

Effects of drought on wildfires in forest landscapes of the Western Ghats, India

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Abstract. Wildland fire is an understudied yet highly important disturbance agent on the Indian subcontinent. In particular, there is uncertainty regarding the degree to which annual climate variation influences inter-annual variability in fire activity. In this study, we evaluate wildland fire at two complementary spatial scales in the southern portion of the Western Ghats mountain range (hereafter ‘Western Ghats’) in India. At the larger regional scale, we evaluate temporal and spatial variability in fire activity from 2001 to 2015. At the smaller scale, we evaluate the relationship between annual area burned and climate variation within two landscapes nested within the Western Ghats (from *c.* 1996 to 2015). At the regional scale, we found that most fire activity was restricted to January–March, although substantial inter-annual variation was evident. For example, in 2004, 2009 and 2012, fire activity was approximately five times greater compared with the 3 years with the lowest fire activity. The landscape-scale analysis also revealed weak to strong correlations between annual area burned and climate variation in both landscapes. Although not the only factor influencing area burned, episodes of drought could be exerting an increasingly significant effect on wildfire activity in the Western Ghats.

Additional keywords: climate variation, fire activity, human factors, protected areas, reserve forests, socioeconomic, wildland fire.

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Introduction

Recent studies have established the impacts of anthropogenic climate change on an increasingly diverse array of meteorological and hydrological phenomena (Mann and Gleick 2015). Drought is one of the most commonly occurring climatic extremes and affects both natural and human systems, including the land carbon budget (Allen *et al.* 2010; Seidl *et al.* 2017). Recent analyses have predicted more frequent and severe droughts in the 21st century (Seneviratne *et al.* 2012; Williams *et al.* 2013; Cook *et al.* 2015). In fact, droughts in several tropical regions have been longer and more intense since the 1970s (Malhi and Wright 2004). In natural systems, apart from the recurring drought conditions, the areal extent of vegetated biosphere affected by drought has increased 3-fold during the past 100 years (Schwalm *et al.* 2017). The observed and predicted occurrence and severity of drought will undoubtedly influence ecological disturbance agents such as wildfire (Williams *et al.* 2010).

Fire activity may be defined as the number of ignitions, the number of active fires, area burned, fire severity, duration of fire event or season, fire season severity, and fire episodes, among others (Keeley 2009). Fire activity at various spatial and temporal scales is influenced by several factors including fuel, climate, climate variation, ignitions, human activity and

topography (Vadrevu *et al.* 2006; Prasad *et al.* 2008; Parisien *et al.* 2016). In the state of California (USA), for example, topographic controls of fire perimeters were most pronounced in mountainous regions and least influential in arid regions, and human influences added to the complexity (Povak *et al.* 2018). In the Cascade Range of the western United States, Cansler and McKenzie (2014) illustrated the relationships between climate and fire size, severity and spatial pattern metrics. In Canadian boreal forests, annual burned area data showed coherence between the spatial patterns of annually varying climatic extremes and long-term climate normals (Parisien *et al.* 2014). In the southern Indian state of Andhra Pradesh, models built with fire count data and explanatory variables such as population density, climate, topography and demand of metabolic energy explained more than 60% of the variability in fire activity (Vadrevu *et al.* 2006).

Recent studies in the Western Ghats have incorporated several explanatory variables to identify fire-prone areas through a two-step process, first at the scale of the Western Ghats and subsequently at the local scale (Renard *et al.* 2012). The study by Renard *et al.* (2012) highlighted the importance of inter- and intra-annual climate variables in driving fire patterns in the Western Ghats. However, annual variation in climate has often been shown to be one of the most highly influential factors

in driving inter-annual variability in fire activity (Littell *et al.* 2009; Bradstock 2010; Littell and Gwozdz 2011; Abatzoglou and Kolden 2013). In particular, decreased water availability (i.e. drought) often corresponded with heightened fire activity (Girardin and Wotton 2009; Dimitrakopoulos *et al.* 2011; Westerling 2016; Holden *et al.* 2018; Parks *et al.* 2018). For example, the 1997–98 Indonesian fires followed an El Niño-induced drought (Siebert *et al.* 2001) and, similarly, the 2015 drought in the Amazon triggered a dramatic region-wide increase in fire activity (Aragão *et al.* 2018). Droughts also played a major role in the occurrences of the Ash Wednesday fires in Victoria (1983), Canberra fires (2003) and the Black Saturday fires (2009) (Jolly *et al.* 2015). Very recently, several very large fires have occurred in California under drought conditions, including the largest and second largest fires ever recorded in the state—the 2018 Mendocino Complex fire and the 2017 Thomas fire each burned over 100 000 ha. Drought also plays a key role in driving fire activity in south-western India (Renard *et al.* 2012). Regional-scale models of fire in the Western Ghats largely reflected climate both at short- and long-term time scales and provided an estimate of the fire susceptibility (Renard *et al.* 2012). However, finer-scale, sub-regional models that included the type of vegetation provided more robust estimates of fire patterns because of their ability to capture forest fuel characteristics and degradation levels (Renard *et al.* 2012).

Here, we describe two complementary analyses of drought and fire occurrences conducted at different spatial scales in the Western Ghats mountain range in south-west India (hereafter ‘Western Ghats’). The first analysis was conducted at the regional spatial scale of the southern Western Ghats and the second analysis was conducted at landscapes nested within the Western Ghats, one composed of protected areas and the other being extensively human modified. Although there are several different forest types in the Western Ghats, they can be grouped into two general types (dry *v.* moist) that are outcomes of and characterised by different mean annual precipitation. The two landscapes are different in their fire regimes, likely because of differences in their vegetation, climate and topography. Accordingly, we divided our finer-scale analysis into two landscapes, one predominantly dry and the other moist, to control for differences in vegetation that might mask fire-activity responses to variations in drought. Nevertheless, the two scales of analyses (regional and landscape) complement each other and provide useful insights into ecosystem processes such as drought and fire occurrences. In this study, we assess the effect of drought at the regional scale using MODIS fire detection data, spanning 2001–2015, and at the nested-landscape scale using detailed fire-history spatial data spanning 1996–2015. Specifically, we aimed to (1) evaluate the spatial and temporal variability of drought and wildfire at the regional scale (southern Western Ghats) and (2) evaluate the relationships between annual climate variation and annual area burned at the landscape scale.

Methods

Study areas

Our regional- and landscape-scale analyses were conducted in the Western Ghats, a mountain range in south-west India



Fig. 1. Location of the Western Ghats study area in India. Location of the Nilgiris and Uttara Kannada landscapes in the Western Ghats.

that is one of the thirty-four global hotspots of biodiversity (Mittermeier *et al.* 2005). It is also the biodiversity hotspot with the highest human density (Cincotta *et al.* 2000). Our regional-scale analysis was focused on the southern and central portions of the Western Ghats (i.e. a study area of 8–16°N, 73–78°E; Fig. 1). Land-cover types include tropical wet evergreen and tropical dry deciduous forest habitats, both in various stages of degradation, and tropical mountain forests and grasslands alternating with zones converted into agroforests, monoculture plantations and agriculture (Renard *et al.* 2012). The two landscape-scale study sites are nested within the central Western Ghats, the Nilgiris landscape (1545 km²; 11.7°N, 76.5°E) and the Uttara Kannada landscape (2825 km²; 15.2°N, 74.7°E) (Fig. 1). The elevation of the Nilgiris (dry) and Uttara Kannada (moist) landscapes was respectively 0–1450 and 39–995 m and the estimated mean annual precipitation (MAP) was respectively 600–2000 and 800–2500 mm year⁻¹ (Hijmans *et al.* 2005). The Nilgiris landscape has a shorter dry season (rainfall <50 mm month⁻¹) of 4 months, whereas the Uttara Kannada landscape has a relative longer dry season of 6 months (Pai *et al.* 2014). Nearly all fires in these two landscapes are accidentally or intentionally ignited by humans (Kodandapani *et al.* 2004, 2008; Mehta *et al.* 2008; Mondal and Sukumar 2014).

Vegetation layer

Two different sources of vegetation data were used in the analysis. The first dataset was derived from three 1 : 250 000-scale forest maps of south India (Pascal *et al.* 1997a, 1997b, 1997c; Ramesh *et al.* 1997, 2002). There were originally over 150 vegetation classes, which were grouped into nine broad vegetation classes based on dryness of vegetation and dominant presence of deciduous species, grasses and weeds, which are important sources of fuel loads in the Western Ghats (Kodandapani *et al.* 2004, 2008; Renard *et al.* 2010, 2012). The second dataset was derived from land-use–land-cover maps of India (Roy *et al.* 2015). There were 100 vegetation types consisting of natural, semi-natural and managed formations grouped under 10 broad categories. Although the first dataset formed the bulk of analysis (95% of the area), only areas that were not recorded in the first dataset were derived from the second dataset.

Indian monsoon and climate

The south-west monsoon is the main source of rainfall for the Western Ghats region (Pai *et al.* 2014). The monsoon advances from the southern tip of peninsular India at the end of May and spreads across the entire country within 10 to 15 days (Pascal 1986). The monsoon gradually withdraws at the end of September commencing from northern India and reaching the tip of southern peninsular India by early December. Thus, the advancing phase and, more importantly the withdrawal phase, contributes to the rainfall pattern and the increasing dry season from the south to the north of the Western Ghats. A second important gradient in rainfall is the west–east gradual decline in summer precipitation. For example, differences in July precipitation in the transitional areas between the humid and dry areas in the Western Ghats are substantial. This variation in the south-west monsoon is observed in the two landscapes in the Western Ghats. For example in the Nilgiris landscape, two peaks in rainfall are observed; one in June–July and the other in October. In the Uttara Kannada landscape, however, there is only one peak in rainfall during July (Pascal 1986). Thus, the number of dry months could vary from 2–4 months in the southern parts of the Western Ghats (i.e. the Nilgiris landscape) to 6–7 months in the northern parts (i.e. the Uttara Kannada landscape).

Fire in context: land-use and burning in the Western Ghats

For millennia humans have modified vegetation in the Western Ghats through the use of fire; slash and burn agriculture in the Western Ghats could have been practised as early as 3000 years before present (Gadgil and Chandran 1988). Low human populations and long fallows between cultivation, which permitted the return of forests in certain parts of the Western Ghats, indicates longer fire rotations during the earlier period (1000 to 300 years before present) compared with the present (Morrison 1994; Chandran 1997; Kodandapani *et al.* 2008). Fire has been an important disturbance regime and has played an important role in the ecological history of the Western Ghats (Chandran 1997; Pascal 1986). Fire has effects on regeneration through its impacts on seeds, seedlings and saplings, with several species showing signs of recovery through sprouting (John *et al.* 2002).

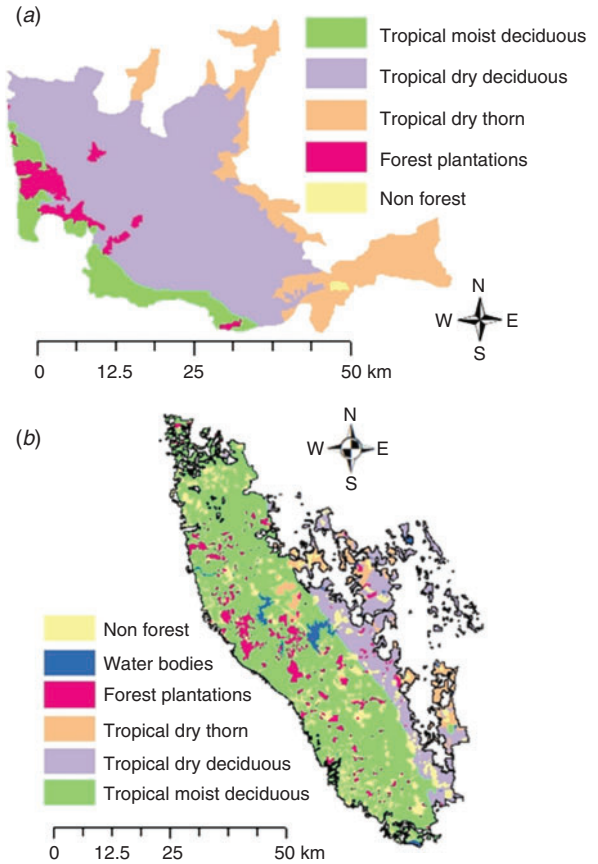


Fig. 2. Forest types in (a) Nilgiris landscape and (b) Uttara Kannada landscape.

Frequent burning has favoured the spread of fire-tolerant species with thick bark, especially into evergreen forests – with fire prevention, evergreen species have recolonised these forests (Chandran 1997).

The Nilgiris landscape (dry) comprises tropical dry deciduous forests (65%), tropical moist deciduous forests (10%), tropical dry thorn forests (20%) and settlements (5%) (Kodandapani *et al.* 2004, 2008) (Fig. 2a). The dry season extends between January and March (Kodandapani *et al.* 2004). The Nilgiris landscape comprises three protected areas, the Bandipur tiger reserve, Mudumalai tiger reserve and Wyanad wildlife sanctuary. Protected areas in general have various management objectives ranging from strict biodiversity conservation to permitting human activities in certain zones (Jones *et al.* 2018). In the Mudumalai tiger reserve, extraction of non-timber forest products (NTFPs) is banned and so are fodder extractions and grazing, with the exception of the eastern part of the reserve. Similarly, in the Bandipur tiger reserve, the extraction of NTFPs is banned. However, in the Wyanad wildlife sanctuary, extraction of NTFPs is allowed through the issue of permits (Narendran *et al.* 2001). The Nilgiris landscape is especially critical from a conservation standpoint, as it has the highest density and largest population of two endangered species in the world, the Asian elephant (*Elephas maximus*) and Bengal tiger (*Panthera tigris*) (Mehta *et al.* 2008; Jhala *et al.* 2015).

The Uttara Kannada landscape (moist) comprises tropical moist deciduous forests (51%), tropical dry deciduous forests (20%), tropical dry thorn forests (9%), non forest (12%), forest plantations (6%) and water bodies (2%) (Fig. 2b) (Pascal *et al.* 1997a, 1997b, 1997c; Ramesh *et al.* 1997, 2002). The dry season extends from October to May (Puyravaud *et al.* 1994). The Uttara Kannada landscape is an intricate socio-ecological landscape, wherein local communities have usufruct rights to collect certain forest products. Forests in this landscape are earmarked by the State Government for the collection of NTFPs by local communities (Puyravaud *et al.* 1994). Farmers living in this landscape graze livestock and collect leaf litter, native grass species and fuelwood (Hegde *et al.* 1998; Bhat *et al.* 2000).

Regional-scale analysis

For the regional-scale analysis, we evaluated annual variability in fire activity (defined here as the number of fire detections) and drought. Fire activity was measured using MODIS fire detection data spanning 2001–2015 (Collection 6: MOD14A1, and MYD14A1; see <https://earthdata.nasa.gov/earth-observation-data/near-real-time/firmss>, verified 14 January 2019) (Giglio *et al.* 2016). MODIS sensors recorded the location of thermal anomalies (i.e. fire detections) four times per day (1-km resolution). Thermal sensors are designed to detect flaming and smouldering fire hotspots from ~ 1000 m² in size. Elaborate algorithms have been developed to improve detection accuracy, especially smaller and cooler fires based on the use of potential fire thresholds (Giglio *et al.* 2016). Monthly MODIS fire detections were then counted within each $5 \times 5'$ pixel (~ 10 000 ha) and were summarised seasonally, annually and over the entire 2001–2015 time period. Summarising the MODIS fire detections within $5 \times 5'$ pixels allow for the evaluation of anomalous fire patterns over time and hence is useful for the regional analysis (Aragão *et al.* 2007). Variability in fire detections for each pixel for each year were computed in units of standard deviations from the mean (i.e. *z*-score). Seasonal summaries comprised the periods January–March (Jan–Mar), April–June (Apr–May), July–September (Jul–Sep) and October–December (Oct–Dec).

Drought and precipitation variability was characterised at the regional scale using variables representing annual climatic variation obtained from the TerraClimate dataset (Abatzoglou *et al.* 2018a), which produces and distributes gridded monthly climate and water balance data at a $1/24^\circ$ (<5 -km) spatial resolution. We used several climate metrics with demonstrated links to fire activity (Littell *et al.* 2009; Abatzoglou and Kolden 2013; Williams *et al.* 2015): (i) Climatic Water Deficit (CWD); (ii) Palmer Drought Severity Index (PDSI); (iii) soil moisture (SOIL); (iv) maximum average temperature (TMAX); (v) Vapour Pressure Deficit (VPD); and (vi) precipitation (PPT). Abatzoglou *et al.* (2018a) calculated CWD as reference evapotranspiration (ET_O) minus actual evapotranspiration (AET):

$$CWD = ET_O - AET$$

where ET_O was calculated using the Penman Montith approach (Allen *et al.* 1998). Note that PDSI and VPD were not originally included with the TerraClimate dataset but were subsequently

added (see <http://www.climatologylab.org/terraclimate.html>; verified 14 January 2019). TerraClimate PDSI applies Palmer's standard methodology (Palmer 1965) and uses ET_O and monthly precipitation in its calculation; it does not incorporate any dynamic or local factors that may influence calculations of drought (cf. Wells *et al.* 2004). All climate metrics were annually summarised over three time periods, January–March (time period 3), October–March (time period 6), and April–March (time period 12). Specifically, CWD, PPT and SOIL were summed over each time period and PDSI, VPD and TMAX were averaged. With the exception of PDSI, these climate metrics were then standardised to per-pixel *z*-scores based on climate normals for 1981–2010. The conversion of raw climate values into *z*-scores to represent and quantify climate variation is becoming a common practice in studies evaluating the relationship between fire and climate (e.g. Parks *et al.* 2018; Stevens-Rumann *et al.* 2018). Note that PDSI was not converted because, by definition, it already represents the per-pixel *z*-score.

For the regional-scale correlation analysis (described below), the spatial resolution of the $5 \times 5'$ pixels representing variability in fire detections (i.e. fire anomaly pixels) was matched with the spatial resolution of the TerraClimate dataset. Subsequently, fire anomalies and the climate metrics were aggregated using a simple arithmetic mean (Abatzoglou *et al.* 2018b) within the boundaries of the nine burnable classes (excluding water, forest plantations, commercial plantations and non forest) at the regional scale. There was one value for each climate metric and vegetation class for each year and each time period. For each vegetation class, we then quantified univariate relationships (e.g. climate metric *v.* fire anomalies) using non-parametric Kendall rank correlation coefficients to account for non-Gaussian distributions that are common in fire data (Abatzoglou *et al.* 2017). We used a two-tailed test, therefore assuming no *a priori* hypothesis as to whether correlations were negative or positive. Statistical significance was assessed at $\alpha = 0.05$. Given the short time series of our datasets, this α level is considered conservative.

Landscape-scale analysis

Annual maps classified as burnt and unburnt forest for the Nilgiris and Uttara Kannada landscapes were produced using Indian Remote Sensing (IRS) satellite imagery (Table 1). Fire years were respectively 1996–2015 and 1999–2015 for the Nilgiris and Uttara Kannada landscapes; however, it should be noted that data were not available because of clouds in the imagery for a limited number of years (Table 1). The spatial resolution for all imagery was 23 m except for the image acquired in 1996, which was 72 m. The 2015 image for each landscape was georectified using one 1:250 000 scanned Survey of India (SOI) topographic map. The root mean square error (RMSE) was respectively ± 9.2 m and ± 11 m for the Nilgiris and Uttara Kannada landscapes. The other imagery in each landscape was georegistered to these reference images, the RMSE ranged from ± 0.07 to 0.1 pixels. All imagery had $\leq 10\%$ cloud cover.

The images were geometrically corrected and they were also atmospherically corrected by applying the dark-object subtraction (DOS) method (Chavez 1996). A methodology specific to the study area was developed by performing supervised

Table 1. Details of satellite data acquired for the landscape scale analysis

IRS, Indian Remote Sensing		
Satellite	Date of acquisition (Nilgiris)	Date of acquisition (Uttara Kannada)
IRS-1B	06-Mar-1996	
IRS-1C	22-Mar-1997	
IRS-ID	12-Mar-1999	05-Mar-1999
IRS-ID		14-Mar-2000
IRS-ID	01-Mar-2001	24-Mar-2001
IRS-ID	24-Feb-2002	09-Mar-2002
IRS-P6	09-Mar-2004	04-Mar-2004
IRS-P6	04-Mar-2005	11-Apr-2005
IRS-P6	27-Feb-2006	13-Mar-2006
IRS-P6	18-Mar-2007	01-Apr-2007
IRS-P6		02-Mar-2008
IRS-P6	07-Mar-2009	21-Mar-2009
IRS-P6	02-Mar-2010	20-Feb-2010
IRS-P6	01-Feb-2011	04-Apr-2011
IRS-P6	03-Mar-2012	05-Mar-2012
IRS-P6	26-Feb-2013	24-Mar-2013
IRS-P6	29-Mar-2014	12-Apr-2014
IRS-P6	16-Feb-2015	18-Feb-2015

classification using training sites from burned areas that we identified (Kodandapani *et al.* 2008). We identified spectral signatures of burnt area in each of the three broad forest types: tropical moist deciduous (TMD), tropical dry deciduous (TDD) and tropical dry thorn (TDT). The advantage of this method over using only a single forest type has been the ability to capture the variability in the spectral signature of burned areas because of differences in the structure, phenology and exposure to soil fractions in these ecosystems. We delineated fire maps by combining burned areas from each of the three forest types. Because shadows of clouds were sometimes misclassified as burned areas (Pereira 2003), we compared the classified image to the false-colour composite of bands 4, 3, 2 and deleted the misclassified areas. Complete details can be found in Kodandapani *et al.* (2008). The fire maps were assessed for their accuracy from field survey fire maps of the Mudumalai tiger reserve. The Mudumalai tiger reserve is a long-term ecological research (LTER) site and field-surveyed annual fire maps have been maintained since 1989; our burned area maps were validated with this dataset (Sukumar *et al.* 1992; Kodandapani *et al.* 2004). The overall accuracy of our burned area maps ranged from 85 to 95% of the burnt areas for the 16-year time period.

Decadal averages of burned areas were calculated in both landscapes and Mann–Whitney tests were conducted to assess differences in decadal means. Burned areas and the climate metrics were aggregated using a simple arithmetic mean (Abatzoglou *et al.* 2018b) within the boundaries of the three vegetation classes in the Nilgiris and the Uttara Kannada landscapes. There was one value for each climate metric and vegetation class for each year for each time period. We tested the relationship between each climate metric and annual area burned using Kendall rank correlation coefficients, as described in the previous section. The statistical analyses were conducted in the

Table 2. Regional scale, annual and seasonal pattern of fire detections in the Western Ghats

Year	Total	Jan–Mar Number of fire detections	Apr–Jun Number of fire detections	Jul–Sep Number of fire detections	Oct–Dec Number of fire detections
2001	301	217	30	38	16
2002	448	335	40	38	35
2003	841	658	66	46	71
2004	2732	2511	52	19	150
2005	1564	1435	57	19	53
2006	1220	955	147	43	75
2007	1561	1304	208	11	38
2008	1060	885	73	23	79
2009	2130	1927	164	14	25
2010	864	756	95	4	9
2011	1315	1079	174	14	48
2012	2241	1982	129	43	87
2013	1069	836	126	15	92
2014	1181	977	149	11	44
2015	881	718	61	16	86
Average	1294	1105	105	24	62

R software program (ver. 3.4.2, R Foundation for Statistical Computing, Vienna, Austria, see <http://www.R-project.org>). We also calculated the fire rotation in each landscape, which quantifies the average number of years required to burn an area the size of each landscape; implicit in the fire rotation is the understanding that some areas may not burn while other areas may burn more than once during a cycle (Van Wagner 1978; Cochrane *et al.* 1999).

Results

Regional-scale analyses

Most (85%) of MODIS fire detections from 2001 to 2015 in the Western Ghats occurred in Jan–Mar (Table 2), with much lower fire activity in the remainder of the year. That said, the Western Ghats exhibited substantial inter-annual variability in fire activity (Table 2). For example, looking at Jan–Mar fire detections, the 3 years with the highest fire activity exhibited approximately five times more fire compared with the 3 years with the lowest fire activity. Inter-annual spatial variability was also evident with a majority of fire activity occurring to the east of the crest of the Western Ghats in the deciduous forests (Fig. 3a).

During the 2004 drought, the total number of 5' pixels summarising the Jan–Mar fire detections with a z -score >0.5 was 325 (33% of study area) (Fig. 3b). Throughout Jan–Mar, notable fire anomalies (z -score >0.5) covered areas from the south to the far north of the Western Ghats. In 2009, the total number of 5' pixels summarising the Jan–Mar fire detections with a z -score >0.5 was 303 (31%) (Fig. 3c). In 2012, the total number of 5' pixels summarising the Jan–Mar fire detections with a z -score >0.5 was 309 (32%) (Fig. 3d).

Although climate variation and fire activity did not exhibit any statistically significant correlations across the Western Ghats as a whole, weak to moderate correlations ($|\tau| = \sim 0.3–0.5$) were

Table 3. Forest burning in the two landscapes
 Imagery analyses were based on multitemporal analyses of Indian Remote Sensing imagery

Study landscape	Nilgiris landscape	Uttara Kannada landscape
Annual percentage of burning		
1996	23.7%	NA
1997	13.6%	NA
1999	15.1%	15.5%
2000	NA	8.4%
2001	4.1%	8.6%
2002	8.6%	16.6%
2004	17.7%	22.5%
2005	14.7%	21.7%
2006	5.4%	5.9%
2007	3.7%	14.5%
2008	NA	0.0%
2009	16.5%	9.3%
2010	0.0%	0.0%
2011	0.0%	6.3%
2012	4.6%	3.2%
2013	0.4%	10.5%
2014	1.4%	8.1%
2015	0.5%	0.0%
Total fire rotation (years)	12.3	10.6
Mean burned area (km ²) (1996–05)	216	440
Mean burned area (km ²) (2006–15)	56	163

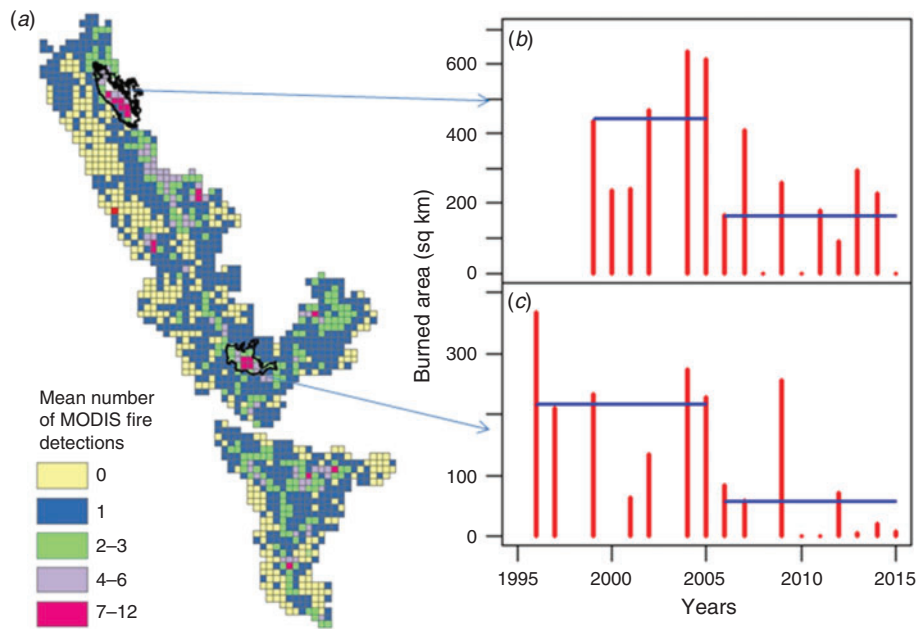


Fig. 5. Temporal pattern of burned areas in the two landscapes showing (a) fire detections for the regional analysis, (b) inter-annual variations in the total burned area in the Uttara Kannada landscape and (c) inter-annual variations in the total burned area in the Nilgiris landscape. Horizontal blue lines indicate decadal averages.

correlation, and whether or not it was statistically significant depended on the forest type and landscape of interest (Fig. 7). Temporal pattern of annual area burned and climate metrics (3-month time scale) in both landscapes are shown in Fig. 8.

In the Nilgiris landscape, weak to moderate ($|\tau| = \sim 0.3-0.5$) correlations were observed between annual burned area and climate variation (CWD, SOIL) in the TDD forests; burned area and climate variation (PDSI, SOIL) exhibited statistically

were observed between annual burned area and climate variation (CWD) in the TDD forests at 3-month time scales.

Overall, the correlations between annual area burned and climate variation were weaker in the Nilgiris landscape compared with the Uttara Kannada landscape (Fig. 7). Another pattern is that the shorter-term (3- and 6-month) time scales, on average, performed better than the 12-month time scale. Though the actual correlation and statistical significance varies, annual area burned was generally positively correlated with CWD, TMAX and VPD, and negatively correlated with PDSI, SOIL, and PPT. The sign of correlations may deviate from this pattern in certain vegetation types such as the TDT forests.

Discussion

Our results generally support the view that fire activity increases during dry years (e.g. Liu *et al.* 2010; Abatzoglou and Kolden 2103; Riley *et al.* 2013; Aragão *et al.* 2018). However, the strength and ubiquity of the response between climate variation and fire activity in our study is somewhat nuanced and depends on the scale of analysis. For example, although there was no statistically significant relationship between climate variation and fire activity when evaluating all vegetation types in the regional scale analysis, statistically significant relationships were observed for some vegetation types. By contrast, statistically significant correlations were evident across both landscapes and within individual vegetation types in the landscape scale analysis, although Uttara Kannada generally exhibited a stronger relationship between climate variation and annual area burned than Nilgiris. We believe our nuanced results are potentially due to the high population density in our study area (Fig. 3a), as studies have shown that the relationship between climate and fire weakens in regions that are heavily influenced by humans (Archibald *et al.* 2010; Parks *et al.* 2014; Syphard *et al.* 2017). Thus, geographic variations in the relationship between fire and climate could be a by-product of differences in environment, human-use, ecological interactions and biogeographic history (Abatzoglou *et al.* 2018b). Nevertheless, our results still show that climate variability is a substantial factor driving inter-annual fire activity in the Western Ghats.

At the regional scale of the Western Ghats, drought severity throughout the fire season, as reflected by increasing water deficit (CWD) and decreasing soil moisture (SOIL), exhibited significant relationships with fire activity in TMD forests (Fig. 4). Similarly, decreasing soil moisture and increased water deficits also exhibited significant relationships with fire activity in DFWZ and TSMD forests (Fig. 4). Intact TEG forests are resistant to fire spread because of the high levels of moisture, but they maybe the most threatened by fire because of the lack of fire-resistant traits (Uhl and Kauffman 1990; Hegde *et al.* 1998; Cochrane and Schulze 1999; Ferry Slik *et al.* 2002; Kodandapani *et al.* 2004). Our research provides some empirical evidence to support the possibility of enhanced fire activity even in TEG forests because of environmental changes brought about by fragmentation, altered fire regimes and possible synergisms, among other factors (Cochrane and Laurance 2002).

Interestingly, average TMAX values and VPD during the fire season (Jan–Mar) were moderately correlated with fire activity in TMD forests, providing some empirical support that increased

warming will result in higher fire activity under a warmer climate (IPCC 2014; Seidl *et al.* 2017). Likewise, in TDEG forests, average TMAX values during the fire season (Jan–Mar) were moderately correlated with fire activity (Fig. 4), again suggesting higher fire activity under a warming climate. These forests are found as remnants amidst a matrix of human transformed landscape elements, but simultaneously, are important for their ecological and cultural values (Parthasarathy *et al.* 2008).

Generally found above 2000 m in the Western Ghats, TMFGs are maintained by a combination of frost and fire (Meher Homji 1967; Sukumar *et al.* 1995). Drought severity throughout the fire season, as reflected by decreasing SOIL and increasing CWD, exhibited significant relationships with fire activity. Multiyear drought stress inferred from the previous-year monsoon precipitation (PPTA) showed some empirical evidence of enhanced fire activity in the montane ecosystems (Fig. 4). Irrespective of the outcome of climate change, the montane forests could be vulnerable to increased fire activity, as most species are sensitive to fire (Meher Homji 1967; Davidar *et al.* 2007).

At the landscape scale, we found that burned area during 2006–2015 decreased in comparison to 1996–2005; mean burned area was ~4-fold higher in the Nilgiris landscape and ~3-fold higher in the Uttara Kannada landscape in the earlier decade (Fig. 5). Inter-annual variability in burned area was correlated with climate variability in both landscapes; changes in human factors such as population (Fig. 3a), cropland area and livestock density could also be contributing to these relationships (Andela *et al.* 2017; Chen *et al.* 2019). Although several studies across the globe have highlighted the importance of climate-driven fire risk in response to climate change (Pyne 2009), ongoing socioeconomic development in regions such as the Western Ghats, could be influencing fire use in predictable ways (Andela *et al.* 2017). Our findings corroborate recent findings regarding a nonlinear decrease in fire activity, especially in tropical forest and savanna regions across the globe (Andela *et al.* 2017). Similarly, our study also emphasises the importance of humans in modulating fires despite the role of climate in driving fire potential in landscapes. India has witnessed an expanding human presence in rural (Fig. 3a) and urban areas (Tian *et al.* 2014); increasing agricultural investments and migrations to cities could also be driving the declining fire activity in the Western Ghats. During the past two decades (1995–2015), human population in India has increased by 36%, or ~0.4 billion, and per capita gross domestic product increased by 186% (World Bank 2018).

Simultaneously, fire plays an important role in the land use and forest-resource dependence in the Western Ghats (Kodandapani *et al.* 2004). The stubble remaining in agricultural fields is regularly burned off and the likelihood of fires escaping into adjoining forests is high (Morrison 1994; Kodandapani *et al.* 2004, 2008). Fire is also used in the extraction of NTFPs in the Western Ghats, e.g. surface fires are set in several seasonally dry forests to stimulate the growth of the mountain date palm (*Phoenix loureiri*) (Mandle and Ticktin 2012; Kodandapani 2013). Pastoral communities living on the fringes of forests, regularly set fire to stimulate the growth of grasses under an open canopy (Schmerbeck and Fiener 2015). For example, the *Todas*, an indigenous pastoral community living especially in

TMFG of the Nilgiris in the Western Ghats, use fire to stimulate the growth of grasses (see references in [Hockings 1989, 1997](#)).

Over short time scales (e.g. 3 to 6 months), increasing water deficits and drought stress could be enhancing fire activity in the Nilgiris landscape, suggesting that the spatial pattern of fires could be influenced by moisture gradients and variability in bio-climate ([Parks et al. 2014](#)). Short-term (3-month) drought exemplified by soil moisture (Jan–Mar) and longer-term (6-month) water deficits and drought stress could be important drivers of fire ([Fig. 7a](#)). In general, the fire season (Jan–Mar) is dry enough to carry fires in the TDD forests, which experiences seasonal droughts ([Murphy and Lugo 1986](#)). Recent studies ([Mondal and Sukumar 2016](#)) suggest that fire potential in the Nilgiris landscape is a result of the previous years' fires, monsoon rainfall and current-year rainfall. Thus, 3- and 6-month time scale analysis of water deficits and soil moisture could be important for fires in seasonally dry forests.

During droughts, reduced precipitation leads to declines in soil moisture, which is also associated with higher temperatures, and enhanced evaporative demand from the atmosphere ([Choat et al. 2018](#)). Correspondingly, longer-term drought severity throughout the fire season, as reflected by PDSI and soil moisture, exhibited significant relationships with burned area in the moist Uttara Kannada landscape ([Fig. 7b](#)). Multiyear drought stress inferred from precipitation occurring from the previous-year monsoon showed significant correlation with burned area for the TMD forests, providing some empirical support for the importance for persistent and prolonged drought and fire in the Western Ghats ([Schwalm et al. 2017](#)).

Although increasing moisture deficits and drought stress had a bearing on fire activity in the Nilgiris landscape at short time scales, all climate variables had a significant effect on fire activity, except precipitation at short time scales and TMAX at longer time scales in the Uttara Kannada landscape ([Fig. 7](#)). Rainfall during the dry season could be suppressing fires, and fuel buildup during wet years before the fire season could be contributing to the fire pattern in the Nilgiris landscape ([Archibald et al. 2010](#)). Further, at longer time scales, the climate metrics do not reflect recent precipitation and thus could have weaker relationships with fuel moisture ([Riley et al. 2013](#)). By contrast, the longer dry season in the Uttara Kannada landscape could be amplifying the fire signal in response to climate. The rainfall deficits and drought conditions before and during the fire season increases forest desiccation and fuel loading in the Uttara Kannada landscape ([Uhl and Kauffman 1990](#)). Dead surface fuels (grass, litter) are primary carriers of the surface fires, ~10–20% of the total fuel load (46.5 Mgha^{-1}) constitute these fine fuels ([Kodandapani et al. 2008](#)). The composition of these fine fuels varies with levels of disturbances in the TMD forests, with higher leaf litter in less disturbed forests. It is likely that this difference in fine fuel moisture could be either limiting or promoting the spread of fire, with grass fuels (Nilgiris) curing more rapidly than the leaf litter (Uttara Kannada) in response to water deficits and droughts ([Riley et al. 2013](#)).

Generality and limitations of findings

Our landscape results suggest that forests in the Western Ghats are experiencing a decline in anthropogenic fires, and that such patterns might be operating at both regional and landscape

scales. Are our findings typical? Both our landscapes are witnessing substantial changes in land use, with transitions from natural landscapes with common land ownership to agriculture on private lands ([Andela et al. 2017; Chen et al. 2019](#)); the Uttara Kannada forests, in particular, have witnessed substantial changes from grazing, collection of NTFPs, fodder, manure and firewood collection during the past several decades. Nevertheless, the temporal patterns of fires observed in the two landscapes are representative of the overall land-use changes in the Western Ghats today.

Given that our study involved fire data spanning only approximately two decades in duration, differences between the Nilgiris (dry) and Uttara Kannada (moist) landscapes in terms of timing *v.* magnitude of drought, and their effect on fire activity, may be difficult to identify. Also, the short fire record analysed in this study may have not adequately captured variability in climate or fire activity, but we will note that there were years with above average rainfall (1996–99, 2005–10, 2014–15) and years with below average rainfall (1993–95, 2000–03) in the two landscapes, and most forest burning occurred during drier years in the Western Ghats ([Kodandapani et al. 2008](#)). Lastly, the short fire duration we analysed may provide uncertain estimates of the fire rotations in our study, but given that our study region has not been well studied to date, our estimates provide a valuable contribution to the literature. Nevertheless, we suggest that future research involving fire activity and climate variation in the Western Ghats would benefit by using a longer fire record.

Our modelling results suggest that water deficits and drought increases the vulnerability of forests in the Western Ghats to anthropogenic fires, and that such fires might be operating at both regional and landscape scales. Relationships were weaker in the Nilgiris landscape compared with the Uttara Kannada landscape, with observed correlations uniformly stronger across all climate variables and time scales. Although this pattern could have resulted from the relatively pronounced dry season of the Uttara Kannada climate, we believe plausible explanations could vary from differences in human transformations ([Andela et al. 2017](#)), presence of large mammals in high densities ([Bond 2005; Madhusudan et al. 2015](#)), proliferation of invasive species ([Hiremath and Sundaram 2005](#)) and increased availability of funds for the management of forests, especially in protected areas such as the Nilgiris landscape ([Reddy et al. 2018](#)). These differences highlight the importance of human activity in influencing burning despite growing climate-driven fire risk ([Andela et al. 2017](#)). We believe correlations at the regional scale are not statistically significant when all vegetation types are combined because the highly diverse study area, in terms of climate, vegetation and human disturbance, likely masks relationships between climate variation and fire.

Implications for forest management

Given projected risks of forests to fire under a changing climate, fire management will be increasingly important for maintaining ecosystem function and services, thereby affecting human livelihoods ([Andela et al. 2017](#)). Although, humans have transformed forests for several millennia in the Western Ghats and forest species have developed fire-adaptation characteristics ([Chandran 1997](#)), moist forests with limited fire-adapted species

may be vulnerable to fire under a future climate. Specifically, TMD forests, DFWZ, TMFG and TSMD forests could be vulnerable to fire under climate-induced increases in fire activity. Fire managers should explicitly include adaptation methods for the management of these forest types in the Western Ghats.

Local communities use fire both legally and illegally to meet various natural resource needs. In protected areas (managed by the State), local residents can extract products for personal use, but in reserve forests (managed by the State forest departments), local residents have no extraction rights unless explicitly permitted (Kodandapani 2013; Moritz *et al.* 2014). Rather than enforcing blanket fire exclusion policies, forest ecosystems in the Western Ghats would benefit from forest management policies that consider the natural resource needs of nearby communities (Kodandapani 2013; Moritz *et al.* 2014; Thekaekara *et al.* 2017). Our results demonstrate that climate exerts at least some control on fire even though fires are generally ignited by people. More importantly, landscape-scale fire monitoring of long and short-term fuel aridity (CWD) and drought stress (PDSI, SOIL) conditions within dominant forests could enhance preparedness of impending fire activity.

Conclusions

We found increased fire activity both at regional and landscape scales in response to drought and dry conditions in the Western Ghats. However, climate variation has a stronger influence on fire activity at the 3- and 6-month time scales compared with the 12-month and antecedent monsoon scales. Both within (Nilgiris landscape) and outside (Uttara Kannada landscape) protected areas, the response of fire to climate variability is similar. Whereas protected areas harbor high biodiversity, especially of charismatic and emblematic species such as the Bengal tiger (*Panthera tigris*), reserve forests are critical from a livelihood perspective for communities living near forests (Kodandapani 2013; Pringle 2017), thereby highlighting a conundrum faced by managers of protected areas. Tropical dry forests are perhaps the most threatened ecosystem in the tropics (Janzen 1988; Miles *et al.* 2006). The primary threats to biodiversity in tropical dry forests arises from the frequent fires, land use change and slash-and-burn agriculture (Murphy and Lugo 1986; Chazdon 2003; Kauffman *et al.* 2003). Using climate information as part of early-warning systems in the Western Ghats would help prepare agencies to mitigate the effects of fires on forest biodiversity and ecosystems services in the short term, and in the long term adapt to the threat of frequent fires due to climate change.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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References

- Abatzoglou JT, Kolden CA (2013) Relationships between climate and macroscale area burned in the western United States. *International Journal of Wildland Fire* **22**, 1003–1020. doi:10.1071/WF13019
- Abatzoglou JT, Kolden CA, Williams AP, Lutz JA (2017) Climatic influences on interannual variability in regional burn severity across western US forests. *International Journal of Wildland Fire* **26**, 269–275. doi:10.1071/WF16165
- Abatzoglou JT, Dobrowski SZ, Parks SA, Hegewisch KC (2018a) TerraClimate, a high-resolution global dataset of monthly climate and climatic balance from 1958–2015. *Scientific Data* **5**, 170191. doi:10.1038/SData.2017.191
- Abatzoglou JT, Williams AP, Boschetti L, Zubkova M, Kolden CA (2018b) Global patterns of interannual climate-fire relationships. *Global Change Biology*. doi:10.1111/GCB.14405
- Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration – guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56, FAO, Rome 300, D05109.
- Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg EH, Gonzalez P, Fensham R, Zhang Z, Castro J, Demidova N, Lim JH, Allard G, Running SW, Semerci A, Cobb N (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* **259**, 660–684. doi:10.1016/J.FORECO.2009.09.001
- Andela N, Morton DC, Giglio L, Chen Y, Van Der Werf GR, Kasibhatla PS, DeFries RS, Collatz GJ, Hantson S, Kloster S, Bachelet D, Forrest M, Lasslop G, Li F, Mangan S, Melton JR, Yue C, Randerson JT (2017) A human-driven decline in global burned area. *Science* **356**, 1356–1362. doi:10.1126/SCIENCE.AAL4108
- Aragão LEOC, Malhi Y, Roman-Cuesta RM, Saatchi S, Shimabukuro YE (2007) Spatial patterns and fire response of recent Amazonian droughts. *Geophysical Research Letters* **34**, L07701. doi:10.1029/2006GL028946
- Aragão LEOC, Anderson LO, Fonseca MG, Rosan TM, Vedovato LB, Wagner FH, Silva CVJ, Silva CHL, Junior, Arai E, Aguiar AP, Barlow J, Berenguer E, Deeter MN, Domingues LG, Gatti L, Gloor M, Marengo JA, Miller JB, Phillips OL, Saatchi S (2018) 21st Century drought related fires counteract the decline of Amazon deforestation carbon emissions. *Nature Communications*. doi:10.1038/S41467-017-02771-Y
- Archibald S, Nickless A, Govender N, Scholes RJ, Leshten V (2010) Climate and the inter-annual variability of fire in southern Africa: a meta-analysis using long-term field data and satellite-derived burnt area data. *Global Ecology and Biogeography* **19**, 794–809. doi:10.1111/J.1466-8238.2010.00568.X
- Bhat DM, Naik MB, Patagar SG, Hegde GT, Kannada YG, Hegde GN, Shastri CM, Shetti DM, Furtado RM (2000) Forest dynamics in tropical rain forests of Uttara Kannada district in Western Ghats, India. *Current Science* **79**, 975–985.
- Bond WJ (2005) Large parts of the world are brown or black: a different view on the ‘Green World’ hypothesis. *Journal of Vegetation Science* **16**, 261–266.
- Bradstock RA (2010) A biogeographic model of fire regimes in Australia: current and future implications. *Global Ecology and Biogeography* **19**, 145–158. doi:10.1111/J.1466-8238.2009.00512.X
- Cansler CA, McKenzie D (2014) Climate, fire size, and biophysical setting control fire severity and spatial pattern in the Northern Cascade Range, USA. *Ecological Applications* **24**, 1037–1056. doi:10.1890/13-1077.1

- Census (2011) Primary Census Abstracts, Registrar General of India, Ministry of Home Affairs, Government of India. Available at: http://www.censusindia.gov.in/2011census/PCA/pca_highlights/pe_data.html [verified 14 January 2019]
- Chandran MDS (1997) On the ecological history of the Western Ghats. *Current Science* **73**, 146–155.
- Chavez PS (1996) Image-based atmospheric corrections. Revisited and improved. *Photogrammetric Engineering and Remote Sensing* **62**, 1025–1036.
- Chazdon RL (2003) Tropical forest recovery: legacies of human impact and natural disturbances. *Perspectives in Plant Ecology, Evolution and Systematics* **6**, 51–71. doi:10.1078/1433-8319-00042
- Chen C, Park T, Wang X, Piao S, Xu B, Chaturvedi RK, Fuchs R, Brovkin V, Ciais P, Fensholt R, Tømmervik H, Bala G, Zhu Z, Nemani RR, Myneni RB (2019) China and India lead in greening of the world through land-use management. *Nature Sustainability* **2**, 122–129.
- Choat B, Brodribb TJ, Brodersen CR, Duursma R, Lopez R, Medlyn BE (2018) Triggers of tree mortality under drought. *Nature* **558**, 531–539. doi:10.1038/S41586-018-0240-X
- Cincotta RP, Wisniewski J, Engelman R (2000) Human population in the biodiversity hotspots. *Nature* **404**, 990–992. doi:10.1038/35010105
- Cochrane MA, Laurance WF (2002) Fire as a large-scale edge effect in Amazonian forests. *Journal of Tropical Ecology* **18**, 311–325. doi:10.1017/S0266467402002237
- Cochrane MA, Schulze MD (1999) Fire as a recurrent event in tropical forests of the eastern Amazon: effects on forest structure, biomass, and species composition. *Biotropica* **31**, 2–16.
- Cochrane MA, Alencar A, Schulze MD, Souza CM, Jr, Nepstad DC, Lefebvre P, Davidson EA (1999) Positive feedbacks in the fire dynamics of closed canopy tropical forests. *Science* **284**, 1832–1835. doi:10.1126/SCIENCE.284.5421.1832
- Cook BI, Ault TR, Smerdon JE (2015) Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Science Advances* **1**, e1400082. doi:10.1126/SCIADV.1400082
- Davidar P, Mohandass D, Vijayan L (2007) Floristic inventory of woody plants in a tropical montane (shola) forest in the Palni hills of the Western Ghats, India. *Tropical Ecology* **48**, 15–25.
- Dimitrakopoulos AP, Vlahou M, Anagnostopoulou CG, Mitsopoulou ID (2011) Impact of drought on wildland fires in Greece: implications of climatic change. *Climatic Change*. doi:10.1007/S10584-011-0026-8
- Gadgil M, Chandran MDS (1988) On the history of Uttara Kannada forest. In 'Changing Tropical Forests'. (Eds J Dargavel, K Dixon, N Semple) pp. 47–58. (Centre for Resource and Environmental Studies: Canberra, ACT, Australia)
- Giglio L, Schroeder W, Justice CO (2016) The collection 6 MODIS active fire detection algorithm and fire products. *Remote Sensing of Environment* **178**, 31–41. doi:10.1016/J.RSE.2016.02.054
- Girardin MP, Wotton BM (2009) Summer moisture and wildfire risks across Canada. *Journal of Applied Meteorology and Climatology* **48**, 517–533. doi:10.1175/2008JAMC1996.1
- Hegde V, Chandran MDS, Gadgil M (1998) Variation in bark thickness in tropical forest community of Western Ghats in India. *Functional Ecology* **12**, 313–318. doi:10.1046/J.1365-2435.1998.00191.X
- Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very-high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* **25**, 1965–1978. doi:10.1002/JOC.1276
- Hiremath AJ, Sundaram B (2005) The fire–lantana cycle hypothesis in Indian forests. *Conservation & Society* **3**, 26–42.
- Hockings P (1989) 'Blue Mountains: the Ethnography and Biogeography of a South Indian Region.' (Oxford University Press: New Delhi, India)
- Hockings P (1997) 'Blue Mountains Revisited, Cultural Studies on the Nilgiri Hills.' (Oxford University Press: New Delhi, India)
- Holden ZA, Swanson A, Luce CH, Jolly WM, Maneta M, Oyler W, Warren DA, Parson R, Affleck D (2018) Decreasing fire season precipitation increased recent western US forest wildfire activity. *Proceedings of the National Academy of Sciences of the United States of America* **115**, E8349–E8357. doi:10.1073/PNAS.1802316115
- IPCC (2014) Chapter 24. Asia. In 'Climate Change 2014. Impacts, Adaptation, and vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change'. (Eds VR Barros, CB Field, DJ Dokken, MD Mastrandrea, KJ Mach, TE Bilir, M Chatterjee, KL Ebi, YO Estrada, RC Genova, B Girma, ES Kissel, AN Levy, S MacCracken, PR Mastrandrea, LL White) pp. 1327–1370. (Cambridge University Press: Cambridge, United Kingdom, and New York, NY, USA)
- Janzen D (1988) Tropical dry forests. The most endangered major tropical ecosystem. In 'Biodiversity'. (Ed. EO Wilson) pp. 130–137. (National Academy of Sciences/Smithsonian Institution: Washington, DC, USA)
- Jhala YV, Qureshi Q, Gopal R (Eds) (2015) 'The Status of Tigers in India 2014.' (National Tiger Conservation Authority: New Delhi, India; and The Wildlife Institute of India: Dehradun, India)
- John R, Dattaraja HS, Suresh HS, Sukumar R (2002) Density-dependence in common tree species in a tropical dry forest in Mudumalai, southern India. *Journal of Vegetation Science* **13**, 45–56.
- Jolly WM, Cochrane MA, Freeborn PH, Holden ZA, Brown TJ, Williamson GJ, Bowman DMJS (2015) Climate induced variations in global wildfire danger from 1979–2013. *Nature Communication* **6**, 7537. doi:10.1038/NCOMMS8537
- Jones KR, Venter O, Fuller RA, Allan JR, Maxwell SL, Negret PJ, Watson JEM (2018) One-third of global protected area is under intense human pressure. *Science* **360**, 788–791. doi:10.1126/SCIENCE.AAP9565
- Kauffman JB, Steele MD, Cummings DL, Jaramillo VJ (2003) Biomass dynamics associated with deforestation, fire, and conversion to cattle pasture in a Mexican tropical dry forest. *Forest Ecology and Management* **176**, 1–12. doi:10.1016/S0378-1127(02)00227-X
- Keeley JE (2009) Fire intensity, fire severity, and burn severity: a brief review of suggested usage. *International Journal of Wildland Fire* **18**, 116–126. doi:10.1071/WF07049
- Kodandapani N (2013) Contrasting fire regimes in a seasonally dry tropical forest and a savanna ecosystem in the Western Ghats, India. *Fire Ecology* **9**, 102–115. doi:10.4996/FIREECOLOGY.0902102
- Kodandapani N, Cochrane MA, Sukumar R (2004) Conservation threat of increasing fire frequencies in the Western Ghats, India. *Conservation Biology* **18**, 1553–1561. doi:10.1111/J.1523-1739.2004.00433.X
- Kodandapani N, Cochrane MA, Sukumar R (2008) A comparative analysis of spatial, temporal, and ecological characteristics of forest fires in a seasonally dry tropical ecosystem in the Western Ghats, India. *Forest Ecology and Management* **256**, 607–617. doi:10.1016/J.FORECO.2008.05.006
- Littell JS, Gwozdz RB (2011) Climatic water balance and regional fire years in the Pacific Northwest, USA: linking regional climate and fire at landscape scales. In 'The Landscape Ecology of Fire'. (Eds D McKenzie, C Miller, DA Falk) pp. 117–139. (Springer: Dordrecht, Netherlands)
- Littell JS, McKenzie D, Peterson DL, Westerling AL (2009) Climate and wildfire area burned in western US ecoregions, 1916–2003. *Ecological Applications* **19**, 1003–1021. doi:10.1890/07-1183.1
- Liu Y, Stanturf J, Goodrich S (2010) Trends in global wildfire potential in a changing climate. *Forest Ecology and Management* **259**, 685–697. doi:10.1016/J.FORECO.2009.09.002
- Madhusudan MD, Sharma N, Raghunath R, Baskaran N, Bipin CM, Gubbi S, Johnsingh AJT, Kulkarni J, Kumara HN, Mehta P, Pillay R, Sukumar R (2015) Distribution, relative abundance, and conservation status of Asian elephants in Karnataka, southern India. *Biological Conservation* **187**, 34–40. doi:10.1016/J.BIOCON.2015.04.003
- Malhi Y, Wright J (2004) Spatial patterns and recent trends in the climate of tropical rainforest regions. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* **359**, 311–329. doi:10.1098/RSTB.2003.1433

- Mandle L, Ticktin T (2012) Interactions among fire, grazing, harvest, and abiotic conditions shape palm demographic responses to disturbance. *Journal of Ecology* **100**, 997–1008. doi:10.1111/J.1365-2745.2012.01982.X
- Mann ME, Gleick PH (2015) Climate Change and California drought in the 21st century. *Proceedings of the National Academy of Sciences of the United States of America* **112**, 3858–3859. doi:10.1073/PNAS.1503667112
- Meher-Homji VM (1967) Phytogeography of south Indian hill stations. *Bulletin of the Torrey Botanical Club* **94**, 230–242. doi:10.2307/2483901
- Mehta VK, Sullivan PJ, Walter MT, Krishnaswamy J, DeGloria SD (2008) Ecosystem impacts of disturbance in a dry tropical forest in southern India. *Ecohydrology* **1**, 149–160. doi:10.1002/ECO.14
- Miles L, Newton AC, DeFries RS, Ravilious C, May I, Blyth S, Kapos V, Gordon JE (2006) A global overview of the conservation status of tropical dry forests. *Journal of Biogeography* **33**, 491–505. doi:10.1111/J.1365-2699.2005.01424.X
- Mittermeier RA, Gil PR, Hoffman M, Pilgrim J, Brooks T, Mittermeier CG, Lamoreux J, Da Fonseca GAB (Eds) (2005) 'Hotspots Revisited: Earth's Biologically Richest and most Endangered Terrestrial Ecoregions.' (Cemex: Mexico City, Mexico)
- Mondal N, Sukumar R (2014) Characterising weather patterns associated with fire in a seasonally dry tropical forest in southern India. *International Journal of Wildland Fire* **23**, 196–201. doi:10.1071/WF13002
- Mondal N, Sukumar R (2016) Fires in seasonally dry tropical forest: testing the varying constraints hypothesis across a regional rainfall gradient. *PLoS One* **11**, e0159691. doi:10.1371/JOURNAL.PONE.0159691
- Moritz MA, Batllori E, Bradstock RA, Gill AM, Handmer J, Hessburg PF, Leonard J, McCaffrey S, Odion DC, Schoennagel T, Syphard AD (2014) Learning to coexist with fire. *Nature*. doi:10.1038/NATURE13946
- Morrison KD (1994) Monitoring regional fire history through size-specific analysis of microscopic charcoal: the last 600 years in South India. *Journal of Archaeological Science* **21**, 675–685. doi:10.1006/JASC.1994.1067
- Murphy PG, Lugo AE (1986) Ecology of tropical dry forest. *Annual Review of Ecology and Systematics* **17**, 67–88. doi:10.1146/ANNUREV.ES.17.110186.000435
- Narendran K, Murthy IK, Suresh HS, Dattaraja HS, Ravindranath NH, Sukumar R (2001) Non timber forest product extraction, utilisation and valuation: a case study from the Nilgiri Biosphere Reserve, Southern India. *Economic Botany* **55**, 528–538. doi:10.1007/BF02871715
- Pai DS, Sridhar L, Rajeevan M, Sreejith OP, Sathbai NS, Mukhopadhyay B (2014) Development of a new high spatial resolution (0.25° × 0.25°) long period (1901–2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region. *Mausam* **65**, 1–18.
- Palmer WC (1965) Meteorological drought. US Weather Bureau, Research paper number 45. (Washington DC, USA)
- Parisien MA, Parks SA, Krawchuk MA, Little JM, Flannigan MD, Gowman LM, Moritz MA (2014) An analysis of controls on fire activity in boreal Canada: comparing models built with different temporal resolutions. *Ecological Applications* **24**, 1341–1356. doi:10.1890/13-1477.1
- Parisien MA, Miller C, Parks SA, DeLancey ER, Robinne FN, Flannigan MD (2016) The spatially varying influence of humans on fire probability in North America. *Environmental Research Letters* **11**, 075005. doi:10.1088/1748-9326/11/7/075005
- Parks SA, Parisien MA, Miller C, Dobrowski SZ (2014) Fire activity and severity in the western US vary along proxy gradients representing fuel amount and fuel moisture. *PLoS ONE* **9**, e99699. doi:10.1371/JOURNAL.PONE.0099699
- Parks SA, Parisien MA, Miller C, Holsinger LM, Baggett LS (2018) Fine scale spatial climate variation and drought mediate the likelihood of burning. *Ecological Applications* **28**, 573–586. doi:10.1002/EAP.1671
- Parthasarathy N, Selwyn AM, Udayakumar M (2008) Tropical dry evergreen forests of peninsular India: ecology and conservation significance. *Tropical Conservation Science* **1**, 89–110. doi:10.1177/194008290800100203
- Pascal J-P (1986) 'Explanatory Booklet on the Forest Map of South India.' (French Institute: Pondicherry, India)
- Pascal J-P, Shyam Sunder S, Meher-Homji VM (1997a) Forest map of south India – Mercara–Mysore sheet. Travaux de la Section Scientifique et Technique Hors Série 18a. (Institut Français de Pondichéry: Pondicherry, India)
- Pascal J-P, Shyam Sunder S, Meher-Homji VM (1997b) Forest map of South India – Shimoga sheet. Travaux de la Section Scientifique et Technique Hors Série 18b. (Institut Français de Pondichéry: Pondicherry, India)
- Pascal J-P, Shyam Sunder S, Meher-Homji VM (1997c) Forest map of south India – Belgaum–Dharwar–Panaji sheet. Travaux de la Section Scientifique et Technique Hors Série 18c. (Institut Français de Pondichéry: Pondicherry, India)
- Pereira JMC (2003) Remote sensing of burned areas in tropical savannas. *International Journal of Wildland Fire* **12**, 259–270. doi:10.1071/WF03028
- Povak NA, Hessburg PF, Salter RB (2018) Evidence for scale-dependent topographic controls of wildfire spread. *Ecosphere* **9**, e02443. doi:10.1002/ECS2.2443
- Prasad VK, Badarinath KVS, Eaturu A (2008) Biophysical and anthropogenic controls of forest fires in the Deccan Plateau, India. *Journal of Environmental Management* **86**, 1–13. doi:10.1016/J.JENVMAN.2006.11.017
- Pringle RM (2017) Upgrading protected areas to conserve wild biodiversity. *Nature* **546**, 91–99. doi:10.1038/NATURE22902
- Puyravaud JP, Pascal JP, Dufour C (1994) Ecotone structure as an indicator of changing forest-savanna boundary (Linganamakki Region, southern India). *Journal of Biogeography* **21**, 581–593. doi:10.2307/2846033
- Pyne SJ (2009) Fire on the fringe. *Environmental Research Letters* **4**. doi:10.1088/1748-9326/4/4/041001
- Ramesh BR, DeFranceschi D, Pascal J-P (1997) Forest map of south India–Tiruvananthapuram–Tirunelveli sheet. Publications du département d'écologie, hors série 22a. (Institut Français de Pondichéry: Pondicherry, India)
- Ramesh BR, DeFranceschi D, Pascal J-P (2002) Forest map of south India–Coimbatore–Thrissur sheet. Publications du département d'écologie, hors série 22b. (Institut Français de Pondichéry: Pondicherry, India)
- Reddy CS, Satish KV, Prasada Rao PVV (2018) Significant decline of forest fires in Nilgiri Biosphere Reserve, India. *Remote Sensing Applications: Society and Environment* **11**, 172–185. doi:10.1016/J.RSASE.2018.07.002
- Renard Q, Ramesh BR, Muthusankar G, Pélissier R (2010) Data paper – high-resolution vegetation cover data for the southern Western Ghats of India. *Pondy Papers in Ecology* **9**, 1–12.
- Renard Q, Pélissier R, Ramesh BR, Kondandapani N (2012) Environmental susceptibility models to predict wildfire occurrences in the Western Ghats of India. *International Journal of Wildland Fire* **21**, 368–379. doi:10.1071/WF10109
- Riley KL, Abatzoglou JT, Grenfell IC, Klene AE, Heinsch FA (2013) The relationship of large fire occurrence with drought and fire danger indices in the western USA, 1984–2008: the role of temporal scale. *International Journal of Wildland Fire* **22**, 894–909. doi:10.1071/WF12149
- Roy PS, Behera MD, Murthy MSR, Roy A, Singh S, Kushwaha SPS, Jha CS, Sudhakar S, Joshi PK, Reddy CS, Gupta S, Pujar G, Dutt CBS, Srivastava VK, Porwal MC, Tripathi P, Singh JS, Chitale V, Skidmore AK, Rajshankar G, Kushwaha D, Karnataka H, Saran S, Giriraj A, Padalia H, Kale M, Nandy S, Jeganathan C, Singh CP, Chandrasekhar MB, Pattanaik C, Singh DK, Devagiri GM, Talukdar G, Panigrahy RK, Singh H, Sharma JR, Haridasan K, Trivedi S, Singh KP, Kannan L, Daniel M, Misra MK, Nipadkar M, Nagbhatla N, Prasad N, Tripathi OP,

- Prasad PRC, Dash P, Qureshi Q, Tripathi SK, Ramesh BR, Gowda B, Tomar S, Romshoo S, Giriraj S, Ravan SA, Behera SK, Paul S, Das AK, Ranganath BK, Singh TP, Sahu TR, Shankar U, Menon ARR, Srivastava G, Neeti , Sharma S, Mohapatra UB, Peddi A, Rashid H, Salroo I, Krishna PH, Hajra PK, Vergheese AO, Matin S, Chaudhary SA, Ghosh S, Lakshmi U, Rawat D, Ambastha K, Kalpana P, Devi BSS, Sharma KC, Mukharjee P, Sharma A, Davidar P, Raju RRV, Ketewa SS, Kant S, Raju VS, Uniyal BP, Debnath B, Rout DK, Thapa R, Joseph S, Chhetri P, Ramchandran R (2015) New vegetation type map of India prepared using satellite remote sensing: comparison with global vegetation maps and utilities. *International Journal of Applied Earth Observation and Geoinformation* **39**, 142–159.
- Schmerbeck J, Fiener P (2015) Wildfires, ecosystem services, and biodiversity in tropical dry forest in India. *Environmental Management* **56**, 355–372. doi:10.1007/S00267-015-0502-4
- Schwalm CR, Anderegg WRL, Michalak AM, Fisher JB, Biondi F, Koch G, Litvak M, Ogle K, Shaw JD, Wolf A, Huntzinger DN, Schaefer K, Cook R, Wei Y, Fang Y, Hayes D, Huang M, Jain A, Tian H (2017) Global patterns of drought recovery. *Nature* **548**, 202–205. doi:10.1038/NATURE23021
- Seidl R, Thom D, Kautz M, Martin-Benito D, Peltoniemi M, Vacchiano G, Wild J, Ascoli D, Metr M, Honkaniemi J, Lexer MJ, Trotsiuk V, Mairota P, Svoboda M, Fabrika M, Nagel TA, Reyer CPO (2017) Forest disturbances under climate change. *Nature Climate Change* **7**, 395–402. doi:10.1038/NCLIMATE3303
- Seneviratne SI, Nicholls N, Easterling D, Goodness CM, Kanae S, Kossin J, Luo Y, Marengo J, McInnes K, Rahimi M, Reichstein M, Sorteberg A, Vera C, Zhang X (2012) Changes in climate extremes and their impacts on the natural physical environment. In 'Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation'. (Eds CB Field, V Barros, TF Stocker, D Qin, DJ Dokken, KL Ebi, MD Mastrandrea, KJ Mach, GK Plattner, SK Allen, M Tignor, PM Midgley) Special Report of Working Groups I and II of the Intergovernmental panel on Climate Change, pp. 109–230. (Cambridge University Press: Cambridge, England)
- Siebert F, Ruecker F, Hinrichs A, Hoffmann AA (2001) Increased damage from fires in logged forest during droughts caused by El Nino. *Nature* **414**, 437–440. doi:10.1038/35106547
- Ferry Slik JW, Vertburg RW, Keblet PJA (2002) Effects of fire and selective logging on the tree species composition of lowland dipterocarp for in East Kalimantan, Indonesia. *Biodiversity and Conservation* **11**, 85–98. doi:10.1023/A:1014036129075
- Stevens-Rumann CS, Kemp KB, Higuera PE, Harvey BJ, Rother MT, Donato DC, Morgan P, Vehlen T (2018) Evidence for declining forest resilience to wildfires under climate change. *Ecology Letters* **21**, 243–252. doi:10.1111/ELE.12889
- Sukumar R, Dattaraja HS, Suresh HS, Radhakrishnan J, Vasudeva R, Nirmala S, Joshi NV (1992) Longterm monitoring of vegetation in a tropical deciduous forest in Mudumalai, southern India. *Current Science* **62**, 608–616.
- Sukumar R, Suresh HS, Ramesh R (1995) Climate change and its impact on montane ecosystems in southern India. *Journal of Biogeography* **22**, 533–536. doi:10.2307/2845951
- Syphard AD, Keeley JE, Pfaff AH, Ferschweiler K (2017) Human presence diminishes the importance of climate in driving fire activity across the United States. *Proceedings of the National Academy of Sciences of the USA* **114**, 13750–13755. doi:10.1016/J.GLOPLACHA.2014.07.005
- Thekaekara T, Vanak AT, Hiremath AJ, Rai ND, Ratnam J, Sukumar R (2017) Notes from the other side of a forest fire. *Economic and Political Weekly* **52**, 22–25.
- Tian H, Banger K, Bo T, Dadhwal VK (2014) History of landuse in India 1880–2010: large-scale land transformations reconstructed from satellite data and historical archives. *Global and Planetary Change* **121**, 78–88. doi:10.1016/J.GLOPLACHA.2014.07.005
- Uhl C, Kauffman JB (1990) Deforestation, fire susceptibility, and potential tree responses to fire in the Eastern Amazon. *Ecology* **71**, 437–449. doi:10.2307/1940299
- Vadrevu KP, Eaturu A, Badarinath KVS (2006) Spatial distribution of forest fires and controlling factors in Andhra Pradesh, India using SPOT satellite datasets. *Environmental Monitoring and Assessment* **123**, 75–96. doi:10.1007/S10661-005-9122-4
- Van Wagner CE (1978) Age class distribution and the forest fire cycle. *Canadian Journal of Forest Research* **8**, 220–227. doi:10.1139/X78-034
- Wells N, Goddard S, Hayes MJ (2004) A self-calibrating Palmer Drought Severity Index. *Journal of Climate* **17**, 2335–2351. doi:10.1175/1520-0442(2004)017<2335:ASPDSI>2.0.CO;2
- Westerling AL (2016) Increasing western US forest wildlife activity: sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society of London – B. Biological Sciences* **371**, 20150178. doi:10.1098/RSTB.2015.0178
- Williams AP, Allen CD, Constance IM, Swetnam TW, Michaelsen J, Still CJ, Leavitt W (2010) Forest responses to increasing aridity and warmth in the southwestern United States. *Proceedings of the National Academy of Sciences of the United States of America* **107**, 21289–21294. doi:10.1073/PNAS.0914211107
- Williams AP, Allen CD, Macalady AK, Griffin D, Woodhouse CA, Meko DM, Swetnam TW, Rauscher SA, Seager R, Grissino-Mayer HD, Dean JS, Cook ER, Gangodagamage C, Cai M, McDowell NG (2013) Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change* **3**, 292–297. doi:10.1038/NCLIMATE1693
- Williams AP, Seager R, Macalady AK, Berkelhammer M, Crimmins MA, Swetnam TW, Trugman AT, Bunnning N, Noone D, McDowell NG, Hryniw N, Mora CI, Rahn T (2015) Correlations between components of the water balance and burned area reveal new insights for predicting forest fire area in the south-west United States. *International Journal of Wildland Fire* **24**, 14–26. doi:10.1071/WF14023
- World Bank (2018) World development indicators. (The World Bank). Available at <http://data.worldbank.org/data-catalog/world-development-indicators> [verified 14 January 2019]