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ORIGINAL ARTICLE

Forest plantations, water availability, and regional climate change: controversies surrounding *Acacia mearnsii* plantations in the upper Palnis Hills, southern India

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Abstract Plantation forests not only impact carbon and water cycles, but also affect biodiversity, livelihoods, and shape regional economies. Each of these impacts differs across varying scales of analysis. This paper illustrates how forest, climate change and hydrology debates play out in the context of the forest plantations of Australian black wattle (*Acacia mearnsii*) in the upper Palni hills of southern India. We outline the contradictory perspectives of different local groups regarding the impact of plantations on catchment hydrology and water availability, and examine these in relation to changes in the regional economy and rainfall patterns. Our analysis indicates that changes in these two factors have played a more significant role than existing wattle plantations in affecting local and regional water availability. We suggest that ongoing debates regarding forest plantation–hydrology–climate change relationships need to broaden their scope to include changes in regional rainfall patterns and shifts in regional economic activity. This approach is likely to provide a more realistic assessment of plantation forests in a dynamic regional context, and offer more resilient strategies for regional landscape and catchment management under conditions of high variability in rainfall patterns.

Keywords Plantation forests · Social perspectives and debates · Kodaikanal (Tamil Nadu, India) · *Acacia mearnsii* · Catchment hydrology · Regional climate change

Introduction

Many proposals for mitigating the effects of global environmental change advocate large-scale afforestation for reducing carbon emissions, increasing carbon sequestration, providing biofuels, and preventing soil erosion (Kohlmaier et al. 1998; Nabuurs et al. 2007; Chazdon 2008; FAO 2007, 2008; Canadell and Raupach 2008). From the viewpoint of critics, however, proposals for large-scale afforestation are more likely to create problems of reduced stream flows, groundwater storage, and water runoff in catchments, and thus exacerbate the effects of climate change at regional and local levels (Le Maitre et al. 2002; Jackson et al. 2005; Farley 2007; García-Quijano et al. 2007; Licata et al. 2008). These contradicting viewpoints have made afforestation and management of existing forest plantations a contentious issue for state forestry agencies that are charged with carrying out a range of economic, social, and environmental responsibilities (Calder 2007). Forest management is further complicated by the intersection of economic forces that drive the revenue potential of plantation forests, regional land use pressures, and environmental campaigns linked to biodiversity protection and control of invasive alien species.

This paper provides an illustration of the forest, climate, and hydrology debates centred on plantations of the Australian black wattle (*Acacia mearnsii*) in the mountains of southern India. *A. mearnsii* was introduced during the 1960s in State forest lands located in the upper altitudes of

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the Palni hills—an eastern offshoot of the Western Ghats, a mountain range that runs parallel to the southwest coast of peninsular India, near the hill-station of Kodaikanal (Mitchell 1972; Matthew et al. 1975; see Fig. 1). The tree species is well established on the southwest and western edges of the upper Palnis between 1,800 and 2,400 m both within state forest plantations and in non-state forest areas near towns and rural settlements (Matthew 1988). The importance of black wattle plantations has declined over the past two decades due to changes in import policies pertaining to wattle bark extracts and declining demand for the resource by the Indian leather industry. All the same, black wattle continues to be used in various ways by local households and industry in the region. In recent years, local environmental groups have accused the black wattle of being an invasive introduced species that reduces stream flows in local catchments and threatens the unique biodiversity of the area (Viraraghavan 1988; PHCC 2007). They have lobbied the Forest Department and local government agencies to clear wattle plantations and replant the areas with native vegetation in order to restore stream flows and native biodiversity, and increase water availability in both highland and lowland areas (Stewart and Balcar 2008).

In this paper, we examine the relationship between *A. mearnsii* plantations and water availability by focusing on changing regional economic conditions and rainfall patterns in the upper Palnis over the past two decades. We begin by outlining the environmental debates regarding the relationship between forests, climate, and hydrology, and identify the problems associated with scale and scope of these studies. This is followed by a brief history of the introduction of acacias in the upper Palnis and their current role in the region's economy. The subsequent sections describe the perceptions of local populations regarding the uses and impacts of black wattle on stream flows and water availability in the region. We then provide an analysis of the changing trends in rainfall patterns in the upper Palnis over multi-decadal to centennial timescales. The final sections discuss the findings and the potential effects of changing rainfall patterns and economic activity on the region's hydrology, and offer alternative ways of thinking

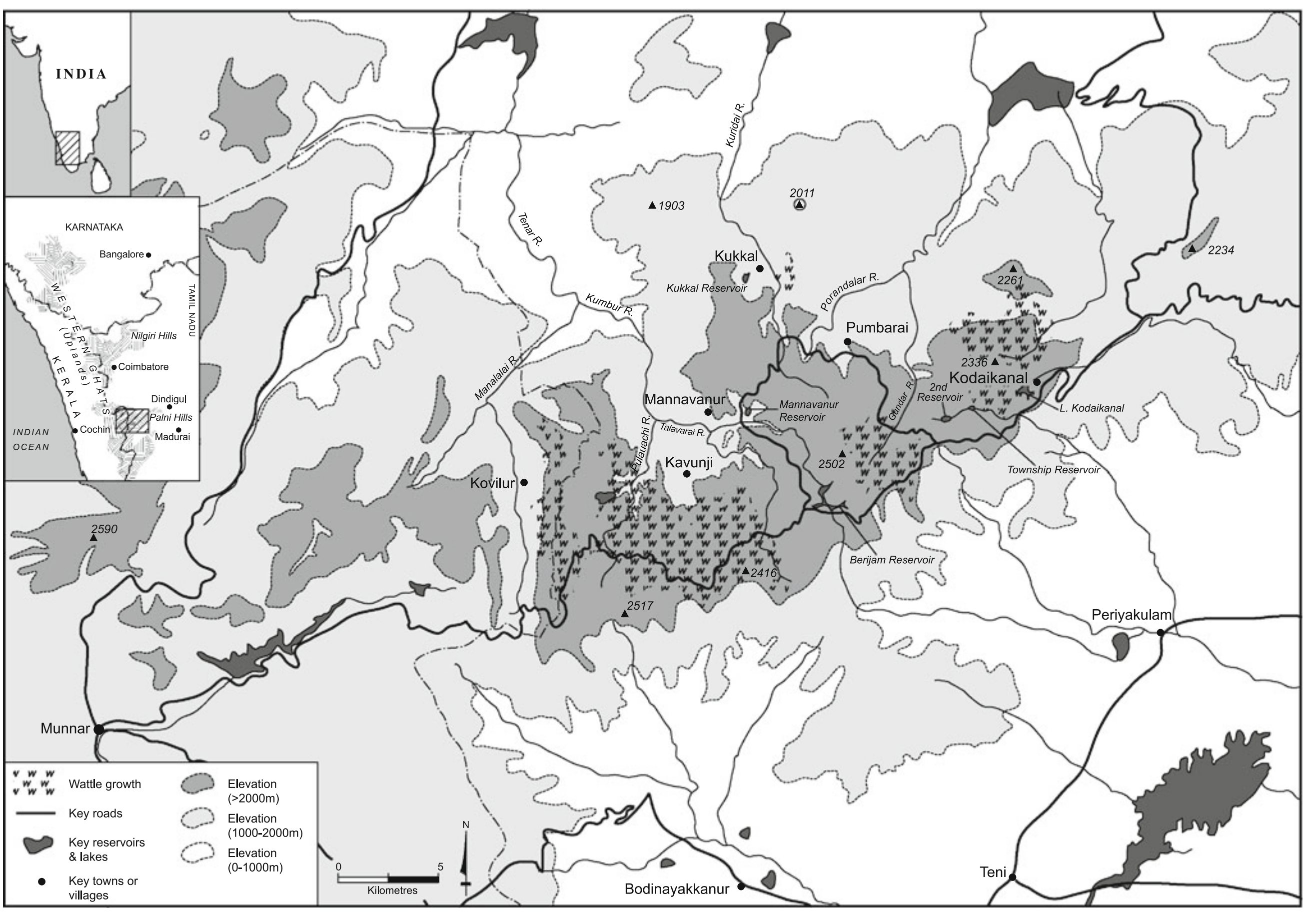

Fig. 1 Map of Palni Hills, showing distribution of wattle plantations, major streams, and reservoirs. Source: Based on Survey of India (1977, 1973–2004), Fontanel (1980), NATMO (2000) and Ramesh et al. (2002)

about plantation forestry in the context of adaptation to regional rainfall variability and environmental change.

Forests, climate, and hydrology

Debates regarding the relationship between forests, climate, and water resources are not new. In the nineteenth century, e.g., dramatic changes accompanying frontier expansion in the Americas and Australia as well as expanding colonial control over land management elsewhere inspired speculation over the links between tree cover, rainfall, and erosion (Marsh 1864; also see Grove 1995). In the early 20th century, trees were seen as the frontline troops called upon to halt new crises of desiccation and dust storms (Stebbing 1935; Swift 1996). Through much of the 20th century, large-scale tree planting was advocated by development agencies to combat soil erosion and desertification and create the basis for agricultural improvement. Throughout, the powerful field of forestry served to institutionalise dominant ideas about the environmentally positive role of forests, ideas which were implemented through formal state policies protecting forests from perceived rampant extraction by local people (Ribbentrop 1900; Grove 1995; Davis 2007; Robbins 2006). The imperial forestry administration in British India, for instance, created categories such as 'reserved' forests for regulated commercial exploitation, and 'protected' forests on mountain ridges, slopes, and along watercourses for maintaining climate and rainfall, preventing soil erosion, and enhancing water supply (Sivaramakrishnan 1999; Rangan 2000).

Current discussions about global warming revive older rationales in advocating tree plantations for mitigating the effects of climate change (Robbins 2006) through preventing deforestation and engaging in large-scale afforestation. Popular and policy-maker understandings have often been follow influenced by the general motto that trees are 'good' for climate and hydrology (Reynolds and Thompson 1988, p. 1; Mathews 2009). However, current scholarship on forest–climate–hydrology interactions suggests that these relationships operate differently at varying scales and contexts of analysis.

Studies that explore the links between forest cover and climate at the global level focus primarily on the cycling of carbon through the earth system. Forests are estimated to contain over 40% of global biospheric carbon (Nabuurs et al. 2007). Deforestation is seen as a key contributor to increased atmospheric carbon, while forest regrowth, particularly through large-scale tree plantations, is seen as a way of reducing atmospheric carbon through sequestration (Kohlmaier et al. 1998; FAO 2007; Chazdon 2008; Canadell and Raupach 2008). Several recent studies have sought to accurately account for carbon fluxes due to changing forest cover, yet a number of uncertainties remain (FAO 2007; Nabuurs et al. 2007; Bonan 2008).

Tree plantations account for approximately 5% of global forests (FAO 2007), but receive substantial attention in discussions of global climate–forest relationships. This is because, in contrast to other types of forest, they are subject to more rapid changes (planting and harvesting) and are more easily affected by policy instruments. However, recent research suggests that the impact of plantation forests on carbon sequestration is highly variable and depends on numerous additional factors such as the ecosystem being replaced, the time frame of measurement, the species used, the types of management plans adopted, and so on (e.g., García-Quijano et al. 2007; van Dijk and Keenan 2007; Zheng et al. 2008).

At the regional level, the impact of forest plantations on climate depends on a variety of feedback loops that may differ from one part of the world to another. For instance, Canadell and Raupach (2008) observe that reforestation in boreal regions would alter albedo by replacing bright snow cover with darker forest canopies, thus warming climate through more absorption of solar radiation. In contrast, in tropical regions, large-scale forest plantations may not only sequester carbon but also increase cloud cover through higher evapotranspiration, thus cooling the climate through additional sunlight reflection.

Researchers focusing on regional climate have long debated the impact of deforestation or afforestation on precipitation (Reynolds and Thompson 1988; Chang 2006; van Dijk and Keenan 2007). Meher-Homji's (1988a) study in the Nilgiri Hills of southern India (an analogous highland area situated some 300 km north of the Palni Hills) revealed that rather than affecting total rainfall, forest cover had a stronger effect on the number of dry days and storm intensity. Bruijnzeel's (2004) comprehensive review observes that most historical analyses which claimed a link between deforestation and decreased precipitation levels failed to take into account other cycles of variability in inter-annual precipitation, such as the El Niño. He notes that some studies, notably in Asia, do show a correlation between cloud forests and precipitation based on empirical measurements of water flows. He states that climate models for the Amazon basin also suggest that large-scale forest clearance (or afforestation) affects the timing and distribution of cloud cover, and thus possibly precipitation.

The debates concerning links between forest cover and catchment hydrology also remain contentious. While a conventional global perspective sees large scale tree cover as the means for preventing soil erosion, increasing water infiltration and retention in soils, and recharging streams and water tables (e.g., FAO 2007; see reviews by Reynolds and Thompson 1988; Bruijnzeel 2004; Chang 2006;

Forsyth and Walker 2008), many scholars working at the watershed scale argue that large-scale tree plantations and afforestation programs can have a substantially negative effect on the hydrology of catchments (e.g., Calder 2002; Jackson et al. 2005; van Dijk and Keenan 2007). They point out that catchments planted with young trees or fast-growing timber species have a higher uptake of water than older and slow-growing forests (or, for that matter, than grasslands), and thus reduce the amount of overall water runoff and, in particular, dry season stream flows. Such research has been particularly prominent in South Africa (Dye 1996; Le Maitre et al. 2000, 2002; Binns et al. 2001; Richardson and van Wilgen 2004) and more recently in Latin America (Farley 2007; Buytaert et al. 2007; Licata et al. 2008). A key point of Bruijnzeel's (2004) review is that soil infiltration—and how it is affected by different land covers and land uses—remains an understudied variable in forest–hydrology relationships.

Other debates centred on catchment hydrology focus on the relationship between forests and flooding (Chang 2006). Two recent studies present opposing conclusions, one arguing that forest protection and tree plantations in upstream catchments reduces the risk of flooding downstream (Bradshaw et al. 2007), while the other arguing that it does not reduce such risk (FAO and CIFOR 2005). Both studies, however, point out that forest composition and condition may be irrelevant in the context of large-scale flooding caused by cyclones (see also van Dijk and Keenan 2007).

Finally, there are disagreements over other side effects in using tree plantations to mediate climate and hydrology (de Wit et al. 2001). Some scholars point out that tree plantations are often established in grassland biomes and thus reduce habitat areas for native grassland biodiversity (Farley 2007; Brockerhoff et al. 2008). Others note that plantations of non-native, fast-growing forestry species are a key source of problematic weedy trees and plants (Binggeli 2001). While some scholars see plantation forests as having a positive effect on regional economies and local livelihoods (e.g., Nabuurs et al. 2007), others urge caution, noting the opportunity costs of forest plantations and the typical tendency to exclude the needs of local communities in forest management (Peluso 1992; Agrawal et al. 2008). As a result, some environmental NGOs campaign against large-scale monocrop plantations (e.g., WRM 2003).

The different perspectives on forests–hydrology–climate relationships generate significant confusion for state forest managers, regional agencies, and local land use planners seeking to understand and respond to global climate change policies and mandates. For example, government foresters are expected on the one hand to engage in a range of activities such as community-oriented forestry, supplying forest resources for domestic industries, biodiversity protection, and climate change mitigation across regional watersheds and localities. Some of these activities involve creating and maintaining plantations of introduced tree species. But, on the other hand, given the arguments that oppose plantations of introduced tree species for their negative effect on hydrology and biodiversity, forestry agencies are also expected to eradicate the plantations and work to restore the landscape with indigenous plant species.

In the case of the upper Palni hills of southern India, the different and sometimes contradictory perspectives regarding plantation forest–climate–hydrology relationships have focused attention on black wattle plantations. On the one hand, local environmental groups claim that wattle and other tree (eucalyptus and pine) plantations have destroyed native plant and animal diversity and reduced water availability in local and regional catchments across the upper Palni plateau and adjacent lowlands. They assert that despite stable average annual rainfall in the upper Palnis, previously perennial streams have had little to no flows during the dry season in recent years due to the high levels of water uptake by plantations in the catchments (interviews with PHCC members and VCT directors, December 2007–January 2008). On the other hand, households living and farming near wattle plantations assert that water uptake by wattle has little to do with dry season stream flows. Instead, they claim that rainfall patterns have changed substantially over the past two decades, and this has been responsible for reduced stream flows during the dry season (interviews with farmers, January 2008). State foresters, on their part, maintain the conventional perspective in claiming that forest plantations ensure adequate rainfall and water supply for the region and provide crucial resources for regional industries and local livelihoods (interviews with DFO, Kodaikanal, December 2007).

The different perspectives regarding wattle plantations raise three issues that have a strong bearing on forest plantation–hydrology–climate relationships at both regional and local levels. First, what are the patterns of change in regional economic activity and land use, and how might these changes influence water demand in catchments? Second, how have changes in forest use and management influenced local perceptions of wattle plantations and water availability? Third, what are the changing trends in *seasonal* (rather than averaged annual volume) rainfall patterns and variability, and how might these affect the hydrology of catchments in the upper Palnis? In other words, changes in regional economic activity, forest management, and rainfall patterns are critical factors that influence both actual and perceived water availability in catchments. These factors are rarely brought together in studies of forest–climate–hydrology relationships, but are extremely important for addressing regional environmental change. The following sections explore these factors in the context of the forest plantation–hydrology debates in the upper Palnis.

Changes in the regional economy of the upper Palnis

Roughly a century ago, the economy of the upper Palnis was predominantly based on small scale subsistence agriculture. With the mid-1800s establishment of the hill station of Kodaikanal as a summer retreat for American and European missionaries, and the later establishment of a school for expatriate children, a small service economy developed that included the production of cool climate, 'English' vegetables (Mitchell 1972; Field interviews January 2008). A new resource-based economy emerged in the region during the 1960s with the establishment of black wattle (*A. mearnsii*) plantations for the production of tanbark on state-controlled forest lands ranging between 1,800 and 2,400 m mainly to the west of Kodaikanal (Mitchell 1972; Matthew et al. 1975). Black wattle was first introduced to the neighbouring Nilgiri hills during the 1940s when import supplies of tanbark for the leather industry were threatened by WW II. These were further expanded after 1948 when the Indian government broke off diplomatic and trade relations with apartheid South Africa, the principal exporter of tan bark (Sherry 1971; Matthew 1969; Matthew et al. 1975). Wattle plantations were established in the upper Palnis during the 1960s to increase tanbark supply for the Indian leather industry.

The economic context began changing again in the 1980s when the Indian government encouraged a switch in the leather industry from exporting tanned hides ('East India leather') to exporting value-added leather goods. This led to increased use of chemical tanning compounds such as chrome sulphate (which shortens the tanning process and produces softer and suppler leather) and increased demand for cheaper wattlebark extract. The National Council for Leather Exports claimed that the supply from wattle plantations from the Palni and Nilgiri hills was inadequate both in terms of strength and volume, and successfully persuaded the government reduce import duties on tanbark extract. With the end of apartheid in South Africa in 1990 allowing for the resumption of trade between the two countries, India began to import wattle extract from South Africa. According to some leather goods manufacturers, the South African tanbark was preferred because of its high strength per volume of extract and, when combined with low import duties, worked out much cheaper than its domestically produced equivalent (Interviews with leather goods manufacturers, Chennai, January 2008).

The rise of imported wattle extract led to a decline in demand for the local product. Tan India, a public sector enterprise and monopoly supplier of wattle extract, closed down during the 1990s.[1] The state forestry department effectively ceased working the wattle plantations in the Palni Hills for tanbark supply, allowing contractors to harvest areas with mixed eucalyptus, pine, and wattle to supply private newsprint and paper industries (Interview with DFO, Kodaikanal, December 2007). Today, the dense wattle plantations fanning out to the west of Kodaikanal represent, in effect, a deindustrialised forest landscape.

Forest plantations in the upper Palnis now play a relatively marginal role in the regional economy when compared to tourism and agriculture. The 2006 tourism statistics for Tamil Nadu state indicate that Kodaikanal received 3.06 million tourists, which is about 7.5% of the total number of people visiting the state. Tourist arrivals in the state have grown at the average annual rate of about 13% between 2003 and 2006. About 97% of the tourists visiting Kodaikanal in 2006 were domestic; most visit Kodaikanal and surrounding scenic spots between December and May, and in August and September (Government of Tamil Nadu 2007).

The resident population of Kodaikanal town has grown alongside the rise in tourism, rising from 16,481 in 1971 (Matthew et al. 1975), to 27,423 in 1991, to 42,327 in 2001, a rate of 8.5% a year. However, the decennial growth of population in Kodaikanal *taluk* (sub-district) as a whole was only 2.1% between 1991 and 2001. This is because the population living in rural settlements falling within the *taluk* declined from 71,175 to 58,347 during the same period (Government of Tamil Nadu 2001). Most rural households in the upper Palnis cultivate vegetables for sale in Kodaikanal and larger urban centres in the plains. Some household members find additional work in Kodaikanal during the peak tourist season or as labourers for timber and pulpwood contractors (field interviews with farmers, January 2008).

The substantial growth of tourist traffic to Kodaikanal, along with hotel establishments and related facilities and increase in the town's resident population, has increased urban water demand. The greatest demand for water is during the main tourist season in April and May, which overlaps with the low rainfall period that roughly extends from early January to the end of May. Kodaikanal municipality receives its water supply from a reservoir that was built in the 1920s on the outskirts of the town. The growth in resident population and tourism led to the

[1] In addition, South India Viscose, a company that processed the debarked wattle boles and eucalyptus trees into rayon, also closed down due to a number of public interest litigation cases that were brought against it for polluting the rivers and streams flowing in the vicinity of its factory (interview with DFO, Kodaikanal Division, December 2007).

construction of a second reservoir above the existing one during the 1980s. Both reservoirs are above 2,000 m, relatively small, and fed by small watersheds. Other reservoirs in the upper Palnis are also located above 2,000 m: the reservoir in Berijam is built within the state forest area and serves the plantations, while those at Kukkal, Kavunji, and Mannavanur supply water to their respective rural settlements (see Fig. 1).

Farmer perceptions of wattle plantations and their impact on stream flows

The Kodaikanal Forest Division contains five forest ranges that have wattle plantations: Kodaikanal, Poombarai, Mannavanur, Berijam, and Vandaravu. We visited settlements located near *A. mearnsii* plantations within these ranges, and sought interviews with diverse stakeholders. We interviewed about 40 farmers in the villages of Poombarai, Kookal, Mannavanur, Kavunji, Poondi, and Polur; 10 forest rangers and guards, 40 firewood collectors, 10 forest labourers and sub-contractors, the station director and grounds manager of the Sheep and Wool Research Centre at Mannavanur, and the grounds manager of the Bryant Park Botanical Garden in Kodaikanal. We conducted group interviews with farmers and forest labourers at teashops in the villages; firewood collectors, mainly women, were interviewed in groups near forest plantations or along the roads leading to their villages; and forest rangers and guards were interviewed at their posts or on beat in the plantation areas. We held longer interviews with older farmers to explore how they saw the long-term trends and effects of *A. mearnsii* on the surrounding landscape and water availability.

Local uses and perceptions of black wattle

There are at least a dozen species of Australian wattle growing on various sites in the upper Palnis. The local population is most familiar with four of these: black wattle (*A. mearnsii)*, silver wattle (*Acacia dealbata)*, green wattle (*Acacia decurrens)*, and blackwood (*Acacia melanoxylon*). Black wattle plantations dominate the landscape to the west of Kodaikanal (see Fig. 1). Green and silver wattles are also found within the plantations. Blackwood is widely distributed in settlements, along roadsides and plantation areas (Matthew 1969).

Most respondents in villages located near plantations use wattles for a variety of purposes. They identified the main commercial uses, such as tanbark production and pulpwood for rayon and paper. Forest labourers and subcontractors were aware of the fact that the private rayon factory (South India Viscose) and the tanbark processing factory (Tan India) had closed down. However, they indicated that there was still a small market for tanbark in the regional centres of Dindigul and Madurai. The majority of forest labourers were involved in harvesting eucalyptus and wattles on private lands and on allotted tracts auctioned by the Tamil Nadu Forest Department to forest contractors. Stripped wattle, along with eucalyptus, was sold mainly to a private firm for paper and newsprint production.

The other major use for the black wattle is firewood, which is mainly harvested by women from the wattle plantations near villages and the town of Kodaikanal. Women respondents in villages mainly collected firewood for domestic use, while those living near Kodaikanal town also harvested wattle for sale. All respondents, female and male, unequivocally stated that the tree provided excellent firewood which produced strong, uniform, and lasting heat and was superior to eucalyptus, pine, and indigenous tree species (referred to as *shola* trees). The silver wattle (*A. dealbata*) was also seen as good firewood, but of less value for tanbark extraction. Both black and silver wattles were also used for building fences, roofs, and walls for homes in the villages. Blackwood (*A. melanoxylon*) is not harvested for firewood or the pulp industry; a few respondents mentioned that it provided good timber for making furniture.

Local perceptions regarding *A. mearnsii* were generally positive. Most of the women firewood collectors noted that the abundance of good fuelwood in the form of *A. mearnsii* made their work a lot easier than before. They no longer had to rely on collecting wood from *shola* (indigenous) tree species that were not as good for burning, and did not have to spend as much time or collect as much quantity of wood for domestic use because of the superior burning quality of *A. mearnsii*. Women who harvested black or silver wattle for sale in Kodaikanal noted that the Forest Department was less stringent about collecting headloads from reserve forest areas near town. Firewood collection was a daily activity for the women, with one head load of wood per week allocated for household use. Around 20 of the 40 women firewood collectors we interviewed in the immediate vicinity of Kodaikanal noted that they held IDs issued by the Forest Department to collect one headload (roughly 35–40 kg) per day. They sold the wood in Kodaikanal to hotels, restaurants, and roadside tea and food stalls for about Rs 80–90 (roughly equivalent to US $2.00), and took home around Rs 60 or 70 (about US $1.50) after covering various daily expenses of transport or food related purchases. Women collectors in outlying villages mentioned that the Forest Department had been more restrictive in the past in allowing them to collect firewood from its wattle plantations. Since these plantations were no longer being worked for tanbark production, forest guards allowed the women freer access for collecting firewood.

Some farmer respondents in the villages indicated that they occasionally maintained small stands of black wattle and eucalyptus on their land as a form of security, to be harvested and sold in times of financial need. They commented that although the market price for eucalyptus was higher, it did not have as many useful qualities as the black wattle. According to them, wattles provided substantial nutrition to the soil, and yields of potato and vegetable crops were higher in plots where black wattle had existed compared to those previously planted with eucalyptus trees.

Perceptions regarding the effects of wattle plantations on local water catchments

When we explored the question of the effects of wattle plantations on local water catchments, almost every respondent in the rural settlements dismissed the negative link between the plantations, soil moisture, and stream flows. They typically contrasted the black wattle with eucalyptus, noting that the taproots of eucalyptus went deep into the ground like 'a nail in a piece of wood' some 6–10 m below and that they 'drank' a lot of water, sometimes drawing it from 20 to 30 m below. In comparison, they described the black wattle's roots as relatively shallow and close to the surface, usually between 1 and 1.5 m and rarely below 2 m and hence not capable of 'sucking up' groundwater. Some farmers and forest labourers noted that the shallow root structure of the wattle made rain water flow off the ground more easily, and that the extent to which wattles hold moisture depends on the type of soil: 'red' soil is very hardy and can store moisture for longer periods at depths of 3 m or more, even on hill slopes, but 'black' soils tend to evaporate easily and become powdery. One respondent who had worked as a caretaker for 40 years in a government animal husbandry research unit noted that even though wattle plantations surrounded the research station, there had been no problems of reduced water availability in the area. Two of the older farmers observed that before the plantations were established in the 1960s, the highlands were mainly covered with grasses, and that *shola* (indigenous) forests were limited to hollows between hill spurs. There was reduced stream flow during the early years when eucalyptus and wattle plantations replaced the grasslands but the flows subsequently recovered.

When we asked older farmers about changes in stream flows and water availability over time, each one stated that the main cause for the reduction of stream flows was because rainfall patterns had altered over the past two decades. They noted that roughly 15–20 years ago, almost every farming household in the area grew 'nine-month' rice to feed themselves alongside seasonal cultivation of vegetables for sale in Kodaikanal. But the changes in rainfall patterns made it difficult to obtain a good rice harvest, and this led most farmers to gradually abandon rice cultivation and increase vegetable cultivation. The conversion of rice plots to vegetable cultivation was made because rice paddy needs standing water during the growing season (April–September), which was supplied by small channels from streams; with changes in rainfall patterns during the growing season, rice yields began to fall, and farmers adapted to the changes by replacing their rice plots with vegetables that did not demand similar irrigation requirements. According to them, this shift in cultivation did not pose great hardship because, by this time, improved roads and transportation made it possible for farmers in the upper Palnis to earn more income from selling their vegetable produce in markets in Dindigul and Madurai. They also noted that around this time, the ruling political party in the state (Tamil Nadu) introduced a low-cost rice scheme which made it affordable for farmers to buy rice for household consumption, and hence they did not have to worry about growing it themselves.

Older farmer respondents identified three main changes in rainfall patterns: (1) there was much less rain during the Southwest monsoon months (June–September), (2) more incidences of cloudbursts or heavy downpours during the non-monsoon and monsoon periods, and (3) lack of a clear sense of the onset of the rainy seasons. According to them, in the past, the annual rain calendar for their area was as follows: the main rainy season was the Northeast monsoon between October and early December; from mid-December to the end of March was the dry season, with little or no rain; April and May brought early summer showers; and from June to early September, there was steady drizzle and light rain from the effects of the Southwest monsoons. They noted that even though the Southwest monsoons did not provide as much rain as the Northeast monsoons, the light yet steady drizzle and rain between June and September kept soils moist and water flowing in the streams throughout the year. However, in recent years, the onset of both the rainy seasons was less predictable and, along with reduction of rain during the Southwest monsoon, resulted in less stream flows and water availability for crops such as their 'nine-month' rice. They also observed that in recent years, rainfall during the rainy season occurred as heavy downpours followed by longer dry spells; this pattern contributed to higher surface runoff within short time periods and not enough time for the rain to penetrate into the soil (Interviews, January 2008).

Objectives and methodology for analysing changing rainfall patterns in Kodaikanal

The views of older farmers in rural settlements near wattle plantations regarding the causes of reduced stream flows and water availability were considerably different from those held by local environmental groups based in Kodaikanal. The latter argued that annual rainfall amounts did not show any marked decrease over the past decades, and that wattle plantations were responsible for reducing stream flow and water availability in catchments. In order to test these contrasting perspectives, we sought to examine seasonal rainfall patterns and variability in the upper Palnis.

The objective of our rainfall analysis was to test three hypotheses based on the changes noted by older farmers: (1) decrease in rainfall during the Southwest monsoon period; (2) increase in rainfall intensity during the non-monsoon and Northeast monsoon periods; and (3) delayed onset of the SW monsoon season. We obtained daily rainfall records from the Bryant Park Botanical Garden in Kodaikanal (1971–2007), and daily and monthly records for Kodaikanal (1901–1980) from the Global Climate Observing System (GCOS), and summary data for an unspecified pre-1970s period from Matthew et al. (1975).[2] The analysis was conducted in four stages.

First, we compared the Bryant Park data with the climatological data provided in Matthew et al. (1975) based on records maintained at the Kodaikanal Observatory to determine how closely the two sites were related. Matthew et al. (1975) provide a graph showing rainfall amounts and number of rain days for each month of the year. Using their data as reference, we compared monthly rainfall totals and monthly rainfall intensity (total rainfall/total number of rain days) for Bryant Park from 1971 to 1980, 1981 to 1990, 1991 to 2000, 2001 to 2007, and the entire period from 1971 to 2007. While it was not clear from the Matthew et al. (1975) study how a rain day was defined, we chose a definition of at least 2.55 mm (equivalent to 1/10th of an inch by the older imperial standards of measurement) falling within a 24-h period. This threshold was obtained from the Tamil Nadu State Gazetteer (Gopalakrishnan 1995) and provided what we estimate to be the most appropriate definition after testing varying thresholds for a rain day.

Second, we used the Bryant Park daily rainfall data to analyse the trends in total rainfall, number of rain days, and rainfall intensity for each month between 1971 and 2007. Trends were calculated using ordinary least squares regression (with missing data weighted as zero). This method can be sensitive to outliers in the time series so in addition we applied the more robust non-parametric Mann–Kendall method (Mann 1945, Kendall 1975) to calculate trend significance at the 5% level throughout.

Third, we analysed the onset date of the Southwest monsoon using the Bryant Park data from 1971 to 2007. Our initial definition for determining the start of the Southwest monsoon is simply given as the date after 1st May when the cumulative rainfall total is greater than 162 mm. While this threshold might seem somewhat arbitrary, it is based on the May climatological rainfall total at Kodaikanal from Matthew et al. (1975). Thus, by our definition, the onset of the Southwest monsoon should begin around the end of May or the beginning of June. The Southwest monsoon is typically defined to start in southern India in the first week of June (Roy 2009), so our definition seems appropriate.

Fourth, since the period we are looking at is relatively short in a climate context, our aim was to determine whether our results would still hold if viewed from a longer-term perspective. Fortunately, the Kodaikanal Observatory (roughly 2 km to the west of, and 200 m higher than, Bryant Park) is part of the GCOS Station Network (GSN) and has daily rainfall records available dating from 1901 to 1970, and monthly rainfall records from 1900 to 1980. To estimate whether it was possible to use the Kodaikanal Observatory as a proxy for Bryant Park rainfall data, we correlated the monthly data from both sites for the overlapping period from 1971 to 1980. Table 1 shows that the correlation for all months over the 10-year period was 0.96 and that the individual monthly correlations ranged from 0.79 to 0.99. While these values are high, indicating that there is indeed a strong relationship between the rainfall totals at the two stations, we are somewhat

Table 1 Correlations between Bryant Park (N10°13′47″E77°29′32″) and the GSN station Kodaikanal observatory (N10°13′52″E77°27′55″; ~2 km west and 200 m higher elevation) using monthly rainfall data, 1971–1980

Data	Correlation
All data	0.96
January	0.99
February	0.96
March	0.79
April	0.91
May	0.93
June	0.91
July	0.83
August	0.90
September	0.81
October	0.98
November	0.99
December	0.95

[2] The daily rainfall data at Bryant Park, recorded by Mr. Sakthivelu, the grounds manager, extended from January 1971 to December 2007. There were some periods for which data was missing, but these gaps were addressed in the rainfall analysis. Unfortunately, there is no way of knowing what period Matthew et al. (1975) used for their summary rainfall data; it could be 1931–1960, or some other period chosen by the authors.

limited in our conclusions because there are only 10 years of overlapping data. However, over this period there does not appear to be a consistent bias between the two stations, i.e., no station is significantly wetter or drier than the other station in any month. Therefore, based on these results, we felt justified in combining the data from the two sites in order to assess longer-term trends in the onset of the Southwest monsoon.

Results of rainfall analysis

Being at the summit of an eastern offshoot of the Western Ghats, the Palni plateau receives rain from both the Southwest and Northeast (also called the 'returning' or 'retreating' Southwest) monsoons, with more than 50% of the annual rain falling during the latter season. The annual average rainfall ranges between 1,650 and 1,800 mm, and is distributed across most months of the year (Meher-Homji 1988b). Matthew et al. (1975) describe the climate of the upper Palnis as having four clearly defined seasons: the *dry season*, usually between January and March, during which rain is scarce and limited to around ten rainy days, the air is crisp, dry and cold, and when ground frost occurs; April and May represent the *warm season* during which most tourists arrive for their holiday in the hills and when summer showers and rain may fall on 18–20 days; the *Southwest monsoon season* extends between June and September, with around 45 days of rainfall spread over the 4 months; and the *Northeast monsoon season* extends from October through early December, when rain is abundant and occurs over 30 or more days. Depending on the timing of the 'retreating' monsoon, the latter half of December may experience a few days of heavy rain or remain completely dry. The climate is described as wet tropical montane (Blasco 1970) with relatively even temperature through the year, the daily maximum ranging between 17 and 25°C and the daily minimum between 5 and 12°C (Matthew et al. 1975; Meher-Homji 1988b).

The data appear to confirm a decrease in rainfall during the Southwest monsoon period (hypothesis 1). A decadal analysis of monthly precipitation totals (Fig. 2) shows that with the exception of the 1971–1980, there has been a consistent reduction in rainfall between May and August in recent decades compared with the summary data presented in Matthew et al. (1975). This result for the upper Palnis differs from studies that show no significant decline in long-term trends for the Southwest monsoon rainfall across India as a whole (Goswami et al. 2006). Further analyses using daily precipitation data from 1971 to 2007 (Fig. 4) reveal statistically significant decreases in total rainfall of 25.9 and 22.5 mm per decade for May and July, respectively. Likewise, the number of rainy days per month has reduced significantly in May and July by rates of 1.8 and 1.1 days per decade, respectively. Conversely, rainfall intensity has significantly increased in January by 5 mm/day per decade although rainfall intensity has significantly decreased in July by 1.4 mm/day per decade.

The data are more equivocal regarding the purported increase in rainfall intensity during the non-monsoon and Northeast monsoon periods (hypothesis 2). Based on decadal analysis of monthly figures, Fig. 3 shows that the 1971–2007 rainfall intensity peaks in March and/or April in contrast to the earlier data in Matthew et al. (1975), which shows a peak in January. Further analysis based on annual daily precipitation data (Fig. 4) for 1971–2007 showed rainfall intensity to have significant trends only in January (an increase of 5.04 mm/day per decade) and in July (a decrease of −1.37 mm/day per decade). Other than these results, our analysis does not show significant increases in rainfall intensity during the Northeast monsoons or the non-monsoon months (but see Goswami et al. 2006; Rajeevan et al. 2008, for increases in extreme rainfall events in India).

The data confirm that the onset of the SW monsoon is likely to have become delayed over the past century (hypothesis 3). Based on the Bryant Park rainfall data (1971–2007), Fig. 5 shows that on average, monsoon onset has shifted from 9th June to 13th July, a change of almost 5 weeks. The trend is significant. However, it is obvious that our method could be sensitive to the choice of threshold (i.e., 162 mm). Therefore, to ensure that our results were statistically robust, we tested the method using various thresholds ranging from 100 mm up to 200 mm with 10 mm increments (not shown). For all thresholds tested, trends in the monsoon onset dates between 1971 and 2007 have significantly increased. For the 150 mm threshold we see an even larger shift in the onset of the monsoon, from 2nd June to 12th July. While it is clear that there is some sensitivity to the choice of threshold, in all cases tested there has been a statistically significant increase of at least 3 weeks in the Southwest monsoon onset date at Kodaikanal between 1971 and 2007.

The same result is obtained from the combined GSN-Bryant Park data (1900–2007). According to this data set (Fig. 6), the start of the SW monsoon has shifted by roughly 3 weeks over the period 1900–2007 from 9th June to 28th June. Following the same methods used for the Bryant Park data, we tested the sensitivity of these results to varying thresholds (not shown). While thresholds between 170 and 200 mm showed further shifts of the onset date, these were not significant. In all other cases there were significant increases in the onset date. For thresholds of 130 mm and below, the onset date was prior to the last week in May indicating that these are probably not appropriate thresholds for classifying SW monsoon onset at Kodaikanal.

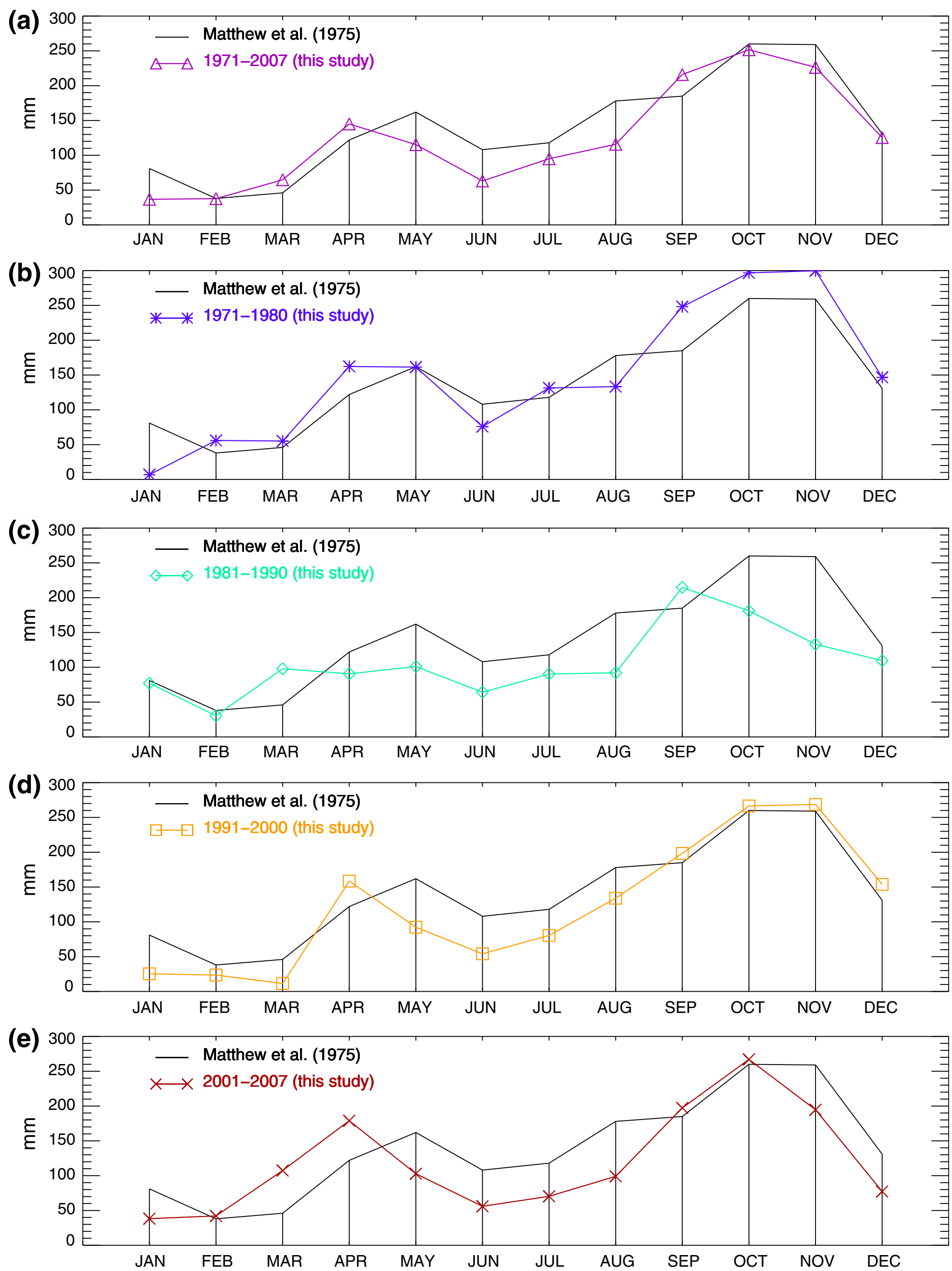

Fig. 2 Average monthly rainfall totals (in mm) for Kodaikanal from Matthew et al. (1975) (*black bars*) and this study for **a** 1971–2007, **b** 1971–1980, **c** 1981–1990, **d** 1991–2000 and **e** 2001–2007. This demonstrates that May–August rainfall (the SW monsoon) has declined beginning in the 1980s

Thresholds of 140, 150 and 160 mm had lines of best fit stretching from 28th May to 20th June, 2nd June to 24th June and 8th June to 27th June, respectively.

In addition to the sensitivity of the results to threshold choice, it is obvious from Figs. 5 and 6 that trend calculations can also be very sensitive to choice of start date. For this reason, we recalculated trends and significance using time periods with different start dates, i.e., 1901–2007, 1902–2007, and so on to 1971–2007. By our definition, irrespective of start date, there has been a significant shift of the onset date of the Southwest monsoon at Kodaikanal of between 16 days (1906 start date) and 40 days (1970 start date). The results indicate that on average, the onset date of the Southwest monsoon is occurring 26 days later than it used to in this region, a shift from the first or second week in June to the last week of June or first week of July. While it is clear that there is some sensitivity to the choice of threshold and start date of trend calculation, the shift

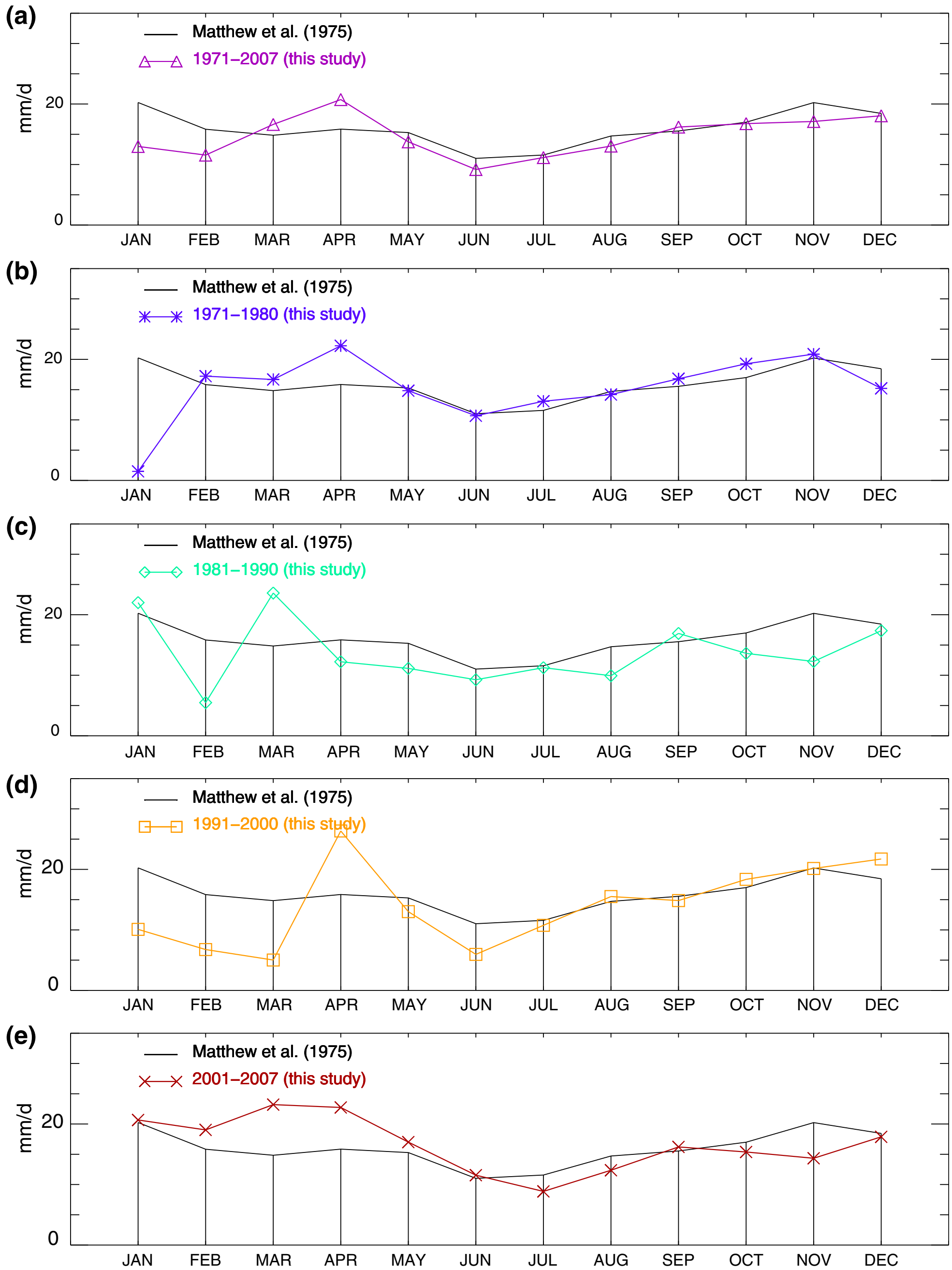

Fig. 3 Average rainfall intensities (in mm/day) for Kodaikanal from Matthew et al. (1975) (*black bars*) and this study for **a** 1971–2007, **b** 1971–1980, **c** 1981–1990, **d** 1991–2000 and **e** 2001–2007. Our data show peaks in March and/or April in contrast to Matthew et al. (1975)

towards a later onset date of the Southwest monsoon in the upper Palnis appears statistically robust and significant.

Discussion of changing rainfall patterns and impacts on water availability in the upper Palni catchments

Our analysis appears to validate some of the changing rainfall trends described by older farmers and long-term residents in the upper Palni settlements and Kodaikanal. The results show significant decreases in rainfall amounts during the Southwest monsoon period for decades subsequent to 1971–1980. The analysis of daily rainfall data from 1971 to 2007 shows decline in rainfall amounts and number of rain days for the pre-monsoon month of May, and the monsoon months of July and September. The claims made by farmers of increasing incidences of heavy downpours appear to be validated in our analysis only for the month of January and not significant for the Northeast monsoon or non-monsoon periods. However, the daily

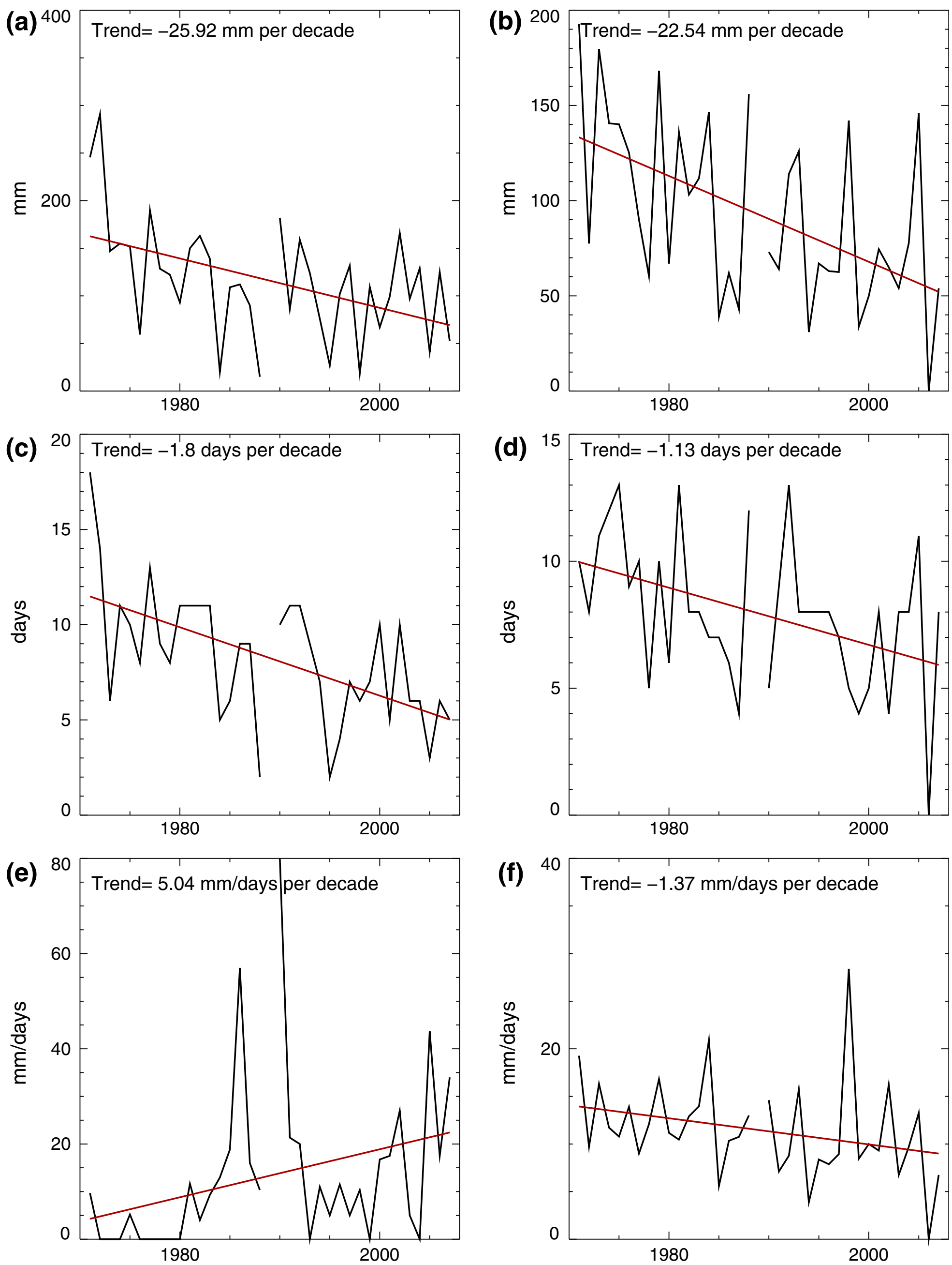

Fig. 4 Trends from 1971 to 2007 for selected months in total rainfall (in mm) from events greater than 2.55 mm for **a** May, **b** July, number of rain days for **c** May and **d** July, and rainfall intensity (in mm/day) i.e., total rainfall/number of rain days for **e** January and **f** July. Results shown are calculated using daily data and trends are statistically significant

rainfall totals used here may not be of a sufficiently high temporal resolution to assess changes in short duration rainfall intensity. Roy's (2009) analysis of hourly rainfall data for India between 1980 and 2002 provides some broad evidence for increases in maximum hourly rainfall events between January and August.

The delay in the onset of the Southwest monsoon by three to 4 weeks appears to support the explanations given by older farmers for the decline of subsistence rice cultivation in the upper Palnis and redirection of effort towards commercial cultivation of vegetables for regional markets. The current predominance of vegetable and potato cultivation indicates that the farming population has effectively adapted to the changes in rainfall patterns and regional political economy.

In summary, reduced rainfall during the Southwest monsoon period, combined with an observed (but not statistically significant) pattern of heavy downpours and longer

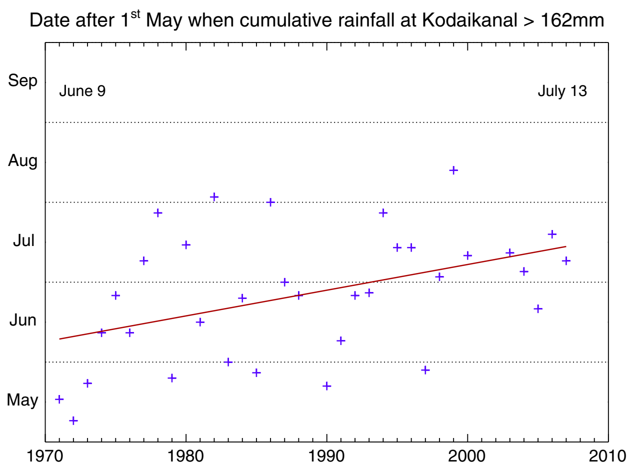

Fig. 5 Start dates (*crosses*) between 1971 and 2007 of the onset of the SW monsoon at Kodaikanal using the definition described in the text. The line of best fit is significant at the 5% level. The *dates* on the graph indicate the start and end dates of the line of best fit

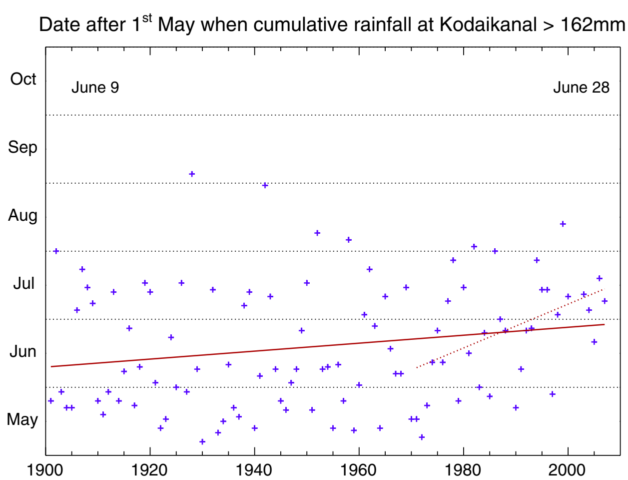

Fig. 6 As Fig. 5 but for the period 1901–2007 using combined data from Bryant Park and Kodaikanal Observatory. The *dashed red line* represents the line of best fit between 1971 and 2007

dry spells between rain events in the non-monsoon months, may well be the dominating factors for reduced soil moisture and stream flows across upper Palni catchments, not the presence of wattle plantations. At the very local scale of the town of Kodaikanal's small water supply catchments, water scarcity may in addition be caused by the growth in water demand associated with increasing urban population and tourism (interview with K. Sakthivelu, 9-10/1/2008).

Conclusion: forest plantations, climate change, and water availability

It is possible that the wattle plantations may have had greater impacts on stream flows and soil moisture in upper Palni catchments when these were first established and when they were being worked for supplying tan bark to the leather industry. As Scott (2005) notes, plant vigour provides the critical difference in water use between productive and older, slow growing forest plantations: "Aging plantations use less water, affording the catchment a period of recharge of subsurface water stores. This 'slowdown' is not unique to plantations, and may be typical of the transpiration component of many forests" (p. 4205; also see Bosch and Hewlett 1982).

The foregoing analysis points to the urgent need for comparative hydrological studies in the upper Palni catchments to examine the differences in water uptake and evapotranspiration between unworked wattle plantations and *shola* (indigenous) forests and between mixed wattle/indigenous forest and grassland areas. Most hydrological studies of tree plantations focus on *working* plantations (e.g., Dye 1996; Dye and Jarmain 2004; Calder et al. 1992; Calder 2002; Calder and Dye 2001; Scott and Lesch 1997). In contrast, the wattle plantations in the upper Palnis have not been managed for production for nearly two decades, and many tracts have trees that have reached the end of their lifespan. Srivastava (1995) observed that the wattle plantations in the upper Palnis and Nilgiris appeared to help regeneration of indigenous plant species and associated wildlife, and also eased human pressure on indigenous (*shola*) forests by providing good fuel wood. Scott (2005) notes that it is probable that non-commercial or 'unthrifty' plantations that are slow-growing, old, or partially invaded with native woody species are probably little different from native forest in terms of water use.

Comparative hydrological studies of upper Palni catchments would offer useful insights into the changing ecology of the upper Palnis and, when combined with analysis of changing rainfall patterns and changes in forest use and regional economic linkages, may provide new ways of understanding the complex mosaic of vegetation change occurring in the region. The studies would also be useful for forest managers to develop appropriate strategies for addressing the multiple responsibilities—economic, social welfare, climate change adaptation, and biodiversity protection—at the regional level.

The unworked wattle plantations of the upper Palnis offer the possibility of creating a new landscape that accommodates a mix of land uses and vegetation that offer a richer diversity of productive and environmental values (Hobbs et al. 2006). Tree plantations are an important economic land use and need to be recognised alongside other social and environmental demands on forests. However, as Scott (2005) points out, plantation forests have specific hydrological characteristics that need to be recognised; economically successful plantations, whether they are planted for industrial use or for global carbon sequestration, require trees to grow quickly, and this, in turn, costs water (Jackson et al. 2005). In this context, instead of viewing forest plantations either as global solutions for climate change mitigation or as local problems for water catchments or biodiversity, it may be worthwhile to adopt a regional approach that incorporates tree plantations and forests in ensuring regional resilience in the face of high rainfall variability and related climate uncertainties. This would involve planning and managing a mosaic of plantations, forests, grasslands, and other non-cultivated areas by taking into account rainfall trends, changes in regional economic activity, urban and rural population shifts and associated demand for water and fuel, and the dynamics of biological and cultural diversity.

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