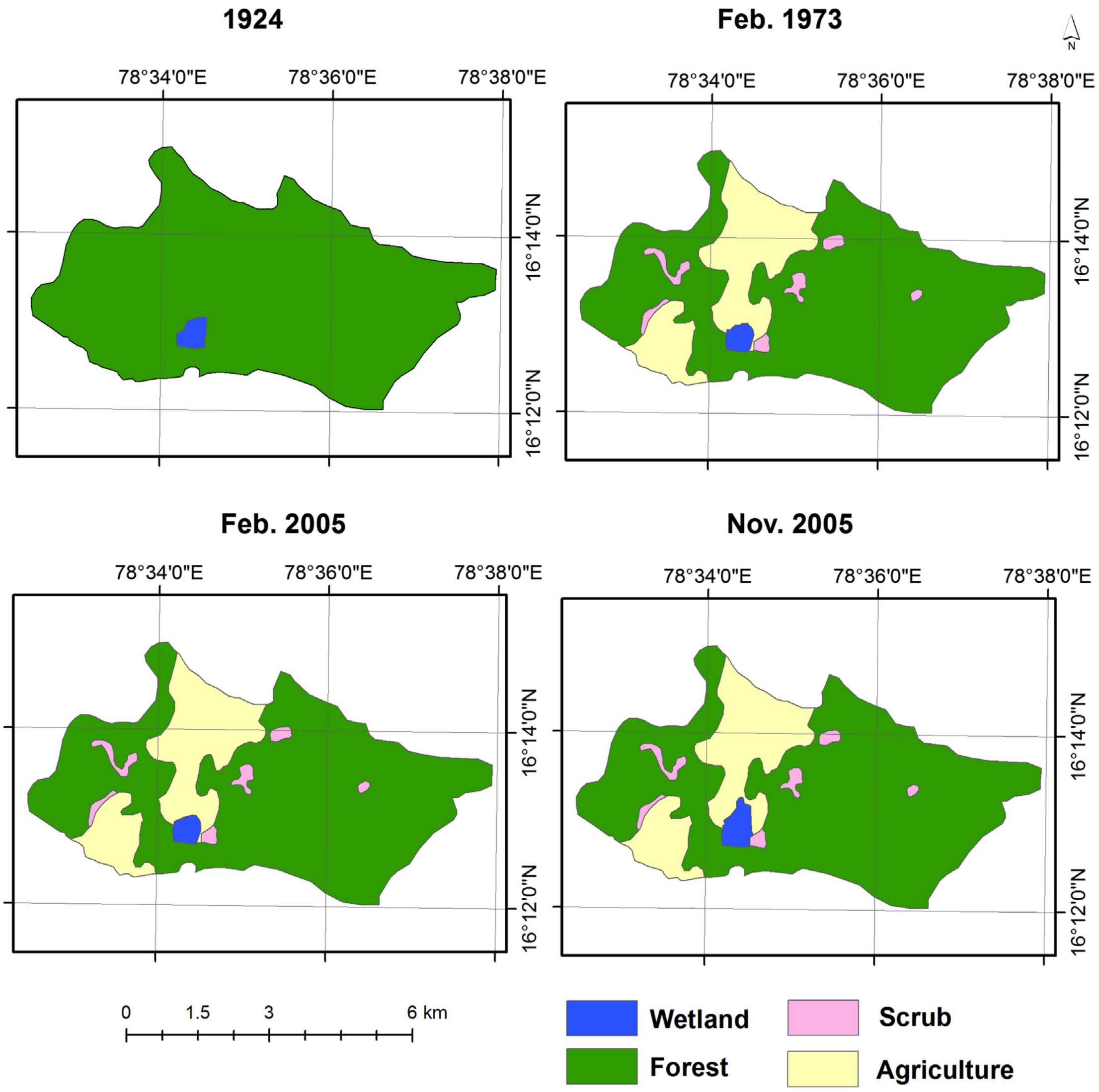

Fig. 3. Remote sensing analyses and land use changes at the study site and its catchments using RS and GIS. For 1923 the Survey of India topographical map was used.

The results from the RS and GIS show that while there was almost no change in the forest cover of the Potapuram Cheruvu watershed between 1973 and 2005, considering the tank's seasonality by accounting for the wet and dry seasons, there was a notable decrease in forest cover between 1924 and 1973 (Fig. 2, Table 2). The wetland area shows temporal dynamics in wet season and dry season, as shown by RS datasets of November 2005 and February 2005. Wetland area in November 2005, which is representative of the wet season, shows spatial extent of 47.7 ha, while in February 2005 it was only 29 ha. During this period, there was also a change in the area covered by scrub and agriculture. The area of the tank was more or less unchanged throughout. Forest cover occupied 98.9% of the study area in 1924 and decreased to 76.6% by 1973. The agriculture around the site presently consists of paddy, pulses, bajra (*Pennisetum glaucum*), and jowar (*Sorghum bicolor*). Footprints of landuse change due to agriculture in the area became significant post-1925 and especially so closer to 1960.

3.3. Pollen record

Overall, 75 pollen taxa were recovered. We have compiled a selection of pollen taxa and the corresponding plants in the surrounding vegetation likely to have contributed to each of them (Table 3). Notable exclusions in the table include large families such as Poaceae and Apiaceae, for which the species lists are available in the regional and local floras (Gamble and Fischer, 1915–1935; Ellis, 1987; Pullaiah, 1997; Pullaiah and Alimoulali, 1997; Pullaiah and Chennaiah, 1997; Reddy et al., 2008). Fig. 5 illustrates the diversity of pollen taxa, inclusive of both abundant and rare ones.

Table 3
Some pollen taxa and their corresponding plants.

Pollen taxa	Plants contributing to the pollen taxa
Justicia-t	*Justicia* spp, *Rungia repens*, *Rostellularia*
Strobilanthes-t	*Mackensia* spp, *Dicliptera* spp, *Stenosiphonium* spp, *Dyschoriste* spp
Lannea/Rhus	*Lannea coromandelica*, *Rhus mysorensis*, *R. paniculata*
Borassus flabellifer	*Borassus flabellifer*
Caryophyllaceae	Some Caryophyllaceae members (*Polycarpon* spp, *Polycarpaea* spp) + Amaranthaceae members (*Celosia* spp, *Allmania* spp)

(*continued on next page*)

Table 3 (*continued*)

Pollen taxa	Plants contributing to the pollen taxa
Mangifera indica	*Mangifera indica*
Caesalpinia-t	*Caesalpinia* spp, *Pterolobium indicum*, *Mezoneuron cucullatum*
Cassia/Senna	*Cassia fistula*, *C. occidentalis*, *Senna auriculata*
Hardwickia binata	*Hardwickia binata*
Tamarindus indica	*Tamarindus indica*
Compositae (Asteroideae)	*Ageratum conyzoides*, *Bidens pilosa*, *Chromolaena* spp, *Tridax procumbens*, *Parthenium hysterophorus*
Compositae (Cichorioideae)	*Elephantopus scaber*, *Vernonia* spp
Xanthium strumarium	*Xanthium strumarium*
Cyperaceae	*Cyperus* spp, *Kyllinga bulbosa*, *Scirpus articulatus*, *Bulbostylis barbata*
Hopea/Shorea	*Hopea utilis*, *Shorea talura*
Croton-t	*Croton* spp, *Givotia rottleriformis*, *Jatropha* spp
Glochidion-t	*Glochidion* spp, *Emblica* spp, *Phyllanthus polyphyllus*
Loranthaceae	*Loranthus* spp, *Dendrophthoe* spp
Melastom./Combretaceae	*Osbeckia* spp, *Memecylon* spp, *Terminalia* spp, *Anogeissus* spp
Acacia/Albizia	*Acacia* spp, *Albizia* spp
Syzygium-t	*Syzygium* spp, *Eugenia* spp, *Psidium guajava*
Haldina-t	*Haldina cordifolia*, *Tarenna asiatica*, *Mitragyna parviflora*, *Anthocephalus* spp
Ixora/Pavetta	*Ixora* spp, *Pavetta* spp
Randia-t	*Randia* spp, *Benkara* spp, *Catunaregam* spp, *Xeromphis* spp
Dodonaea viscosa	*Dodonaea viscosa*
Tectona grandis	*Tectona grandis*

An illustration of some of the pollen taxa and their contributing plants from the vicinity of *Potapuram Cheruvu*. Note: 1. Some pollen taxa are attributed to precise species in the regional context while many are represented by more than one genus. 2. This list is dynamic and some plants can be added/removed based on further studies. 3. Plants included are only in the perspective of the study area and not for all regions. For example, pollen of *Mangifera indica* and *Anacardium occidentale* are similar but we have not included the latter in the list because the plant does not occur in the study area. Some pollen taxa are attributed to species (e.g., *Hardwickia binata*, *Dodonaea viscosa*) based on the regional occurrence while *Tamarindus* is a monotypic taxon with *T. indica* as the only species.

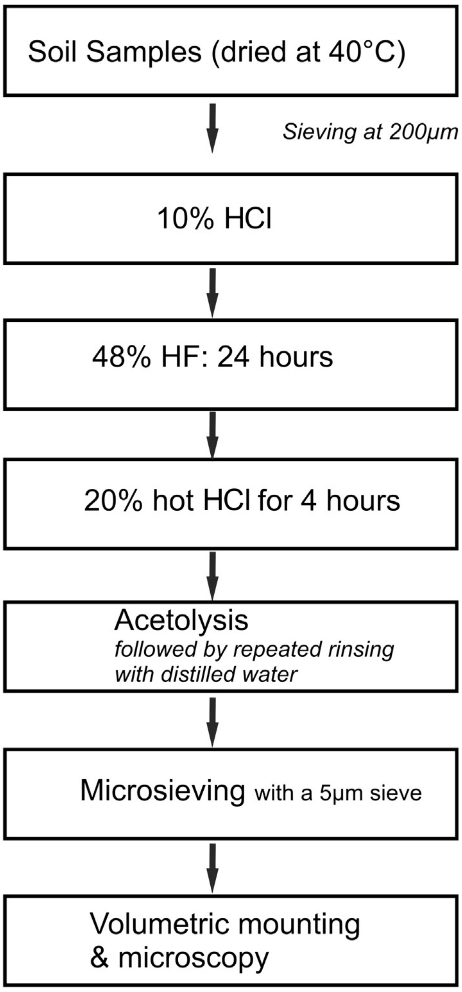

Fig. 4. Steps in the chemical processing of sediment samples for a quantitative, volumetric palynological study.

A selection of 24 pollen taxa is represented diagrammatically (Fig. 7). The stratigraphically-constrained cluster analyses (CA) of the pollen percentages implied three major pollen zones, each of which consists of two subzones making a total of six LPAZs (Local Pollen Assemblage Zones 1a, 1b, 2a, 2b, 3a, and 3b; Fig. 7). In the CA SoS ca.0.8 defines 3 major zones and SoS ca. 0.6 defines 2 subzones in each of the 3 major zones.

Broadly, LPAZ 1 (surface to 37 cm), corresponded to the period ca. AD 1925–2005, LPAZ 2 (38–62 cm) to ca. AD 1869–1925 and LPAZ 3 (63–95 cm) to ca. AD 1772–1869. Within each zone, two subzones were identified based on minor variations in the occurrences of pollen taxa.

In LPAZ 3, *Xanthium strumarium* barely occurred, while other Non Arboreal Pollen (NAP) including Caryophyllaceae, *Oldenlandia* and Compositae-Asteroideae were encountered in small percentages. The maximum percentage of *H. binata* occurred in this zone. In LPAZ 3a, Compositae-Asteroideae and Cyperaceae were in lesser percentages as was *Oldenlandia*, while *H. binata* was at the highest with concentrations of *Glochidion*-t, *Holoptelea integrifolia* and other Arboreal Pollen (AP) in comparison with the lowermost subzone LPAZ 3b.

LPAZ 2 was the smallest of the three zones, marked by NAPs Compositae-Asteroideae, *Justicia*-t, Chenopodiaceae/Amaranthaceae with Poaceae and Cyperaceae. The chief AP encountered here was Melastomataceae/Combretaceae along with *Drypetes* and *Dodonaea viscosa*. LPAZ 2a recorded lesser *Oldenlandia* and *X. strumarium* and an increase in Melastomataceae/Combretaceae in comparison with LPAZ 1b. LPAZ 2b recorded the maximum percentage of Cyperaceae with a decrease in Poaceae. *X. strumarium* was concentrated for the first time. A slight decrease was noted in Melastomataceae/Combretaceae. *H. binata. Lannea/Rhus and Hopea/Shorea* remained broadly the same as in subzone 2a.

LPAZ 1 was marked by Poaceae, Cyperaceae with other NAP taxa such as *X. strumarium*, *Justicia*-t, Compositae-Asteroideae and AP taxa such as Melastomataceae/Combretaceae, *Hopea/Shorea*, *Lannea/Rhus* and in smaller proportions, *H. binata*. LPAZ 1a was marked by an increase in Compositae-Asteroideae, Chenopodiaceae/Amaranthaceae, *Justicia*-t and AP like *Hopea/Shorea*, with a decrease in *H. binata* in comparison with the subzone beneath. LPAZ 1b had lesser Cyperaceae and Compositae-Asteroideae with increases in *X. strumarium*, *H. binata* (in the middle of the subzone) and *Oldenlandia*.

Fig. 8 depicts the variations in the pollen concentrations (PPG) for the same pollen taxa along with the variations in the total PPG and percentage organic carbon. The total organic carbon fluctuated around 2% all through the core.

The diagram of the PPG variations highlights a trend of variations for even ubiquitous taxa such as Poaceae. The variations in the total pollen per gram of sediment allow the definition of high and low pollen concentration (hpc/lpc) zones. Three hpc zones alternate with three lpc zones (Fig. 8). Each of the three LPAZs has one hpc. The maximum and minimum PPG occurred in LPAZ 3, the second minimum occurring almost at the top in LPAZ 1a. Some

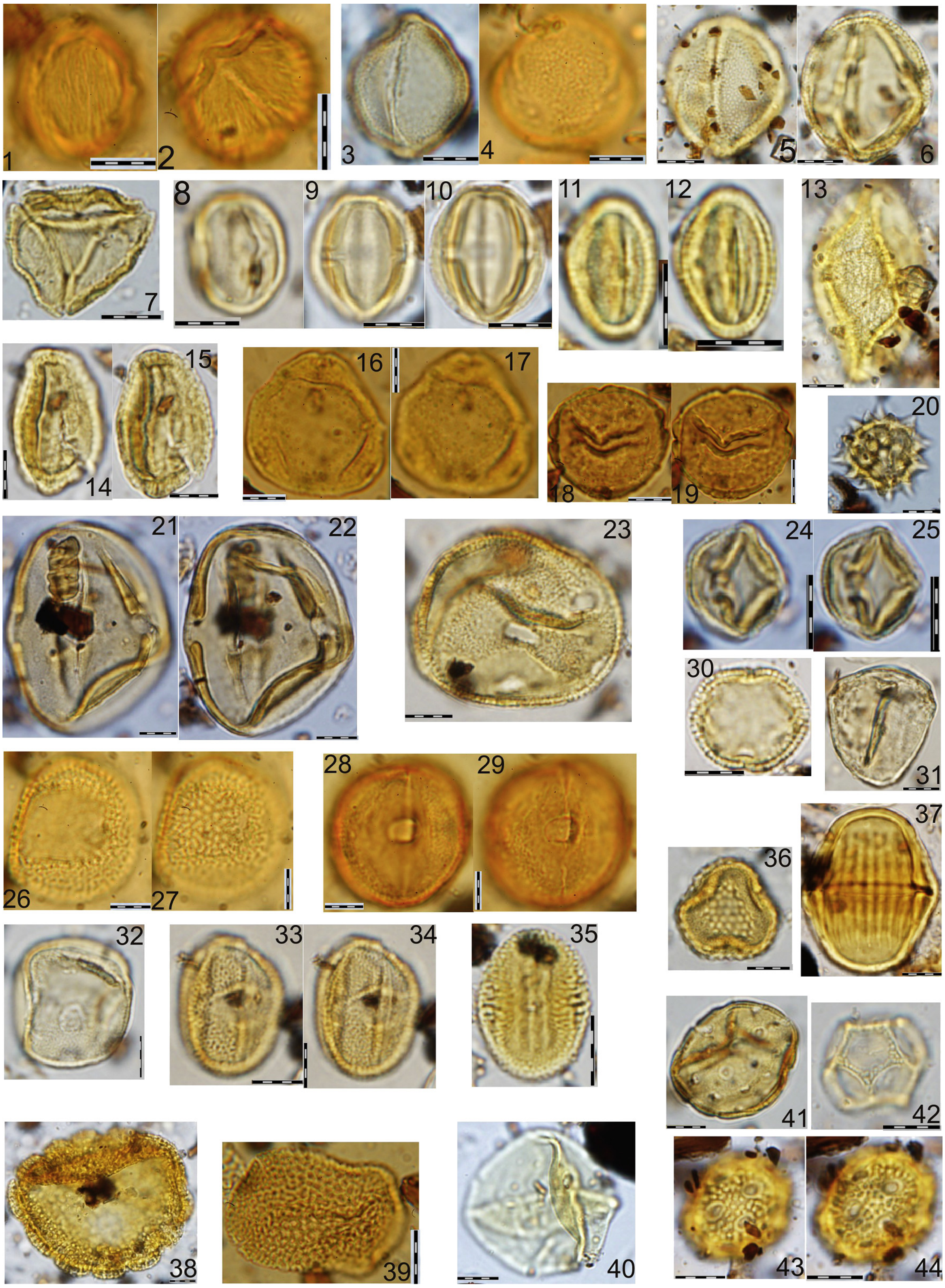

Fig. 5. Pollen taxa recovered from *Potapuram Cheruvu* core. 1–2. *Lannea/Rhus*. 3–4. *Hopea/Shorea*. 5–6. *Drypetes sepiaria*. 7. *Schleichera oleosa*. 8–10. Melastomataceae/Combretaceae. 11–12. *Securinega*. 13. *Grewia*. 14–15. *Lagerstroemia*. 16–17. *Helicteres*. 18–19. *Holoptelea integrifolia*. 20. Compositae-Asteroideae. 21–22. *Madhuca*. 23. *Hardwickia binata*. 24–25. *Haldina*-t. 26–27. *Typha angustata*. 28–29. *Dodonaea viscosa*. 30. *Glochidion*-t. 31. *Casuarina*. 32. Cyperaceae. 33–34. *Oldenlandia*. 35. *Justicia*-t. 36. *Xanthium strumarium*. 37. Polygalaceae. 38. *Borreria*. 39. *Impatiens*. 40. Poaceae. 41. Chenopodiaceae/Amaranthaceae. 42. *Aerva/Alternanthera*. 43–44. Caryophyllaceae.

sharp changes in the total PPG were noted all through the core, although the highest values were confined to LPAZ 3.

For several taxa, including Poaceae, Chenopodiaceae/Amaranthaceae, Melatomataceae/Combretaceae and *H. binata*, pollen concentrations were maximum in LPAZ 3. For some others like *X. strumarium* and *Typha angustata* the concentrations were minimum. For these maximum taxa, there was a marked lowering in pollen concentrations in the top half of LPAZ 3a.

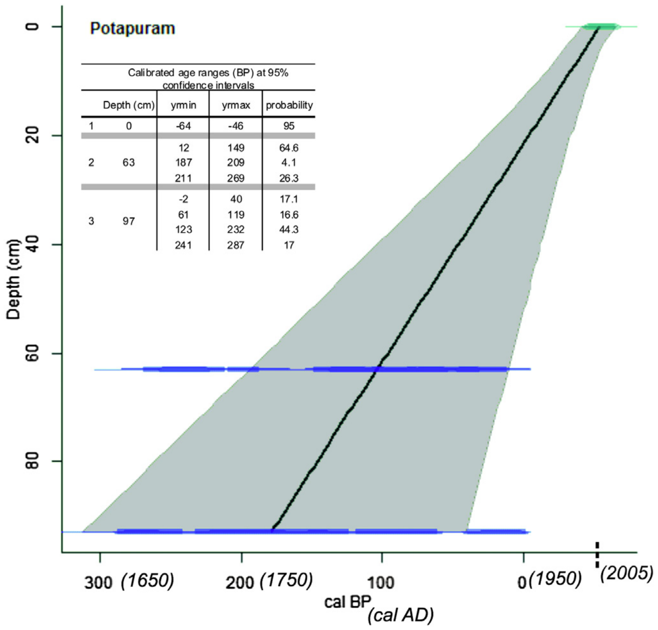

Fig. 6. Age depth model of the studied core. Table inset shows the probabilities of calibrated ages for the samples dated at 3 depths along the core.

The smallest of the three zones, LPAZ 2, was generally characterized by an increase in the concentrations of Cyperaceae, *Justicia*-t, *T. angustata*, *Madhuca* and *Schleichera oleosa* and a decrease in the concentrations of Poaceae, Chenopodiaceae/Amaranthaceae, Caryophyllaceae, Melastomataceae/Combretaceae, *H. binata* and *Lannea/Rhus*. *X. strumarium* and *Casuarina* are more consistent in their presence and increase in their concentrations in this LPAZ. Most taxa including Cyperaceae show decreased pollen concentrations in LPAZ 2a compared to LPAZ 2b, *T. angustata* and *Justicia*-t excepted.

Some taxa showed increased pollen concentrations in LPAZ 1 (*Oldenlandia*, *X. strumarium*, *Hopea/Shorea*, *Holoptelea* and *Madhuca*) while several others were low or in reduced concentrations (*T. angustata*, Melastomataceae/Combretaceae and *H. binata*). Concentrations of *Justicia*-t, *Oldenlandia*, and *X. strumarium* are distinctly higher in LPAZ 1b compared to LPAZ 1a. Cyperaceae and Caryophyllaceae show a decrease followed by an increase within LPAZs 1b and 1a. Chenopodiaceae/Amaranthaceae, Melastomataceae/Combretaceae and *Lannea/Rhus* are present at almost constant low percentages in both subzones. Some plantation markers such as *Casuarina* and *Borassus* occur in this zone in distinctly higher concentrations.

Among the trees, there were greater pollen concentrations in the lower part of the pollen diagram of Melastomataceae/Combretaceae, *H. binata*, *Haldina*-t, and *Lannea/Rhus* in contrast to *Hopea/Shorea*, *Drypetes sepiaria* and *Madhuca*, which increased

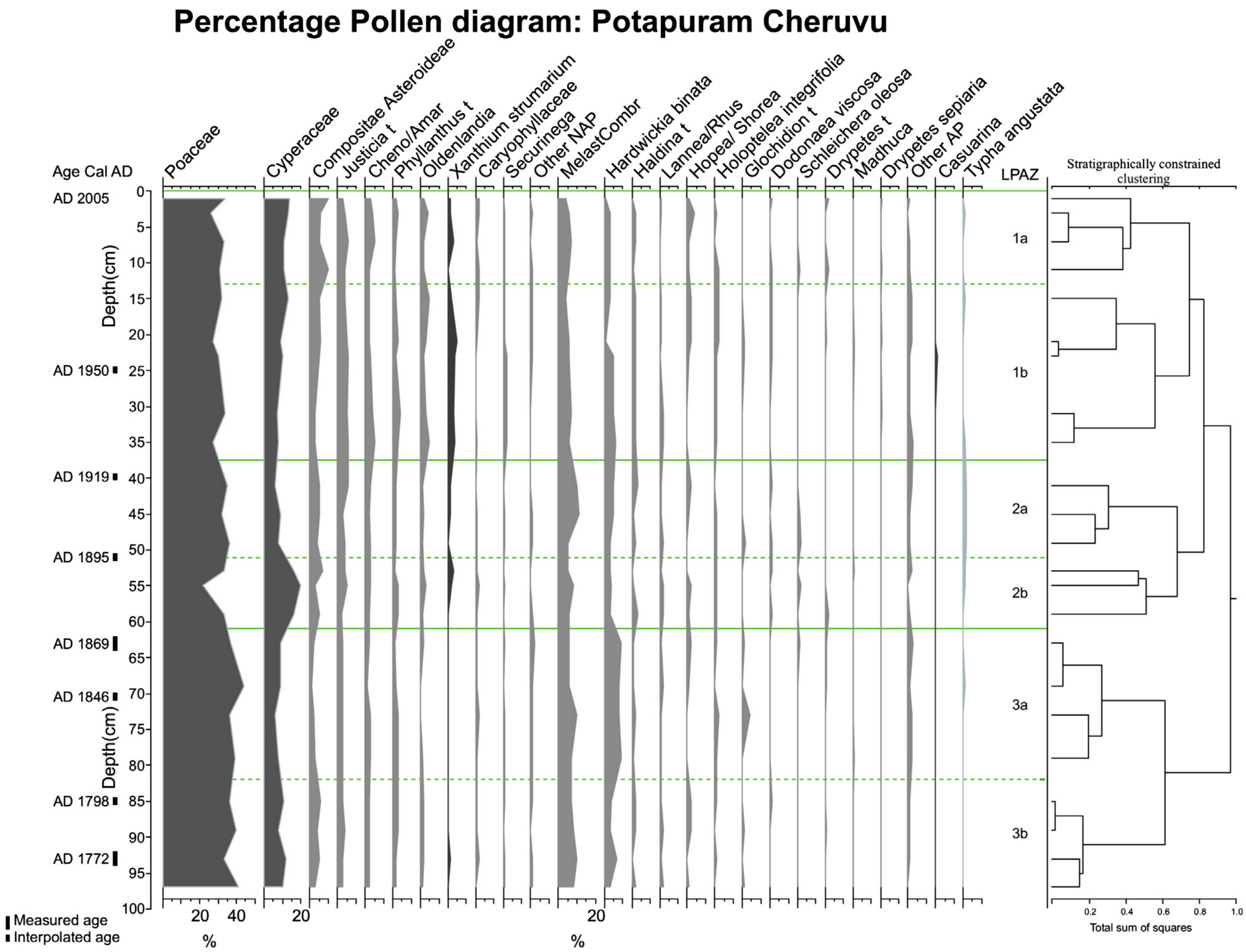

Fig. 7. Percentage pollen diagram of the core depicting pollen zones based on stratigraphically constrained cluster analyses including measured and radiocarbon ages interpolated in Cal AD from an aged depth model and six Local Pollen Assemblage Zones (LPAZ) (redrawn from Anupama et al. (2008)).

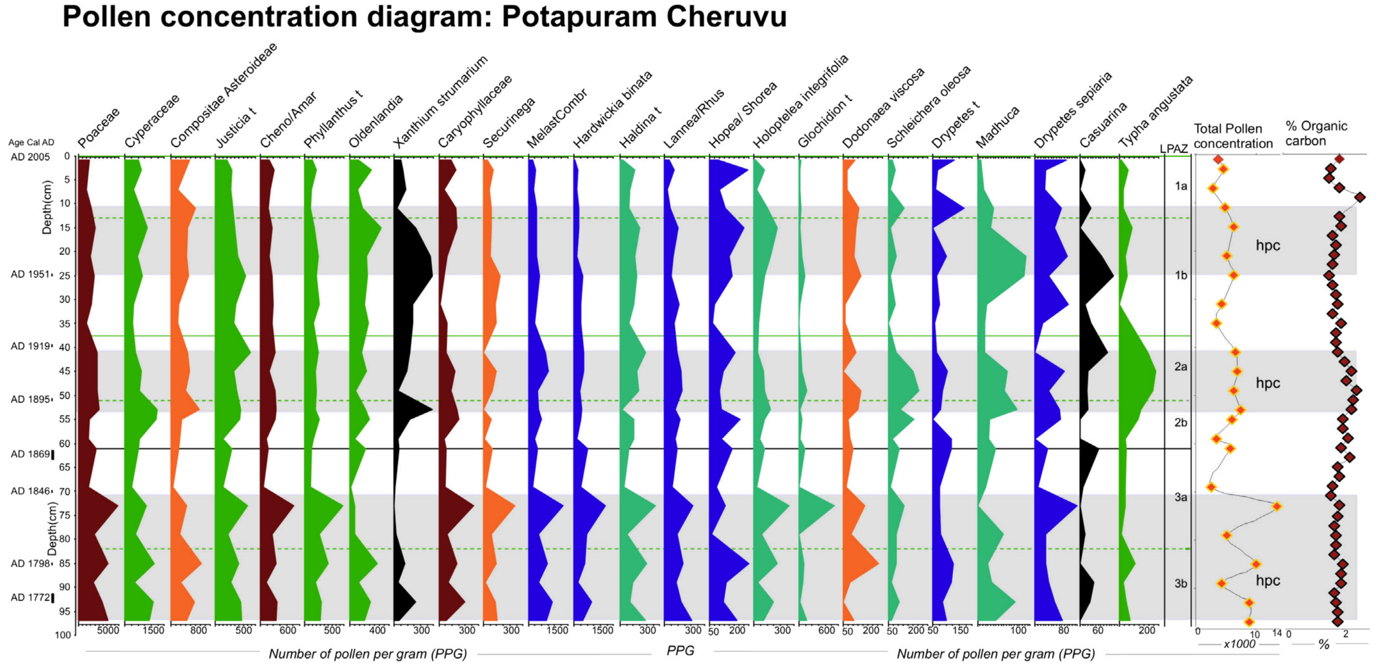

Fig. 8. Variations in the pollen concentrations (PPG) of selected taxa and total PPG. Zones of high pollen concentrations (hpc) have been shaded grey. Graph at the extreme right shows that the total organic carbon fluctuates around 2% all through the core. The six LPAZs based on pollen percentages are marked. *X*-axis scales are not uniform for all the taxa. Colours are given to groups of taxa with common ecological attributes (for example, Cyperaceae, *Typha angustata* are coloured green as wetness indicators and *Securinega* orange as a dryness indicator). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

towards the top. Among the herbs, there were increased pollen concentrations in the lower part of the pollen diagram of Poaceae, Chenopodiaceae/Amaranthaceae, and Caryophyllaceae in contrast to *Oldenlandia* and *T. angustata*. *X. strumarium* and *Casuarina* showed increased concentrations at the top, and *D. viscosa* and Poaceae decreased. *Borassus flabellifer* and *Tectona grandis* (not shown in the diagrams) were recorded only sporadically and in small quantities.

While Poaceae was the main and ubiquitous constituent of the pollen diagram from this core, there were a number of forest taxa typical of the mainly dry deciduous forests in the present day catchments of the Achampet plateau and other areas surrounding this tank. These correspond to arboreal pollen taxa such as *H. binata*, Melastomataceae/Combretaceae, *Hopea/Shorea*, *Haldina*-t, and *Lannea/Rhus* (Table 3). A number of herbs and shrubs in the forests and in the clearings and the *in situ* tank bed and local elements were also represented in the pollen assemblages by *Phyllanthus*-t, *Oldenlandia*, Chenopodiaceae/Amaranthaceae, *Dodonaea viscosa*, and Caryophyllaceae.

Pollen of *Casuarina*, a common cash crop, was seen in small percentages all through the core. *Tamarindus indica*, an avenue tree in this region, started appearing in insignificant percentages in the middle of the core. A chief pollen marker of forests, Melastomataceae/Combretaceae, showed an overall declining trend in the top layers, along with *H. binata* and *Lannea/Rhus*. Cyperaceae, occurring at high percentages in the lower levels, showed a dip at the middle levels and increased significantly in the top 20 cm. *Oldenlandia* also recorded an increase at the top of the core, and *T. angustata* in the middle. Overall, the percentages of forest taxa showed a decrease in the upper part, where the ubiquitous grass pollen percentages were also marginally lower.

4. Discussion

The pollen spectrum of *Potapuram Cheruvu* has components that indicate, singly or as assemblages, changes in land cover composition of its catchments and surroundings over time. The local pollen assemblage zones (LPAZs) and the phases of high and low total and individual pollen concentrations (hpc/lpc) provide the basis for discerning the temporal dynamics of this ∼200 y sediment core.

A simple age model was established using the available AMS radiocarbon dates. The simplicity of these results is due to the fact that effectively there are only two dates measured and these two dates span a period in the calibration curve where not much can be done due to repeated wiggles. A longer core taken underwater at the centre of the tank may facilitate the use of radiocarbon and ^{210}Pb and Cs to more firmly establish the chronology of these tank sediments.

By assigning the plant species that could contribute to the pollen assemblages of these taxa (Table 3), we are able to interpret the changes in land cover (vegetation). Some ecological attributes of the assigned plant species provide an indirect link to specific environments (wetter/drier) that supported this land cover.

4.1. Pollen markers of wetness/dryness

There are at least two main means by which sediment/pollen enters this rainfed reservoir: (i) with the water that runs off from the catchment forests, slopes and plateaus surrounding it and (ii) through aerial transport. Thus, periods of reduced rainfall (drier) probably favoured substantially more aerial transport that could reflect in the pollen record as increased percentages/concentrations of "drier" pollen taxa markers. Periods of increased rainfall (wetter) may be reflected in the pollen record as increased percentages/concentrations of "wetter" pollen taxa markers, indicative of the availability of more local (wetter) microhabitats of standing water, marshy slush and moister soils.

Based on their ecological affinities and edaphic adaptations, the "wetter" pollen markers include mainly *T. angustata* and Cyperaceae, elements easily associated with tank beds and hence of "local" origins in this pollen record. The chief pollen marker of dryness and openness is *Securinega*, which is a “forest” element and hence not of local origin.

We have also used some additional markers for wetness and dryness. *Oldenlandia*, a marker of precipitation in other parts of India (Singh et al., 1990) is considered as a wetness marker. The caveat is that in the Deccan peninsular region and especially in the erstwhile Madras Presidency, there are several species of this genus, some favouring drier habitats (Gamble and Fischer, 1915–1935). An additional forest marker of wetness that correlates well with the main “wetter” zone is *S. oleosa*. *D. sepiaria*, another forest marker, is used additionally for dryness. All other markers that can, with caveats, be included as dryness indicators include Poaceae, Chenopodiaceae/Amaranthaceae, Caryophyllaceae and Compositae-Asteroideae. Taken together, the pollen concentrations of these taxa show a variation almost synchronous with the main forest dryness/openness markers and in opposition to the wetness markers. The main caveat here is that these taxa are one or more large and diverse families or infra families whose ecological amplitude will necessarily be high. Considering the possible plant species associated with the taxon Chenopodiaceae/Amaranthaceae in the study area, it was found that the members of Amaranthaceae, found in drier regions, were more common than Chenopodiaceae, and so this taxon may be assigned as one indicative of drier habitats.

Classical pollen analyses from peats and lakes usually disregard or remove from the total pollen sum the “local aquatic” markers such as *T. angustata* and Cyperaceae. The nature of the sedimentary archive we have used – an almost closed and completely rainfed reservoir, allows us to use these markers for ecological interpretation. Neither the ubiquitous Poaceae nor the local aquatic Cyperaceae, ever reach percentages as high as 80% (Sutra, 1997; Suryaprakash, 1999), always remaining within 50%.

Between ca. AD 1798–1846, LPAZ 3 is marked by an increase in the forest taxon *Securinega*, a dry scrub element, and successive increases in Compositae-Asteroideae, Poaceae and Chenopodiaceae/Amaranthaceae overlapping with successive decreases in *Oldenlandia*, *T. angustata* and Cyperaceae. Taken together, this may be interpreted as a period corresponding to locally drier conditions probably as a result of a decrease in the annual average rainfall during that time. Before ca. AD 1798, the tendency is towards a wetter phase, but only a longer core can establish that.

Between ca. AD 1876 and AD 1920, LPAZ 2 is marked by an increase of pollen taxa such as *T. angustata* and Cyperaceae that would flourish in locally wetter microhabitats. *Oldenlandia* records an increase in concentrations during this time. *T. angustata* requires substantial amounts of standing water to thrive in such a seasonal tank, implying such water availability over several successive years. During this time, among the forest taxa there is an overall increase in pollen concentrations for *S. oleosa*, Melastomataceae/Combretaceae, *Haldina*-t, *Hopea/Shorea*, and *Madhuca*. Among these, *S. oleosa* has a tendency to prefer riparian habitats, which probably became available as non-perennial streams in the forest catchments. This is only possible if there had been an increase in the annual average rainfall during that time.

Between ca. AD 1920 and AD 1950, LPAZ 1 is marked by an increase in *Securinega* and a simultaneous decrease in *T. angustata*, and hence can be considered a drier period. However, the main feature of this zone is an increase of human impact markers and so the drier and wetter signals need to be delineated carefully.

4.2. Pollen markers of human impact

The top of the core characterized by LPAZ 1 is to be carefully interpreted in terms of wetness and dryness, because the increase in human impact markers such as *X. strumarium* and *Casuarina* in tandem with *T. grandis* and *Borassus* is the most striking feature of this zone. The drier period in this zone also corresponds to an increase of most dryness markers. These show a decline in the top part of the core, indicating that the period post-1950 may have been a wetter one, simultaneous with slight increases of *Oldenlandia*, *T. angustata*, and Cyperaceae.

The forest pollen markers taken as a whole showed a decrease in this zone. In terms of the forest composition, there were changes in selected forest pollen markers that seem more related to human activities than to climate. Examples are: changes in the pollen influx and percentages of *H. binata*, a tree that is still extensively used as fodder (Singh and Rathod, 2007; field observation notes), in conjunction with that of a major deciduous forest component (Melastomataceae/Combretaceae) and in contrast to changes in forest components such as *D. sepiaria*, *Haldina*-t., and *Madhuca*.

Taken together and linked to the variations of the individual forest tree markers, this leads to the following story: a definitely drier period between around ca. AD 1798–AD 1846 and definitely wetter around ca. AD 1876–AD 1920. Mooley and Parthasarathy (1984), studying the summer monsoon of India during 1871–1978, report that the lowest summer rainfall in India was in 1877. Later, the southwest monsoon over the entire country showed a continuous rise in the 10-year mean from 1899 to 1953. Although the forest pollen markers taken as a whole showed a decrease at the top of the core, this is more likely due to human activities, marked distinctly by an increase in *X. strumarium* around the time the wetter period started.

4.3. Land cover changes

The pollen record back to ca. AD 1772 shows the persistence of the vegetation assemblage through this time, particularly the major elements of this dry deciduous forest type in terms of presence-absence. The record also shows that human impact was present all through this time, although its magnitude was strongest since ca. AD 1950.

From RS and GIS, it is clear that the forest cover decreased substantially between 1924 and 1973, with a simultaneous increase in the areas under scrub and agriculture. Results from the pollen analyses broadly support this because the increase of *X. strumarium*, the maximum influx of *Casuarina* and the overall decrease in pollen concentrations of forest taxa were during this period. Between 1973 and 2005, RS data show insignificant change in the broad scale land cover and land use in the *Potapuram Cheruvu* watershed, indicating that there was no further loss in forest cover. Broadly, this is also supported by pollen analysis, as the uppermost part of the pollen record shows a slight increase in the overall percentage and concentration of forest taxa.

With pollen analysis, it is possible to further assess the actual vegetation composition. Results indicate that though the overall forest cover remained unchanged, recovery of the important “type” species such as *H. binata* and Melatomataceae/Combretaceae is not really evident and as such, a point of concern for the forest managers. In conjunction with our field observations of the practice of “loping” of *H. binata* trees, we caution that while this does not destroy the tree in the short-term, it may affect its flowering cyclicity and pollen productivity and hence its reproductive cycle, in the long run.

Even at the time of sampling, the agriculture around the tank was of a limited extent only. This is reflected in the pollen record, where we do not find significant agricultural markers, but more (tree) plantation markers.

H. binata, an important constituent of the deciduous forest of the Eastern Ghats is one of the important markers that emerged through this study. As a natural forest component that is also used by people as fodder, this has the potential to represent both "natural" and "human induced" changes. In addition to the Eastern Ghats, this species is also important in the central Indian forests, including those within the core monsoon zone. Such markers have an additional regional relevance, as they are well-preserved even in organically poorer clayey soils. Several species of the families Combretaceae and Melastomataceae, taxa that occur in large proportions through the core, are also of regional significance with reference to the mixed tropical dry deciduous forests.

Taken together, results from remote sensing and pollen analyses indicate that forest conservation measures in this watershed have been reasonably positive: practically no change in the land cover and land use for the past ~30 years and a slight increase in the total forest pollen at the top of the core attest to this. Given the complexity of the system, we can only say that this is a good beginning: there is substantial value in combining traditional palynology with modern, sophisticated RS and GIS. Further, finer resolution RS and multi-proxy studies on spatially well distributed terrestrial sediment cores at a regional scale are required for an assessment of the long term dynamics of the forest, with a view to its conservation and sustainable management (Gillson and Duffin, 2007; Dearing et al., 2010).

5. Conclusions

The story of human–environment interactions during the last two centuries through the analysis of *Potapuram Cheruvu* using RS and GIS, the instrumental climate record and palynology, reads as follows: Human activities are evident throughout this period but not implicated in a major change of the actual forest cover. Although this record is mainly one of land cover and land use changes, local wetter and drier phases could be inferred using ecological attributes of the pollen markers. These phases could then be linked to probable increases and decreases in monsoon (rainfall) which is the only source of water and sediment to this tank. Changes in the forest composition, especially in the first half of the 20th century, are more likely due to human impacts.

The period we have found to be drier, 1798–1846, is also a period where several droughts and famines are documented in the Presidency of Madras, especially the Guntur famine of 1833–35 (Raman, 2009). It may also be significant that this period overlaps with what is broadly defined as the Little Ice Age, globally when the monsoon was weaker.

However, the main strength of this sediment record and its study supported by instrumental observations and RS and GIS is that it provides a coherent picture of land cover and land use, at the local-regional scale and highlights the indirect link to specific environments (wetter/drier) that supported this land cover. Such studies, definitely required in the tropics (PAGES 2K consortium paper, 2013), are the first steps towards obtaining quantitative reconstructions of land cover and land use (Sugita, 2007a,b,c) for tropical peninsular India, similar to those already obtained for Europe and North America (Gaillard et al., 2010; Commerford et al., 2013) and ongoing in Africa (Duffin and Bunting, 2008; Gaillard et al., 2012).

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