Wildfires, Ecosystem Services, and Biodiversity in Tropical Dry Forest in India

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Abstract This review is intended to contribute to the understanding of the interlinkage between wildfire in India's tropical dry forest (TDF) and selected ecosystem services (ES), namely forest provisioning and water regulating services, as well as biodiversity. TDF covers approximately 146,000 km^2 (4.4 %) of India, whereas according to the MODIS fire product about 2200 km^2 (1.4 %) burns per year. As studies on wildfire effects upon ESs and biodiversity in Indian TDFs are rare we partly transferred findings from other (dry) forest areas to the environmental situation in India. In India (intentionally lit) wildfires have a very important connection to local livelihoods and the availability of non-wood forest products. Very important adverse long-term effects are the deterioration of forest ecosystems and soil degradation. The potential for TDF to regulate hydrological cycles is expected to be greater in the absence of fire than with it. A general judgment on the effect of fire on biodiversity is difficult as it depends on the community and species involved but a loss of biodiversity under regular burnings is apparent. Consequently, forest managers need sound knowledge regarding the interplay of wildfires and ecosystem behavior in general and more specific knowledge regarding the effects on taxa being considered for conservation efforts. Generally, much more research is needed to understand the trade-offs between the short-term benefits gained from forest provisioning services and long-term adverse effects.

Keywords Wildfire · Tropical dry forest · Ecosystem services · Water regulation · NWFP · Biodiversity

Introduction

Humans have a long history of modifying the physical environment for their own benefit. These modification processes are inextricably interwoven with the use of fire (Pyne 1995). Humans have substantially expanded the spatial extent of 'background fires' (Bowman et al. 2011), which are based on the natural predisposition of the terrestrial world to burning (Pyne 1995). The FAO (2007) estimates that around 80 % of the world's fires are caused by humans. Despite the significant impact that fires have on terrestrial ecosystems, our knowledge regarding the interaction between human-induced fires and our natural environment is limited (Bowman et al. 2011).

In the tropics, forests can be found under a wide range of environmental conditions. Tropical dry forest (TDF) formations are often maintained as early successional stages of other forest formations due to human interference: mostly by causing fires (Schmerbeck 2011). Due to human interference TDFs also occur in areas with relatively high amounts of rainfall and often merge with other vegetation formations like savannahs, woodlands, and wet forest types (Furley et al. 1992). The very broad definitions available for TDFs address this situation, for example, Janzen (1988) defines a TDF as a forest formation that experiences 4–7 months without

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precipitation but on an annual basis receives 1000–3000 mm of rainfall. Another definition by Murphy and Lugo (1986) describes TDFs as characteristically having 2–3 months per year without precipitation.

According to Miles et al. (2006), TDF covers 1,048,700 km^2, or around 6 % of the land surface in the topics. Almost all TDF is exposed to human interference in one way or the other causing a reduction of its spatial extent (Miles et al. 2006). The reason for the decline of TDF ecosystems can partly be explained by the preferential use of these areas for human activities due to the suitable climate for farming, the slow growth of vegetation, and the relatively small stature and open structure of the forest (Murphy and Lugo 1986; Janzen 1988).

TDFs in India cover large areas of the country with slightly varying extent depending on used definition (e.g., Champion and Seth 1968 or Meher-Homji 2001). For our analysis, we did not combine rainfall information (amount and duration of dry period) with a general forest map, but used the results of a recent nation-wide remote sensing-based vegetation mapping approach of Joshi et al. (2006), because this provides the most detailed vegetation-type inventories. Based on a multi-temporal and multi-spectral analysis of spaceborne data Joshi et al. (2006) determined two forest types, namely tropical dry deciduous forest and tropical thorn forest, which we pool into the class TDF. As the classes of Joshi et al. (2006) used to determine TDFs show some rare outliers in areas above 1000 m.a.s.l. we used digital elevation information from the SRTM mission (Jarvis et al. 2008) to restrict the further on used TDF to areas below this height. The results show that approximately 146,000 km^2 or 4.4 % of India consists of TDF (Fig. 1).

In general, fire plays a key role in land management in India. It is assumed that humans have been using fire on the Indian subcontinent for the past 50,000 years (see Gadgil and Meher-Homji 1985 in Saha 2002). The British administration was most likely the first in India to realize the extent to which fires transform the landscape and have negative effects on forests. At the end of the 19th century, Brandis (1897) noted that from one-half to three-quarters of the mature trees in the plains and lower hills of India were hollowed out by fire. Today, fire is clearly seen as being the major cause for the degradation of Indian forests (Bahuguna and Upadhyay 2002). According to the Government of India (1999), 35 × 10^{-5} km^2 of India's forest (5.4 %) is affected by fire each year. The total forest area prone to fire is likely to be around 50 % according to inventory data from the Forest Survey of India (1995) but the proportion varies among the states, ranging from 33 % in West Bengal to 93 % in Arunachal Pradesh (Government of India 1999). Fires affect forest management as well as conservation efforts (Kodandapani et al. 2004, 2008).

There are several reasons for occurrence of fires in the TDF, however many authors agree that almost all of them are caused by humans (Brandis 1897; Pyne 1994; Government of India 1999; Bahuguna and Upadhyay 2002; Semwal et al. 2003), some unintentionally, but the majority are assumed intentional. Generally these fires can be attributed to one of three categories: (i) uncontrolled arson; (ii) fire management (prescribed burning); and (iii) targeted application of fire to make one or more specific ecosystem services (ES) available for a short term.

The main objective of this review is to contribute to the understanding of the links between wildfire in the Indian TDF and important ES as well as biodiversity. In India systematic studies addressing the effects of fire on ESs and biodiversity are lacking and generally, broader fire studies are relatively rare. We provide an overview of the existing literature from India but also use results from studies generally dealing with wildfire and TDF in other parts of the world to estimate and discuss potential effects in India. We start by looking at the extent of wild fires in India's TDFs and the fire detection mechanisms established by the Indian administration. This is followed by an analysis on the interplay of wildfires with ES and its impact on biodiversity based on the existing literature on Indian TDFs and findings from other TDFs of the world. In general we looked into two ESs groups which include forest provisioning services (grazing and hunting, wood and non-wood products), water-related (mostly) regulating services, as well as effects on biodiversity of plants and important animal groups. We then discuss the changes in management we see as necessary for optimizing the applications of fires in TDF and highlighted future research needs.

Extent of Wildfires in India's TDF

A nation-wide monitoring of forest fires by the Forest Survey of India (FSI) started in 2005 as a joint collaboration with NASA and the Geography Department of University of Maryland. For this, the active fire products based on satellite imagery from MODIS, with a resolution of 1 × 1 km are used on an ongoing basis to determine fire spots. The coordinates of these fire spots (2005–2011) are available on the FSI (2013) website. Since the data set from 2005 has some larger gaps, we used the period between 2006 and 2011 for our study. Assuming that each MODIS raster cell identified as fire spot represents on average burned area of 1 km^2, between 1.1 and 2.2 % (mean 1.4 %) of TDF was burned per year between 2006 and 2011 (Table 1). About 28 % of the burned TDF area burned more than once between 2006 and 2011 using the fire data (FIS 2013). The mean monthly precipitation data for 1950–2000 as available via the WorldClim data set (WorldClim 2014) indicates that on

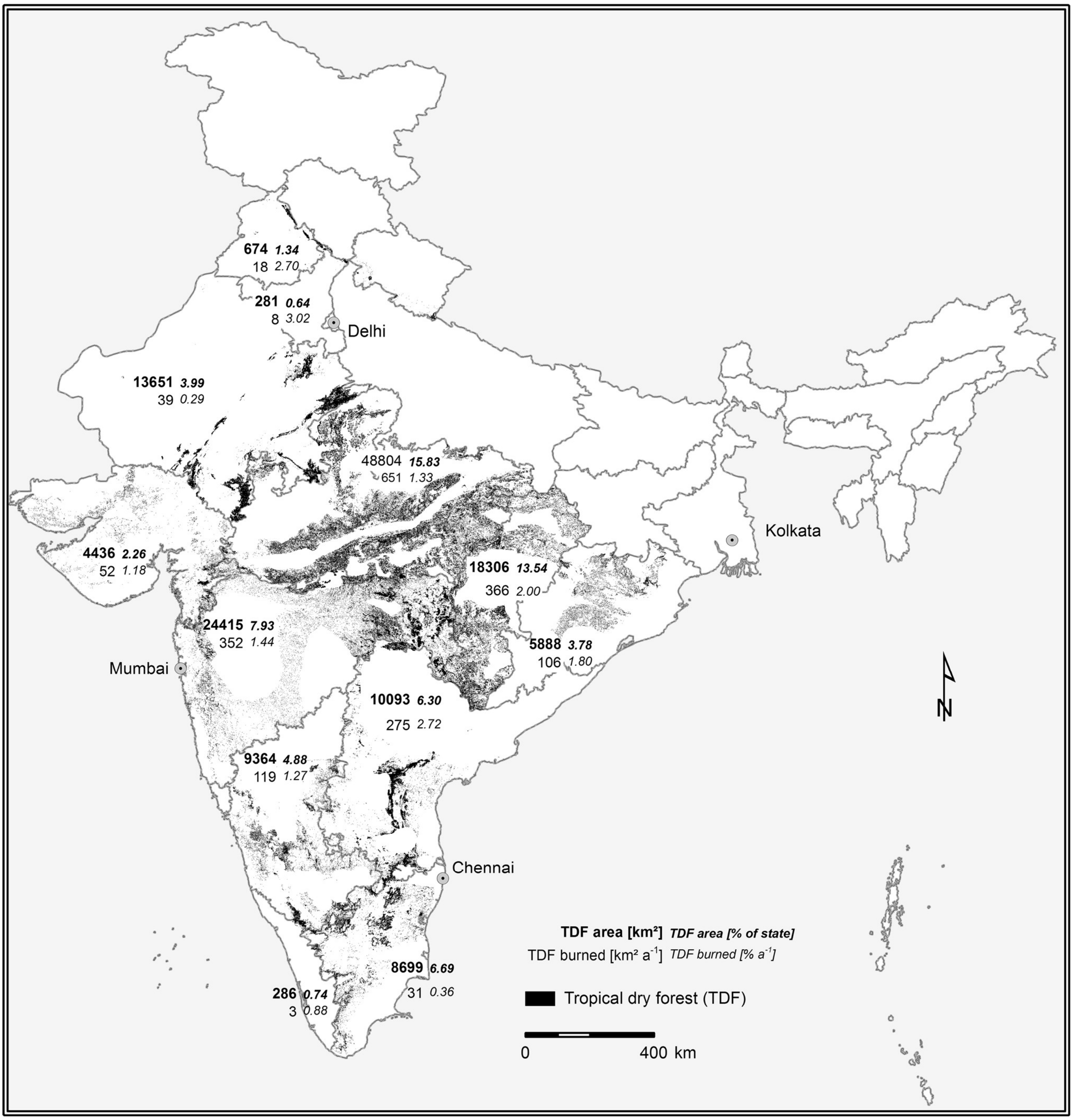

Fig. 1 Distribution of Indian tropical dry forests (summarizing tropical deciduous and tropical thorn forest below 1000 m.a.s.l. as given by Joshi et al. 2006); for all Indian federal states with more than 100 km^2 of TDF the forest area and the burned area detected by the MODIS active fire product between 2006 and 2011 are given

average fires occurred after a dry spell (monthly rainfall <60 mm) of 5.7 (±1.4) months.

On average the TDFs are located in mean height of approximately 310 m.a.s.l., on mean slopes of approx. 5.5 % with no obvious preference for slopes with a specific aspect. There is a slight difference in topographical parameters of unburned and burned TDF areas, whereas the latter show a tendency to be located in higher elevations and steeper slopes (Fig. 2). The mean annual precipitation in TDF areas in India is about 1100 mm with a dry period (month <60 mm precipitation) of about 7.5 months (data from Worldclim 2014). Interestingly the burned areas are on average located in slightly wetter locations (Fig. 3b) but cannot be found if there is not at least a period of 2 months

Table 1 Annual number of fire spots in Indian tropical dry forests between 2006 and 2011 as detected via the MODIS 1 × 1 km system; data available via the Forest Survey of India (FSI 2013

Year	Tropical dry forests	
	No of fires detected	Area burned (%)
2006	1582	1.08
2007	1797	1.23
2008	2335	1.60
2009	3202	2.20
2010	2792	1.91
2011	1485	1.02

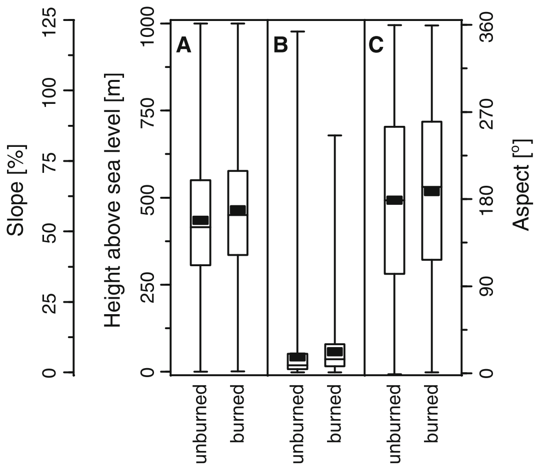

Fig. 2 Height above sea level (*A*), slope (*B*), and aspect (*C*) of unburned and burned tropical dry forest (TDF) in India; data of fire spots between 2006 and 2011 from FSI (2013); topographic information derived with ArcGIS 10 based on SRTM digital elevation data with an original resolution of 90 × 90 m (Jarvis et al. 2008) aggregated to 200 × 200 m; *box-whiskers* give median, 1. and 2. quartile as well as minimum and maximum; *black rectangles* indicate mean

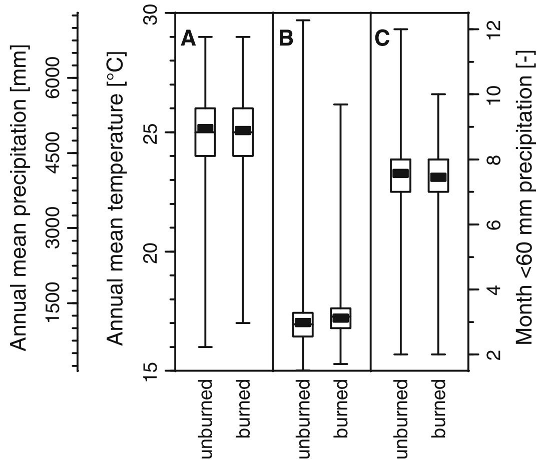

Fig. 3 Annual mean temperature (*A*), Annual mean precipitation (*B*) and average number of month with precipitation below 60 mm (*C*) of unburned and burned tropical dry forest (TDF) in India; data of fire spots between 2006 and 2011 from FSI (2013); climatic data for 1950–2000 from the Worldclim data set (Worldclim 2014); *box-whiskers* give median, 1. and 2. quartile as well as minimum and maximum; *black rectangles* indicate mean

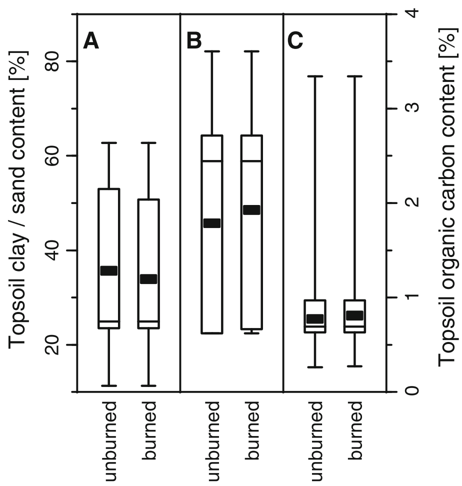

Fig. 4 Topsoil clay (*A*), sand (*B*), and soil organic carbon SOC content (*C*) of unburned and burned tropical dry forest (TDF) in India; soil data taken from the FAO GeoNetwork (2013); *box-whiskers* give median, 1. and 2. quartile as well as minimum and maximum; *black rectangles* indicate mean

with <60 mm precipitation. It is also worth noting that the combination of the remote sensing-based forest mapping of Joshi et al. (2006) with the Worldclim data (Worldclim 2014) indicates that a small number of forest areas mapped as TDFs are located in regions where precipitation is higher and dry periods are shorter than that typically assumed for TDFs (e.g., Janzen 1988). All TDFs are located on relatively sandy soils (mean 46 %) with mean soil organic carbon contents below 1 % (data from FAO GeoNetwork 2013; Fig. 4). Burned areas show a tendency to be located on slightly sandier soils. Overall, the differences in the tested natural boundary conditions between unburned and burned TDF areas are small and not significant ($\alpha = 0.05$) for all parameters given in Figs. 2, 3, and 4. Due to the importance of human-induced fires in India it can be assumed that the proximity to human activities is more important for the spatial patterns in wildfire occurrences. However, testing this while, e.g., using distances to settlements, is difficult for two reasons: Firstly, there are hardly any data available which represent every small settlement, or existing data (e.g., OpenStreetMap) are not consistent throughout the entire country. Secondly, it has to be recognized that India is very densely populated country with 421 inhabitants per km^2 (Worldbank 2014) with about 70 % of the population living in rural areas, which to a certain extent means that TDFs are always in the proximity of human activities. However, we used an available data set of all main roads similar to the ArcGIS online world street map as a proxy variable for human activities in an area and calculated the mean distances to TDF in general and burned TDF specifically (Fig. 5). Against the above mentioned assumption, burned TDF areas can be found in larger distances to the main road network than the mean TDFs distance. One can speculate that this results from an increase in human burning activity in more remote, less developed areas, but this cannot be proved using the available data.

The fire detection service of the FSI also provides information about individual fires within 12–24 h of a fire start (FSI 2013) and is therefore widely used by forestry departments (FDs). According to the FSI (2013), the feedback from the FDs indicates that the remote sensing data have an accuracy of over 95 % in detecting forest fires. However, despite this high level of accuracy reported, there seems to be a large uncertainty and potential underestimation by the data due to the following constrains. The MODIS active fire product can detect fires with relatively good accuracy on flat terrain (see e.g., Maier et al. 2013) but its accuracy tends to drop in many other cases, which are typical for the location of TDFs in India (Fig. 2). Hawbaker et al. (2008) tested the detection rate of the MODIS active fire product in North America using the Aqua and Terra Satellite and concluded that these products are not adequate to detect small fires (50 % rate of detection for fires smaller than 334 ha from the Terra Satellite). Limitations to the detection ability of the MODIS active fire product were also reported by Miettinen et al. (2013) when used in Southeast Asia. Both fire intensity and tree cover played an important role in whether the fire was detected or not. In the light of these results of MODIS fire detection evaluations, the wildfire frequency information available for Indian TDF need to be treated with caution. Especially, in case of small, low-intensity fires and ground fires (Fig. 6) typical for many regions in India (e.g., Krishna and Reddy 2012; Kodandapani 2013), the MODIS active fire product will most likely lead to an underestimation of the true extent of wildfires. Hence, the 1.4 % of TDF area burned per year between 2006 and 2011 (FSI 2013) should be treated as a conservative estimate.

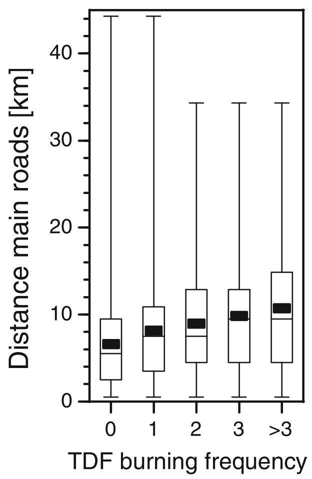

Fig. 5 Distance of tropical dry forests TDFs in India with different burning frequency (not burned = 0; 1… >3 times burned within 7 years of observation) to the next main road; *box-whiskers* give median, 1. and 2. quartile as well as minimum and maximum; *black rectangles* indicate mean

Interdependency Between Ecosystem Services and Wild Land Fire Regimes in TDFs

We use the term ecosystem services (ES) as defined by the Millennium Ecosystem Assessment (2005) as benefits people obtain from ecosystems including both, tangible and intangible services. Fire can have a detrimental effect on these services (Cochrane 2003; Harrison et al. 2010). However, it remains that there are a number of benefits that people gain from applying fire to ecosystems, including: hunting (Hough 1993; Schmerbeck 2003; Mistry et al. 2005), fishing (Dennis et al. 2005), fodder production, creating pasture land (Vayda 1996; Laris 2002; Eriksen 2007; Shaffer 2010), security from wild animals (Hough 1993; Roveta 2008), increasing agricultural production (Sinha and Bawa 2002; McDaniel et al. 2005; Mistry et al. 2005), supplying non-timber forest products (NTFP) (Kepe and Scoones 1999; Roveta 2008; Shaffer 2010), producing timber and fuel wood (Vayda 1996; Schmerbeck and Seeland 2007), and for cultural purposes (Roveta 2008; Schmerbeck 2003).

The main role fire plays in the supply of ES is through its use in maintaining fire-dependent (predominantly open) vegetation formations. A change in the fire regime is likely to bring about a change in the vegetation structure (Hopkins 1992; Favier et al. 2004) and consequently altering the supply of services. The pattern in which fire is used (frequency, seasonality, spatial extent) can therefore be seen as a function of the services gained by those who apply the fire (Fig. 7). However, the (short term) ES are to a certain degree off-set by a large number of unintended effects on (more complex) interacting ES (and disservices). These are mainly long-term effects on soil properties and on catchment hydrology in general as well as long-term effects on biodiversity. To come up with a more holistic view of what is necessary for sustainable forest management, we examined two very important ES related to wildfire (forest provisioning services, water regulation). As the conservation of biodiversity is a main focus of the forest and environmental policy of the Indian Government (Government of India 1988 and 2006, respectively) we also addressed the effects of fire on biodiversity in Indian TDFs.

Fig. 6 Ground fires in Indian tropical dry forests are generally of low intensity and happen under a more or less open tree canopy; here a typical example in a tropical dry forest in Sitamata Wildlife Sanctuary (Rajasthan) (picture taken by Schmerbeck in 2011) is shown

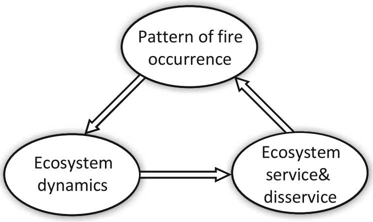

Fig. 7 Fire–ecosystem service cycle: Theoretical link between pattern of fire application, ecosystem dynamics, and the supply of ecosystem services and disservices

Wildfire and Forest Provisioning Services

Livestock and Hunting

One of the dominant motivations to ignite fire in Indian TDFs is to increase the availability and quality of grasses for pasture use (Brandis 1897; Goldammer 1993; Government of India 1999; Sinha and Brault 2005; Schmerbeck and Seeland 2007; Roveta 2008; Kohli 2010). Therefore, the understory of dry forests are regularly burned (e.g., Saha and Howe 2003; Schmerbeck and Seeland 2007) to control colonizing by woody and thorny plants and to promote the sprouting of grasses (Schmerbeck 2003; Mistry et al. 2005). For the latter it is important to remove dead organic matter and fertilize the soil through ash deposition (Laris 2002). Based on data form savanna regions it can be assumed that these fresh grasses are of better fodder quality as they tend to have higher nitrogen (Lü et al. 2012) and crude protein content (Mbatha and Ward 2010) than grasses in unburned patches. Pasture burning practices are reported from TDFs all over the world (Hough 1993; Kepe and Scoones 1999; Laris 2002; Mistry et al. 2005; Roveta 2008; Shaffer 2010) and can be seen as the main reason why fire is applied to TDFs in India.

Possibly of equal importance on a global level is the utilization of fire to facilitate hunting. Hunters use fire in two ways: (i) to drive prey to where it can be easily killed (Lewis 1989) and (ii) to prepare hunting grounds by attracting prey to the fresh flush of grasses (Laris 2002; Mistry et al. 2005). Moreover, burned sites make hunting easier because the animals are easier to see (see section biodiversity). Fire was used by early inhabitants of India for hunting (Goldammer 1993; Government of India 1999) and it is likely that these practices exist still today, even though on a much smaller scale. However, the principles behind attracting herbivores (and therefore also species preying on them) to certain areas by modifying the vegetation with fire is still applied in biodiversity conservation approaches in India (Takahata et al. 2010, see section biodiversity).

For both fire applications (pasture as well as hunting) it is likely that these fires burn much larger areas of the Indian TDF than are needed to achieve the targeted results.

Non-wood Forest Products (NWFP)

India has a very wide range of fire-related NWFP (Table 2); nevertheless, scientific studies are rarely available. The majority of these NWFPs are gained by modifying the vegetation with the help of fire. The most famous and often-cited example is the use of *Diospyros melanoxylon* tree leaves (tendu leaves) that function as cigarette paper for the small Indian cigarettes called "*beedis*" (Saigal 1990; Goldammer 1993). Fire is applied to the forest in the dry season (mainly April–May) so that the trees produce new leaves which can be harvested once they are fully green (Hunter 1981). According to Hunter (1981) 10 million people in rural India depended on *beedi* leaf collection as a source of income in 1980. Another NWFP from India's TDFs, gathered with the aid of fire, comes from the Mahua tree (*Madhuca indica*) whereby the tree flowers are used in locally brewed liquor (Nanda and Sutar 2003) or used as food (Saigal 1990). With the help of fire the ground under the trees is cleared so that when the flowers fall their collection is made easier (Saigal 1990).

Globally, an important product in many dry forests areas that is managed through the use of ground fires, though often not noticed, is fuel wood (Hough 1993; Laris 2002; Schmerbeck and Seeland 2007). Low-intensity ground fires kill (at least partially) the above ground parts (top kill) of woody plants without consuming their biomass, making them available and accessible as fuel wood. Reports on the use of fire in fuel wood production are rare in India even though it can be expected that this is a common practice in Indian TDFs. E.g., Schmerbeck (2003) showed that fire was used by local forest dwellers to facilitate fuel wood collection. Similar findings were reported by Roveta (2008), and in a survey done by Kohli (2010). In the latter study, villagers responded that fuel wood collection was facilitated by the use of fire and out of 557 household interviews fuel wood was the second most frequently named forest product.

A product that does not depend mainly on the modification of vegetation is the ash production by the burning of (mainly) forest land adjacent to agricultural areas which can serve to fertilize the agricultural areas when the ash gets transported by water—especially on slopes—or by wind (e.g., Vayda 1996; Shaffer 2010). Pyne (1994) states that this was a common practice prior to the British period and Roveta (2008) found evidence for such fire application among the Soliga tribe in the Biligirirangan Hills, Karnataka. However, for India this relation hardly appears in the available literature and is not known what proportion of this application holds among other reasons for forest fires.

Table 2 Non-wood forest products extracted from forests in India with the help of fire as reported by empirical field studies; (*x*) = product was not explicitly mentioned by respondents as managed by fires, but the utilized plant is present as a result of frequent burning

Products	Kohli (2010) Andhra Pradesh	Roveta (2008) Karnataka	Schmerbeck (2003) Tamil Nadu
Honey-fire-induced flowering	*x*	*x*	
Honey-drive bees from beehive		*x*	*x*
Thatching material	*x*	*x*	(*x*)
Increase productivity of fruits/seeds of			
Amla (*Phyllanthus emblica*)	*x*	*x*	
Karakkai (*Terminalia chebula*)	*x*		
Sarapapu (*Buchanania lanzan*)	*x*		
Brooms	*x*	*x*	
Edible tubers	*x*	*x*	
Control plant and human diseases	*x*	*x*	
Beedi leaves	*x*		
Leaf cup	*x*		
Gum	*x*		
Bark	*x*		
Bark manufactured to charcoal			*x*
Roots	*x*		
Ash as fertilizer		*x*	
Medicinal plants		*x*	
Grass and other plants for fodder		*x*	
Inducing rain		*x*	*x*
Accessibility and safety	*x*	*x*	

An important land use practice utilizing fire commonly in some parts of India and elsewhere in the tropics is the slashing and burning of forest patches to grow agricultural products for a period of a few years (Slash and Burn). This practice is intensively carried out in North East India where it is known as Jhum. It considered to be the "most predominant farming system practiced by the hilly communities" causing a fire hot spot on the map of India (Vadrevu et al. 2013). This practice enables a flow of agricultural ES and is seen as a potential sustainable agricultural system (Kleinman et al. 1995) but also as a threat to biodiversity that endangers the flow of ES (Goswami et al. 2012). However, this practice is hardly applied in the TDF of India as it depends on a relative fast regrowth of the vegetation, which is not given in the water-limited environment of TDFs.

Wildfire and Water Regulation Services

ES related to water include water provision, regulation, supporting services as well as cultural services directly linked to water (see Gadgil and Meher-Homji 1985 in Vigerstol and Aukema 2011). The most important services potentially affected by wildfires in Indian TDFs are water (i) retention, (ii) yield, (iii) filtration and quality regulation, and (iv) erosion and sediment regulation. Fire directly or indirectly affects all four of these ESs by removing vegetation and litter, changing microbial and faunal activity in soils and changing soil structural and hydraulic qualities (Shakesby and Doerr 2006). The impacts that fire has on water resources moreover varies according to spatial and temporal scales such as fire size, frequency, timing, and severity (Shakesby 2011), all factors only roughly known for fire events in India. In general, studies explicitly focusing on wildfire and water regulation are very rare for Indian forests. Therefore, we added estimates of potential effects of TDFs burning combining the available environmental data from India, e.g., soil texture information, with results regarding fire effects, e.g., on soil water repellency, found in other areas of the world. Focusing firstly on potential changes in soil properties following wildfires it has to be recognized that despite large efforts since the early 1990s to provide modern and homogenous soil maps for the different Indian states (e.g., Krishnan et al. 1996; Natarajan et al. 1996; Harindranath et al. 1999), no high-resolution digital soil data are available for the entire country. Hence, our analysis of fire impacts on the soil hydraulic properties of areas under Indian TDF is restricted to the FAO global soil map (resolution 30 arc-seconds; FAO GeoNetwork 2013) in combination with the location of the Indian TDFs as determined in this study. The texture of the topsoil in the TDF covers a wide range (Fig. 4) with a mean clay content of approximately 35.5 ± 15.5 % with soil organic carbon (SOC) content mostly below 1 % (Fig. 4). Following Mataix-Solera et al. (2011) fire should have relatively small effects on aggregate breakdown in the case of soils with low SOC and high clay contents. Therefore, it can be assumed that the tropical Indian soils in general are not prone to aggregated breakdown due to wildfires. The effect that burning has on water repellency in Indian soils is potentially more diverse as it is strongly related to fire temperatures (DeBano 2000) which unfortunately are not reported for wildfires in Indian TDFs. However, it should be relatively small for most TDF fires where the understory is burned regularly, thereby, preventing high fuel loads (see Bond and van Wilgen 1996) which could lead to high fire temperatures (>200 °C) initiating pronounced water repellency (DeBano 2000). Moreover, differences in soil texture, clay mineralogy, and SOC content affect the development of water-repellent soil layers (DeBano 1981, 1991). When focusing on the dominant soil types in the areas of the Indian Peninsula, where most of the TDFs are located (Fig. 1), a low susceptibility to fire-induced water repellency can generally be assumed. In the eastern part of the Peninsula, Luvisols are dominant (FAO 1998). They can be characterized as having relatively high sand content, low SOC content (<1 %), and clays which typically show development toward a Kaolinite type of mineralogy (Bardy and Weil 2008). While the high sand content may increase susceptibility of fire-induced water repellency (DeBano 1991) the low SOC content and the high Kaolinite content should prevent the development of water-repellent soil layers (DeBano 1981; Mataix-Solera et al. 2013). In the western part of the Peninsula where Vertisols (FAO 1998) have developed on deeply weathered basaltic rock (Dekkan Traps; Stang 2002), the sand content of the topsoil is typically lower (<25 %; FAO GeoNetwork 2013), topsoil SOC content is also small (<1 %), while the clay mineralogy is not dominated by Kaolinite (Bardy and Weil 2008). Following results from other forested areas (e.g., DeBano 1981, 1991), this combination of soil properties should also prevent the development of pronounced fire-induced water repellency. Moreover, an increase in fire-induced water repellency would likely be small as the soils of the TDF are expected to already be water repellent (Shakesby et al. 2007) after a dry period of several months before the onset of the monsoon. However, one aspect of fire-induced water repellency, especially important for surface runoff generation and erosion, is the monsoon-driven rainfall regime in India. This typically is characterized by heavy rainfall on recently burned areas where no pre-wetting cycles of light rainfall occurred which could decrease repellency without generating surface runoff. This is exemplified by data from the meteorological station Paud located near the city of Pune on the lee side of the Western Ghats (Fig. 8), where approximately every third year, more than 100 mm of rainfall occurs within the first 10 days after the onset of the monsoon. However, more detailed data would be needed to estimate cycles of water repellency and soil recovery following the wildfires in Indian TDF (Fig. 9).

To our knowledge, no measurements of vegetation and/or litter interception storage have been made in Indian TDFs. Hence, the effect fire has on interception storage loss, which depends on fire intensity and consequently canopy loss, can only be roughly estimated. Most fires in Indian TDFs have a relatively small spatial extent (Kodandapani 2013) and that makes them difficult to detect via the MODIS 1 × 1 km fire product. This is also indicated by the relative large number of fires detected on only one MODIS raster cell (35 % of all fire spots between 2006 and 2011). Moreover, due to the regularity of the wildfires, there is little build-up of fuels and subsequently fires most often occur as ground fires (Fig. 6). Therefore, their effect on canopy interception and transpiration can be assumed to be small.

Since the canopy of Indian TDFs is often not affected by wildfires, the short-term effect on water yields are expected to be minor compared to other regions where large areas of TDFs burn at high temperatures (e.g., Australia; see Pyne 1995). It needs to be recognized that the long history of extensive fire use to maintain vegetation at a certain stage/condition in India has degraded soils and forest stands (see e.g., Misra 1983; Pyne 1994). These degradations might negatively affect the forest ecosystems' capacity for water storage. Hence, the long-term effects of regular small-scale burning causes the water yields to increase initially (due to reduced transpiration) but more significantly regular burning decreases soil water retention. Moreover, long-term soil degradation due to soil erosion

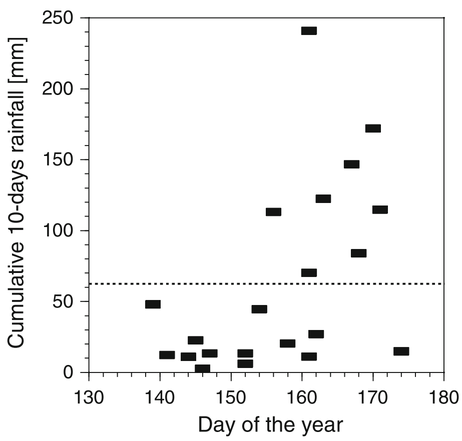

Fig. 8 Exemplary illustration of the rainfall amounts typically measured during the first 10 days after monsoon onset; data taken from the meteorological station in Paud (600 m.a.s.l.; mean rainfall between 1988 and 2008: 1791 mm) located west of the city of Pune on the lee side of the Western Ghats; the *dotted line* indicates the mean cumulative rainfall within the first 10 days of monsoon

following regular wildfires also reduced soil water retention as well as water filtration capacity and water quality regulation (Fig. 9). However, no data are available for India analyzing the long-term change in water regulating services following the long history of TDF burning.

Therefore, it can be assumed that the impact of wildfires on soil erosion and thus sediment regulation is one of the most important short- and long-term water-related ES to be taken into account in Indian TDFs. Besides the effects of fire on soil hydraulic properties, its effects on soil erosion are mostly associated with a loss of soil cover protecting the soil surface from splash erosion and soil crusting (Shakesby 2011; Moody et al. 2013). Splash erosion occurs even when part of the forest canopy remains intact, such as in the case of ground fires, as throughfall and coalesced drops falling from the canopy have high kinetic energy that can cause erosion. Additionally, ground fires may burn the litter layer which could decrease rainfall interception and surface roughness. The latter might be off-set on steeper hill slopes in Indian TDFs where there is often a high cover of stones (e.g., Fiener et al. 2014) which potentially result from long-term erosion of fines. The combination of increasing effective rainfall, decreasing infiltration capacity, and potential soil crusting leads to an increase in surface runoff and soil erosion as protection from raindrop splash due to living leaves and/or a litter cover is missing. The heavy rainfall associated with the onset of monsoon (e.g., Figure 8) may locally lead to pronounced muddy floods. This is especially true for India where most TDFs are located on sloping land (Fig. 2) where it is more difficult to cultivate crops and where the use of the typical flood irrigation system (Krishna 2010) is more or less impossible. In this context it is interesting to note that there is a tendency that the MODIS fire spots in Indian TDFs are located on the steeper slopes (mean 7.4 ± 7.4 %) compared to the slopes of all TDFs (mean 5.6 ± 7.4 %) and that those areas that burned more than three times between 2006 and 2011 were located on even steeper slopes with a mean of 8.2 ± 8.4 %. TDF areas most prone to post-fire erosion and hence muddy flood events are those with the highest rainfall amounts and intensities, the steepest slopes, and the soils most susceptible to erosion. Using an Universal Soil Loss Equation-based approach (USLE; Wischmeier 1971) with a simplified parameterization, the relative post-fire erosion potential at the detected fire spots (2006–2011) could be derived for the different states of India. Therefore, we combined rainfall erosivity calculated from mean annual rainfall (Jain and Das 2010), with soil erodibility, derived using topsoil texture and SOC content (Auerswald et al. 2014), and an assumed mean erosive slope length of 200 m and slopes from the aggregated 200 × 200 m SRTM DEM. In general, the Indian states in the south-eastern part of the country (Tamil Nadu, Andhra Pradesh,

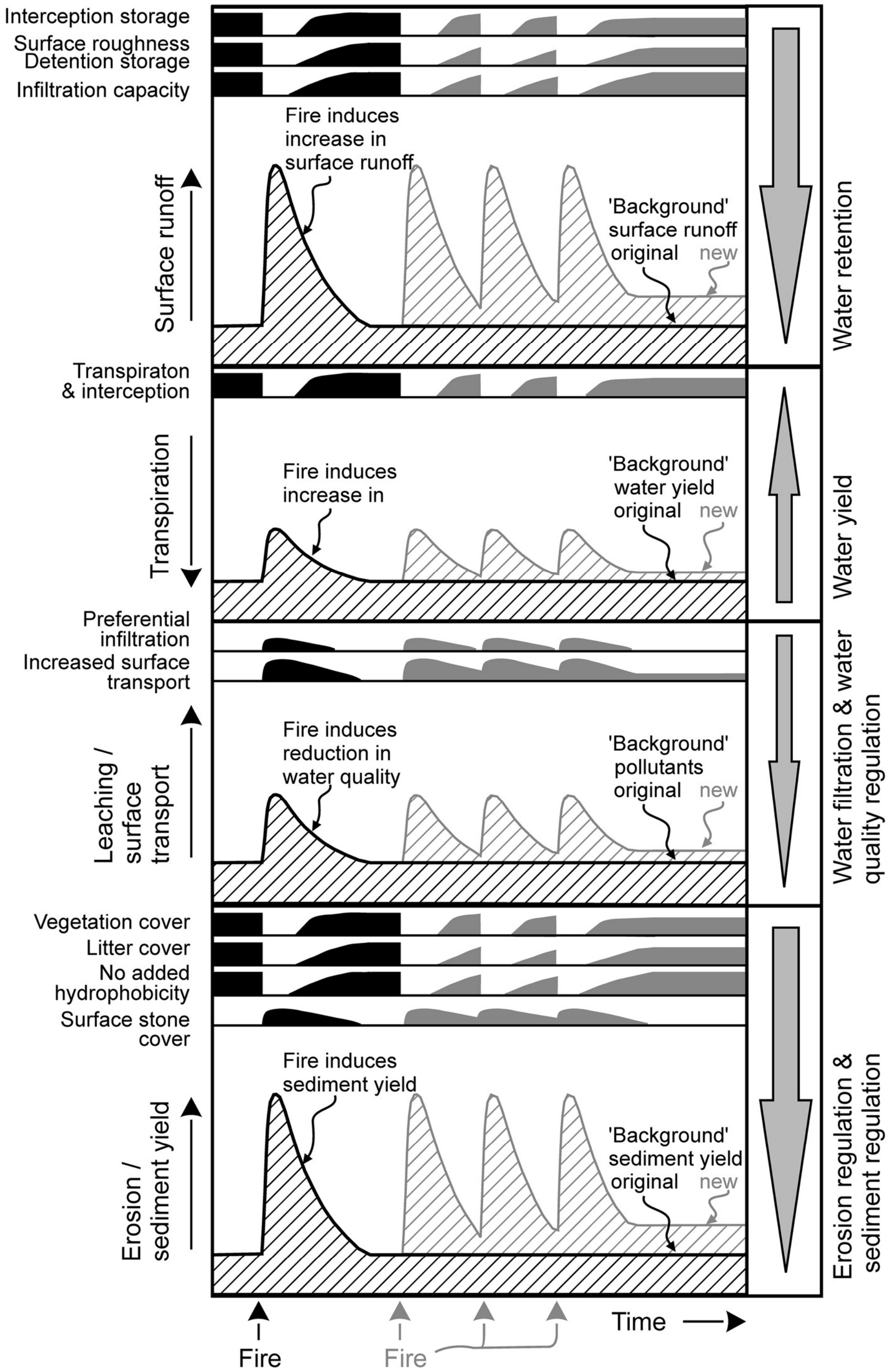

Fig. 9 Scheme illustrating potential short-term and long-term effects of wildfire on water-related ecosystem services; size of disturbance of different processes is related to the overall tendency found in literature and is also indicated by the size of the arrows associated with the different ES (*right*-hand side of the scheme); above each given process the parameters mostly affecting these are indicated; the idea for this type of figure illustrating fire disturbance is taken from Shakesby and Doerr (2006)

and Orissa) where large areas of TDFs exist on relatively erodible soils seem to be most endangered in respect of TDFs post-fire erosion events (Fig. 10).

Wildfire and Biodiversity

The impact of fire on biodiversity has been studied for many taxa in different ecosystems and many climatic regions of the world (see e.g., Bush et al. 2008; Ylisirniö et al. 2012; Spies et al. 2012; Taylor et al. 2013; Vicente et al. 2013). The bulk of this work dealing with savannahs, different types of dry forest, and Mediterranean vegetation types was carried out in North and South America, Australia, Africa, and the Mediterranean region. Against the background of the commitment the Indian Government has made toward the conservation and enhancement of its

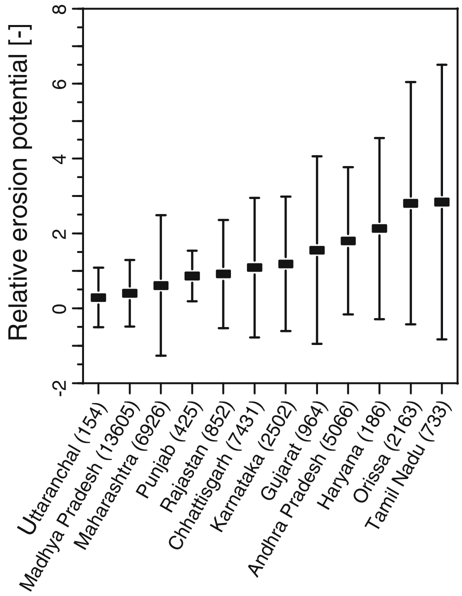

Fig. 10 Relative erosion potential under TDFs of the different Indian states where TDFs exist and where on average at least 100 fire spots per year were detected between 2006 and 2011; erosion potential was calculated relative to the modeled mean under all TDFs using the soil erodibility factor, the rainfall erosivity factor, and the slope length factor of the USLE; *error bars* indicate one standard deviation; values in *brackets* on the *x*-axis labels are the mean number of fires detected per year

biodiversity (Government of India 1988, 2006, 2008, 2014) and the extent tropical forests in India face fire, there are relatively few studies analyzing the effect of wildfire on biodiversity.

The importance of fires in the context of biodiversity is underlined looking into published literature on fire and biodiversity of tropical dry forests of the world (e.g., Driscoll et al. 2010). We used this literature in combination with the rare studies for India's TDFs focusing exemplarily on three groups of organisms: Plants, insects, birds, and megafauna.

Plants

When investigating the diversity of plant communities it is inevitable to look at their dynamics as a response to disturbances. However, studies analyzing not only snap shots in time but focus on long-term dynamics in the interplay between wildfires and vegetation dynamics in TDFs in India are very rare (e.g., Meher-Homji 2001; Saha 2003; Saha and Howe 2003; Kodandapani et al. 2009) and hence general patterns displayed in the global literature (see Miles et al. 2006, Ratnam et al. 2011) need to be transferred to Indian conditions. To understand the effects of TDF fires on plant diversity both the diversity of TDFs and savannah ecosystems must be taken into account as both are part of one successional series (Furley et al. 1992; Favier et al. 2004, Miles et al. 2006). There is abundant evidence that high fire frequency hinders woody plants from establishing in savannah and TDF ecosystems (e.g., Hopkins 1992; Setterfield 2002; Favier et al. 2004; Sankaran et al. 2008; Ratnam et al. 2011) while the season in which fire occurs influences the density and composition of the regenerating species (e.g., Bond and van Wilgen 1996). Frequent fires seem to maintain a soil seed bank of short-term plant species (Graminoids) over life forms with a longer-term life cycles like broadleaved herbs and woody plants (Gashaw et al. 2002). This results in a higher proportion of annual grasses than perennial grasses in the herbaceous layer (Legge et al. 2011; Savadogo et al. 2008) and this likely reduces overall diversity (Legge et al. 2011; Andersen et al. 2012).

In general terms, it can be stated that fire promotes fire-tolerant species (Furley et al. 2008) and that an increase in fire frequency selects for plant communities dominated by C4 graminoids in the herbaceous layer (Ratnam et al. 2011; Veldman et al. 2012). This selective attribute of fire also reduces tree seedling species diversity as Saha and Howe (2003) found in a TDF in central India and Verma and Jayakumar (2015) as well as Kodandapani et al. (2009) report form TDF of the Western Ghats. However, when looking at biodiversity there is a need to consider the potential long-term development of dry forest plant communities in the absence of fire covering at least several decades. There are only few studies available that have made such observations for the tropics. These empirical studies report a trend of increasing tree diversity in the absence of fire (Puyravaud et al. 1995; Saha and Howe 2003; Wanthongchai et al. 2011). Conversely, Cantarello et al. (2011), who simulated fire scenarios over a 400-year period in a TDF, found that fire exclusion from an area does not necessarily lead to an increase in tree species diversity. However fire regulation as a tool for conservation depends on the plant species or communities in focus. Ecosystems that have evolved with a relatively high fire frequency may require regular burning to maintain current plant diversity (Schwilk et al. 1997) but this may not be true for ecosystems that can develop a high biodiversity under fire exclusion (Ruiz et al. 2005).

For India, empirical studies that indicate the potential forest types under long-term exclusion of fire are hardly available. However, that fire exclusion leads to a shift to more diverse plant species compositions seems evident from existing data (see Meher-Homji 2001 and Schmerbeck 2011).

Insects

Insects play a crucial role in terrestrial ecosystem functioning on several levels (e.g., for pollination see Klein et al. 2007). In general, many species are significantly reduced immediately after a fire. Those spared reside mainly below ground in unburned patches and above the flames in tree canopies or are those capable of escaping from a fire. A clear trend for insect biodiversity over longer periods after fire cannot be established (Swengel 2001). For Indian TDFs studies on the impact of fire on insect communities do hardly exist. For the global TDFs and savannahs some studies have been done on termites and ants. Termite species are the dominant group of decomposers in the tropics (Davies 1997) and it seems that fire can have either a stimulating, detrimental, or no effect depending on the species. Fire reduces the abundance of termites but their diversity is not affected to the same degree (Davies et al. 2010). This implies that the decomposition rate of the Indian TDF is reduced right after fire, but fire may not lead to a loss of species and the capacity of the forest to mineralize organic matter remains. However, the diversity of termites might reduce over longer time periods in the absences of fire. E.g., Davies (1997) found more termite species in burned dry forest compared to forest that had not burned over a period of 26 years. However, clear pattern to which extent fire affects the performance of termite communities and therefore affect short- and long-term nutrient cycling, is not known for India TDFs.

Ants are also a well-studied group of insects but their interaction with fire is poorly understood (Barrow et al. 2007). Ant communities seem to be well associated with the vegetation formation they are living in and therefore with the fire regime that drives this vegetation type. It is assumed that ant species associated with savannahs are resilient to fire and able to persist after fire exclusion (Parr and Andersen 2008). Andersen et al. (2006) tested the diversity of ant communities in a long-time fire exclusion experiment (23 years) and found a decline in ant species richness from 72 species on burned sites to 45 species on unburned sites; however, the proportion of forest ant species increased, indicating a change in the ant community along with the change in vegetation. This implies that the application of fire to Indian TDFs is likely not to eliminate ants per se, but changes the composition of species while with time the number of species may reduce. If knowledge about the ant species of different successional stages of forest vegetation is available for India, they could be used as indicators for the time passed since fire occurred.

Birds

Birds can also play a crucial role in ecosystem functioning, therefore changes in bird communities can alter ecosystems significantly (Galetti et al. 2013). Fire is surely an important driver of bird diversity, especially when fire is partly responsible for the transition of dry forest to savannah. Little et al. (2013) identified fire as the predominant factor in determining bird diversity in South African grasslands. The authors found a reduction in the overall bird abundance and the number of species on grasslands (loss of grassland species) while bird diversity increased with increasing vegetation cover and biomass. Pons and Wendenburg (2005) found that in Madagascar a clear reduction of bird diversity coincided with the transformation of a forest to savannah, but significantly more bird species were counted in burned compared to unburned forest. Studies from north and southeast Australia show that fire is generally negatively correlated with bird diversity (Valentine et al. 2012; Levin et al. 2012; Reside et al. 2012; Taylor et al. 2013) but not always with bird abundance (Kutt and Woinarski 2007; Valentine et al. 2007). This would mean that a reduction of fires in the TDFs of India might enhance bird diversity. Especially bird species that depend on late successional forest stages would benefit from a long-term exclusion of fire. However, fire can have a positive effect on the feeding options of insectivorous birds by removing the grass layer, where such burned patches supporting also birds residing on unburned parts of the landscape (Woinarski 1990). This could lead to the conclusion that a variety of fire patterns on a landscape level enhances bird diversity, which is in fact generally assumed to be true for a wide range of animal species (Huston 1994; Tews et al. 2004 in Taylor et al. 2012). However, this could not be verified by Taylor et al. (2012) who found no strong correlation between fire-induced landscape heterogeneity and bird diversity, but he did find a positive association between bird species richness (especially rare species) and older vegetation types. The highly fire-affected TDFs of India are therefore likely to carry less species as they could if they would give time to develop to more matured stages and an exclusion of fire would contribute to the conservation of rare bird species in highly fire-prone landscapes.

Megafauna

Megafauna species are often targeted by biodiversity conservation efforts. The abundance and diversity of herbivores and carnivores are related to the fire regime in a region (Landsberg and Lehmkuhl 1995). An increase in fire intensity and frequency leads to the transformation of forests to savannah or grasslands (see above). The grass provides more opportunities for grazing species and their abundance increases accordingly (Johnsingh 1986; Main and Richardson 2002; Tomor and Owen-Smith 2002). After fire, a high abundance of herbivores can be observed. This can be explained by the higher nutrient levels available in the herbaceous layer compared to pre-fire levels (Carlson et al. 1993; Moe and Wegge 1997). The more nutritious fodder not only attracts herbivores (Watson et al.

2005) it also increases the likelihood that predator populations will increase. Fire-prone habitats may be attractive for herbivores long after a fire (Zavala and Holodo 2005). This may not be true in all cases because Kutt and Woinarski (2007) observed a strong correlation between mammals and fire but not with grazing in an Australian savannah. Grazing and browsing alone select for non-palatable plants and it is assumed that this in turn favors tree and shrub growth which subsequently reduces resources for grazers and browsers (van Langevelde et al. 2003; De Michele et al. 2011).

In India fire is used as a tool to maintain habitats of large herbivores such as the one-horned rhinoceros (*Rhinoceros unicornis*) and predators like tigers (*Panthera tigris tigris*) (Landsberg and Lehmkuhl 1995) and they are an important management tool for large herbivores in protected areas (e.g., Badarinath et al. 2009). This creation and/or maintenance of fire-dependent habitats by fire managers can surely be credited with the survival of one or more endangered species (e.g., Watson et al. 2005). However, this does not provide any insight into the correlation between fire and the overall diversity of Megafauna species. The preferences for patches with different fire history within a given landscape vary among megafauna species. This is likely to result in different megafaunal compositions over a landscape (Tomor and Owen-Smith 2002; Kutt and Woinarski 2007). A comprehensive study investigating the dependence of ungulate diversity on fire is missing for India but was done by Klop and Prins (2008) for all of West Africa. The authors found that besides evapotranspiration and soil fertility, fire occurrence was the only other factor that could explain the richness of grazing species. However, fire does not only indirectly impact megafauna by altering vegetation it can also have severe direct impacts on slow moving animals and cause local extinctions (Silveira et al. 1999).

Concluding Discussion

Ecosystem services and Biodiversity in India's TDFs are strongly interlinked with ecosystem dynamics and wildfires are a clear diver of such dynamics. With the help of fires people arrest the successional sequence of plant communities and maintain successional stages that are required for tangible services. These connections are obvious in the context of livestock rearing, maintenance of herbivory abundance, and supply of NTFP. Fires in India's TDF are therefore important for local livelihoods (e.g., Schmerbeck et al. 2015), but they also affect other functions as well as biodiversity of the forest ecosystems.

As water management is of major importance in the wet and dry tropics where agricultural yields are directly linked to the availability of water for irrigation it is essential that fire management accounts for negative effects on water regulation. As most of the wildfires in India's TDFs are relatively patchy affecting a large number of small areas each year, their effects on water regulation services vary on different spatial and temporal scales. An area locally affected by wildfires may substantially loose short-term water retention if heavy rainfall occurs after the dry period. In this case a pulse of surface runoff and associated sediment transport can be expected leading to local damages, e.g., silting of water harvesting structures. The short-term effect of such local wild fires on water yields, water retention, and water quality diminish moving from single hillslopes to meso-scale catchments, where water management is carried out by public administration. More important for water regulation services are probably the long-term effects of the widespread wildfires leading to a long-term degradation of forest vegetation and forest soils, which reduces evapotranspiration as well as water holding capacities in canopies and soils (Fig. 9).

Fire also affects the biodiversity and therefore the functions of ecosystems, especially those depending on species interaction like pollination and dispersal. A focus in protected areas on megafauna stimulates the fire application to maintain degraded stages of the potential forest vegetation to support herbivory communities. But this comes at the cost of other plant and animal communities, especially those of late successional, fires sensitive stages of the ecosystem development.

However, any integrated TDF management in India, which should account for different ES and biodiversity needs a more solid scientific basis, whereas a number of deficits can be identified:

(1) Improved data are needed regarding frequency and intensity of fire in Indian TDF. The MODIS active fire product is a reasonable starting point, but more high-resolution remote sensing fire monitoring tools (e.g., Hawbaker et al. 2008; Röder et al. 2008) are needed, especially to detect the small (ground) fires (e.g., Kodandapani 2013) located on steep slopes. To our knowledge there are no data available determining different fire intensities and/or fuel loads for different TDFs in India. Hence, any attempt to estimate the effect of these wildfires on water regulation and biodiversity are somewhat vague.

(2) Regarding wildfire effects on water-related ES no direct measurements are available for India, hence, potential effect can only be estimated transferring the findings form the Mediterranean (González-Pelayo et al. 2006), the United States (e.g., Benavides-Solorio and MacDonald 2005), or Australia (e.g., Noske et al. 2010) to Indian conditions.

Therefore, a plot-based evaluation under different climate, soils, and TDF characteristics are essentially needed to create a basis for further research. Even more problematic are the missing studies regarding long-term forest and soil degradation following regular burning. Assuming that the forest vegetation recovery is a relatively fast process taking several years to decades, a systematic evaluation of burned vs. unburned TDFs using the MOSIS fire data available since 2005 could be a first attempt. Regarding soil degradation this is much more challenging as it would require long-term fire information. Hence, using the data collected during future plot experiments to parameterize long-term erosion models might be the avenue to follow. To validate such models the siltation of reservoirs widely available in the wet and dry tropics could be utilized, as done in other erosion modeling contexts (Verstraeten 2006), or colluvial and alluvial soils might be dated (e.g., Meyer et al. 1995).

(3) The available studies focusing on the effects of fire in Indian TDFs on biodiversity (e.g., Saha and Howe 2003) to our knowledge mainly represented snap shots rather than long-term process studies. Moreover, these studies are mostly restricted to relatively small plots (e.g., Puyravaud et al. 1995; Saha 2003) which make it difficult to evaluate effects on faunal diversity of birds and mammals. More large scale studies are mostly focused on single species (e.g., Landsberg and Lehmkuhl 1995), which makes any general conclusion of fire effects on biodiversity difficult. It is time to work with permanent observation in a range of representative sites. Representative sections of landscapes with stand/ecosystem level empirical observations over decades will allow reliable conclusion of fire-induced ecosystem dynamics and the associated flow of ESs.

Despite the obvious deficits in our knowledge of wildfire effects upon ES and biodiversity in Indian TDFs a number of recommendations for an improved, more integrated TDF management can be drawn from our study. As burning of TDFs in India is important for local livelihoods but not part of an organized forest management (see Schmerbeck 2011), we propose a forest management that integrates fire with the aim to optimize the flow of ES from forest by reducing the negative effects and concentrate burning on those site that are needed to satisfy local needs. To integrate fire in management plans despite only fighting it has been recently proposed by Moritz et al. (2014) for regions where the fires are disasters and only to a very low extent agents for gaining services from forests (USA, Mediterranean, Australia). A need to integrate fire in forest management plans is even more needed, in a context like India where fire is an essential part of the local people's daily life.

To reduce the area under fire accidental fires should be avoided and fires that support ES should be limited to the area needed for the desired amount.

The first step here is to determine the causes of fire, and categorize them as either accidents or prescriptions. The challenge will be to estimate the amount of land that needs to be burned to enable the flow of the demanded ES, especially if several stakeholders are involved. This might be achieved with a periodization of the ES wanted, clear responsibilities among local communities and authorities and the lookout for alterative techniques to gain ES or even a shift to other sources of livelihood.

The diversity of ES maintained by fire (Table 2) and the fire specifics required by their facilitation would surely challenge fire management policy. The policy would certainly need to go far beyond a ban and punishment approach. It is likely only in rare cases that fires originate from one community only such as the Soliga tribe (Roveta 2008). In such a case, the implementation of a fire management plan would be relatively easy. However, multi-causal origins for forest fires are much more the norm as observed by Schmerbeck (2003), thus each situation needs to be addressed on a case-by-case basis. Regulation that also allows for improvements in other services like water regulation and biodiversity require a much longer time span and therefore more planning and regulation effort.

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