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Declining severe fire activity on managed lands in Equatorial Asia

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Fire activity is declining globally due to intensifying land management, but trends remain uncertain for the humid tropics, particularly Equatorial Asia. Here, we report that rates of fire events deemed severe (≥75th severity percentile of 2002-2019) and very severe (≥90th percentile) for Indonesia declined 19-27% and 23-34% over 2002-2019, respectively, controlling for precipitation, where fire-event severity is given by total fire radiative power and duration. The severity of seasonal fire activity – a measure of extremeness – declined 16% in Sumatra and moderately elsewhere. Declines concentrated over mosaic croplands and nearby forest, accounting for one-fifth and one-quarter of fire activity, respectively, with each class contracting 11% amongst severe fire events. Declines were limited over mosaic lands with relatively limited cropping, despite accounting for a similar extent and one-fifth share of fire activity. Declines had an uncertain association with agricultural development but seemingly reflect related political and economic forces for economic and environmental security.

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Trends in fire activity are of increasing interest as indicators of human-driven environmental change, particularly vegetation transformation and climatic feedbacks[1–3]. Despite increasing wildfire risk due to climate change[4], fire activity has declined by ~15–23% globally over recent generations[1,5], perhaps especially the last 30 years[1,6–10]. Modelling by Ward et al.[5] attribute declines in global burned area over the 20th century to the conversion of natural vegetation to cropland. Satellite observations by Andela et al.[1] similarly suggest that agricultural expansion as well as intensification and landscape fragmentation have reduced burned area in the Global South since 1997, as by fragmenting burning into smaller, cooler fire fronts, by converting flammable biomass, and/or promoting more effective fire prevention. These reductions have concentrated in the savannahs and sub-tropics of northern Africa and eastern South America[1,5–7,9,11], where natural burning is relatively extensive. Reductions are less clear for the humid tropics, where extensive burning is caused largely and directly by humans. There, agricultural development might trace trajectories of increasing then decreasing fire activity, perhaps in step with increasing then decreasing deforestation rates[9,12] or certain agricultural activities; or agricultural development may alternatively stoke persistently elevated fire activity due to the loss of mitigating microclimates and soil moisture following forest degradation[13–15].

Fire-activity trends remain particularly uncertain for the equatorial and broader Southeast Asian regions due to discrepancies amongst studies. Reported regional trends are variously decreasing but non-significant, controlling for precipitation[1]; increasing-to-decreasing, depending on period, absent any reporting of statistical significance[7,10]; and non-significant[6,16], including for Indonesia, which dominates regional trends[16]. Discrepancies centre on fire data sensitivity, observation period, whether the confounding effects of drought are observed, and whether trends are tested for significance. Crucially, reported trends invariably reflect aggregate fire activity that conflate large fire events with less destructive but ubiquitous smaller-scale agricultural burning[17–19], potentially masking shifts to fire regimes driven by changing economic, political, or climatic factors.

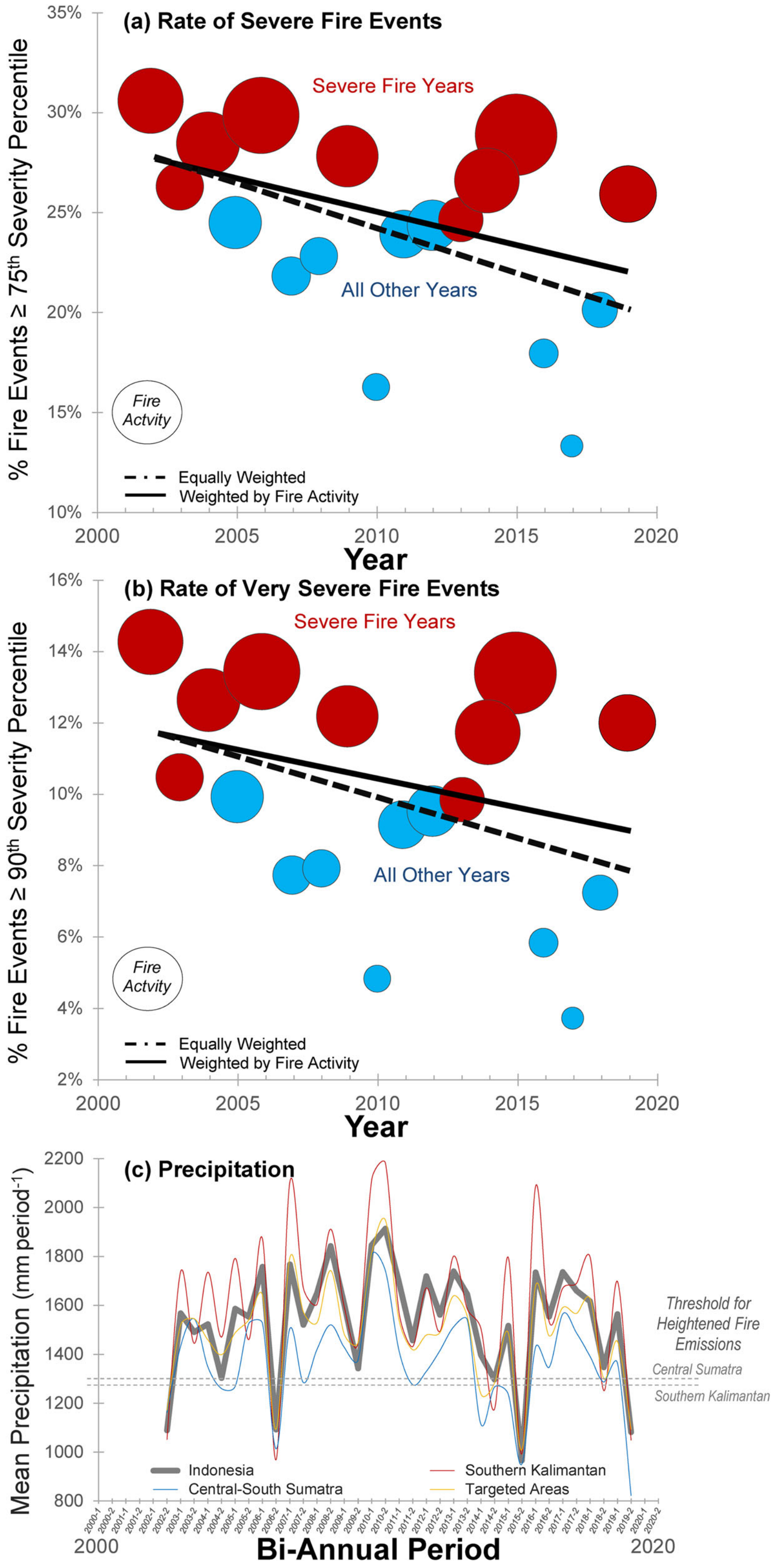
Current patterns and magnitudes of Indonesian fire activity emerged during the 1970s[20], when industrial forestry and agriculture began opening forests and peatlands to recurrent El Niño drought. Seemingly in keeping with historical trends, 2019 experienced severe drought and burning[17], while 2015 burning and drought were the most severe since unprecedented 1997 fire season[21,22], provoking between 12,000 and 100,000 excess respiratory deaths[23–25] and $16 billion in economic losses[26]. Despite continued extremes, Indonesian burning arguably reflects emergent trends consistent with fire abatement described by Andela et al.[1] and Ward et al.[5] The propensity for burning increased but then diminished over 1980–2010 in Kalimantan (Indonesian Borneo), in step with forest degradation and conversion, according to AVHRR satellite active-fire detections (AFDs) controlling precipitation and land use/cover[2]. Significant associations between MODIS satellite AFDs and oil-palm concessions in 2002 became insignificant by 2015[27], controlling for precipitation and land cover, while total AFDs declined across oil-palm concessions over 2003–2013 in Kalimantan and Sumatra[28]. Although total annual MODIS burned area (BA) exhibit no clear trend in Sumatra and Kalimantan over 2001–2018[29], given pronounced inter-annual variability due in turn to variation to precipitation, burning did shift from tall vegetation to low/degraded mosaic vegetation and occurred in areas extensively deforested since 1990[29,30]. Since 2015, fire-suppression and land-management programmes have maintained MODIS AFD frequencies below expected levels across 11 Mha of fire-prone agricultural areas, particularly in Sumatra[17,31,32].

Potential fire abatement remains challenged by vast degraded peatlands and forests in Indonesia. Whilst incrementally converted by agriculture, degraded land is also continuously (re) generated[2,33,34] and, particularly for peatlands, become more fire prone with degradation[30]. Degraded peatlands account for one-third to half of Indonesian burning[18,30,35,36], or as much as 60% during the severe 2015 drought[37], according to aggregate AFD or BA observations. Due to their very high-carbon stock, peatlands are a major source of fire emissions, estimated to have accounted for ~80–85% of Indonesian fire emissions during the 2015[21,38] and 1997/98[39], or slightly over 50% during 2005–2009[28], notwithstanding lower estimates of ~40% for Indonesia in 2015[40] and for Equatorial Asia over 1997–2016[41]. Given the higher estimates above, emissions from Indonesian burning in 1997 were 13–40% of mean annual global carbon emissions from fossil fuels[39], while fire emission rates in late 2015 exceeded fossil emission rates of the European Union[21]. Likely reflecting the steady progression of peatland degradation since the 1990s, Field et al.[42] report an increased susceptibility to burning in southern Kalimantan as of 2015, given severe drought. This was not the case for Central-South Sumatra, however, where peatlands were first and most widely degraded by agriculture[30,33,43] and where drought is historically most severe[44], suggesting decreased susceptibility there.

Here, we clarify the long-term trend to Indonesian fire activity, accounting for the changing susceptibility to burning given drought, as well as the nature of land management driving the trend. We reveal a significant attenuation of severe fire activity over 2002–2019 despite recurrent drought, and indicate that the coordinated management of mosaic agricultural lands is responsible. To this end, we disaggregated overall fire activity by the severity of discrete fire events and the management intensity of burned lands. Fire events are spatio-temporal clusters of daily MODIS AFDs, the severity of which is defined by the product of fire-event duration (days) and fire-event scale (total fire radiative power; FRP) (Eq. 1) and which is therefore correlated with, but distinct from, FRP. We report an attenuation of severe fire activity in terms of (i) declining annual rates of severe and very severe fire events, controlling for fire-season precipitation (July–December), and (ii) declining severity of seasonal fire activity (January–June, July–December), controlling for seasonal precipitation. We show that this attenuation of severe fire activity is underlaid by a declining incidence of cultivated mosaic lands amongst severe fire events and their ignitions, but that attenuation remains partially countered by an increasing incidence of peatswamp forest amongst these fire events and ignitions.

Results

Attenuating severe fire activity. An attenuation of severe fire activity is apparent given declining rates of severe and very severe fire events. Here, severe and very severe fire events are those meeting or exceeding the 75th and 90th percentiles of national fire-event severity over 2002–2019, respectively. Annual rates of severe and very severe fire events decreased significantly by 19–27% across Indonesia over 2002–2019 (Fig. 1a, b, $p < 0.01$), controlling for fire-season precipitation (Fig. 1c; model $R^2 = 0.76$ & 0.81, respectively). Declining rates were despite the regularity of drought at levels historically associated with elevated fire activity, particularly in 2015 and 2019[17,44] (Fig. 1c). Declining rates described by dashed lines in Fig. 1 capture the 2002–2019 time series 'as is', treating all years equally. As certain years host fire activity disproportionately due to recurrent drought[37,44] and, therefore, are arguably more important to long-term trends, a case can be made for unequal treatments. Declines in rates of severe and very severe fire events notably remain highly significant if weighting trends by overall national annual fire activity,



defined by annual AFD frequencies, as depicted by the solid lines in Fig. 1a, b ($p < 0.01$, model $R^2 = 0.79$ & 0.84, respectively).

The downward effect of time on national rates of severe and very severe fire events was substantial, at 39–67% that of precipitation (Supplementary Table 1). In practical terms, over a given 8–12-year interval, rates declined by an extent equivalent to the average difference in rates between a drier year of heightened burning, such as 2019, and moderately dry or normal year, such as 2018. This downward effect of time is particular to severe and very severe fire activity. Annual total fire activity exhibited a downward but statistically insignificant trend nationally over 2002–2019, controlling for precipitation, consistent with the aforementioned studies of aggregate AFDs and BAs for Indonesia and Southeast Asia[1,6,16,29].

Fig. 1 Declining annual rates of severe and very severe fire events, Indonesia, controlling for fire-season precipitation, alongside mean total seasonal precipitation by region. In **a** and **b**, years of severe fire activity are those for which ≥25% of fire events are severe, i.e., 2002, 2003, 2004, 2006, 2009, 2013, 2014, 2015, and 2019. Fire activity is defined as national annual AFD frequencies, being also model weights. The area of annual fire-activity circles in **a**, **b** is proportional to annual AFD frequencies. Trend lines in **a**, **b** are as per regressions on total precipitation per fire season (July–December) and time elapsed since 2002. For visualisation of the effects of time elapsed in **a**, **b**, trend lines hold precipitation constant as the July–December mean for 2002–2019. Precipitation in **c** is according to IMERG v06B monthly estimates[88]. X-axis labels ‘1’ and ‘2’ denote the first (January–June) and second (July–December) bi-annual seasons per year, respectively. Dashed lines in **c** describe regional estimates of six-monthly total precipitation thresholds below which fire-related carbon emissions are relatively acute, according to Field et al.[85] for 1997–2006. These are indicative only, given (i) differences in the precipitation datasets, observation periods, and regional delineations between this study and Field et al.[85], (ii) the sizable 95% confidence envelopes surrounding these thresholds, and (iii) the fact that the 6-monthly periods defining these thresholds are not necessarily our bi-annual seasonal intervals. Labels for the thresholds are as per Field et al.[85].

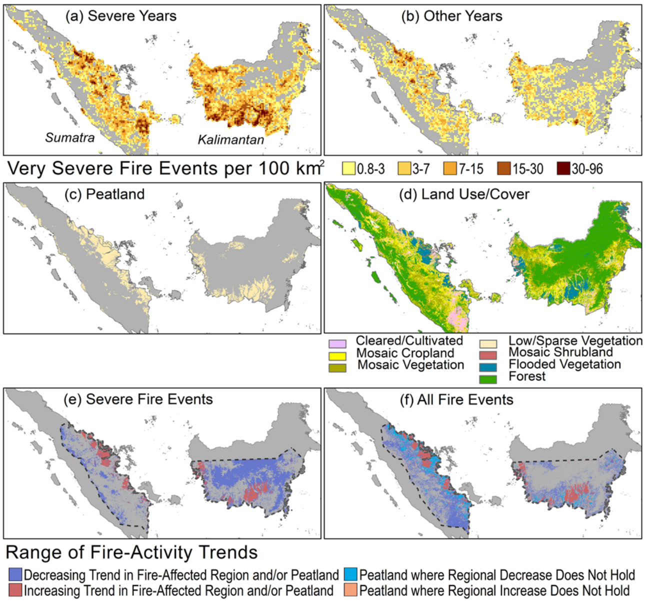


Fig. 2 Density of very severe fire events in Sumatra and Kalimantan for years of severe fire activity during 2002–2019 and all other years of 2002–2019, relative to Peatland and land-use/cover classes as of 2015, as well as the geographic ranges of significantly decreasing and increasing trends amongst severe fire events and all fire events over 2002–2019 for South-Central Sumatra, Southern Kalimantan, and Peatland therein separately. Years of severe fire activity in **a** are those for which ≥25% of fire events are severe, i.e., 2002, 2003, 2004, 2006, 2009, 2013, 2014, 2015, and 2019. See Supplementary Fig. 6 for a time-series version of **a**. **d** Classes are adapted from the Copernicus Climate Change Initiative Land-Cover Product[100, 101] (Table 1). **e**, **f** Significant trends are as per Table 2a, c, signifying the increasing/decreasing incidence of a given land use/cover amongst severe fire events or all fire events over 2002–2019, respectively. Dark coloured areas denote land-use/covers with significant increasing/decreasing trends in a fire-affected region and/or in Peatland therein. A land use/cover is shaded separately inside and outside of Peatland accordingly. Land use/covers with increasing/decreasing trends across a given region but not across Peatland therein are shaded lightly within Peatland and are exclusive to **f**. Supplementary Fig. 13 repeats **a** through **d** for other areas of Indonesia.

Rates of severe fire events also declined significantly in Indonesia’s fire-affected regions, namely Central-South Sumatra and Southern Kalimantan (Fig. 2e), as well as in predominantly agricultural areas recently targeted for fire suppression (hereafter, Targeted Areas; $p < 0.01$, model $R^2 = 0.49$–0.67; Supplementary Fig. 1), controlling for precipitation. Regional declines were appreciable but statistically weaker when weighting trends by national fire activity ($p \leq 0.6$, model $R^2 = 0.36$–0.74). Regional rates of very severe fire events declined significantly only in Southern Kalimantan ($p < 0.01$, model $R^2 = 0.82$), again less acutely when weighted ($p = 0.07$, model $R^2 = 0.75$), contrary to reported increased susceptibility to burning there given severe drought as of 2015[42]. The weakening of statistical relationships amongst weighted regional trends reflects the partial annual correspondence between regional rates and national fire activity.

An attenuation of severe fire activity is also apparent given the declining severity of seasonal fire activity over 2002–2019. This measure is given as the skewness of fire-event severity scores per season and is indicative of both the extremeness and extensiveness of fire activity (Eq. 2, Supplementary Note 1). Precipitation accounted for 30–53% of the severity of seasonal fire activity over 2002–2019, depending on region (Supplementary Table 2). Net of this effect of precipitation, seasonal severity declined significantly over time in Central-South Sumatra ($p < 0.05$), moderately in Southern Kalimantan and the Targeted Areas ($p < 0.1$), and non-significantly nationally (Supplementary Table 2, Fig. 3), reflecting in the latter case the greater variability of seasonal severity at the national scale. Absolutely, declines in the severity of seasonal fire activity over time were appreciable only in Central-South Sumatra where, not incidentally, droughts are also relatively acute[44] (Fig. 1c), consistent with assertions of diminished susceptibility to burning there[42]. There, the passage of time affected the severity of seasonal fire activity 62% as much as precipitation, accounting for slightly more than one-third of observed decline (Supplementary Table 2).

No significant trends to rates of severe or very severe fire events or to the severity of seasonal fire activity were apparent if not controlling for precipitation. This was expected, given extreme inter-annual variability of Indonesian burning[29]. The large magnitude of this variability frustrates the reliable detection of relatively minor trends to absolute fire activity, as affirmed by studies reporting no trends for Equatorial Asia[16], and is itself underlaid by the highly non-linear relationship between precipitation and burning[45]. Accordingly, above we report on *attenuating* fire activity, that is, significant declines in rates of severe fire events and in the severity of seasonal fire activity for a given level of drought. It is plausible that, over longer periods (e.g., >30 years), attenuation will translate into unambiguous declines to absolute burning. Preliminary support for this possibility arguably exists, namely significant declines in total annual fire-event severity amongst severe ($p < 0.05$) and very severe ($p < 0.1$) fire events in Central-South Sumatra over 2002–2019, and similarly negative but insignificant trends for Southern Kalimantan (Supplementary Fig. 12). The ~5% decline in total burned area for Equatorial Asia during 2010–2019 compared to 2000–2009[10] is also consistent with a declining trend.

Managed lands and fire-activity severity. The role of progressive land management in the observed attenuation of severe fire activity would be indicated by shifting associations between severe fire activity and certain land-uses/covers, particularly fire-

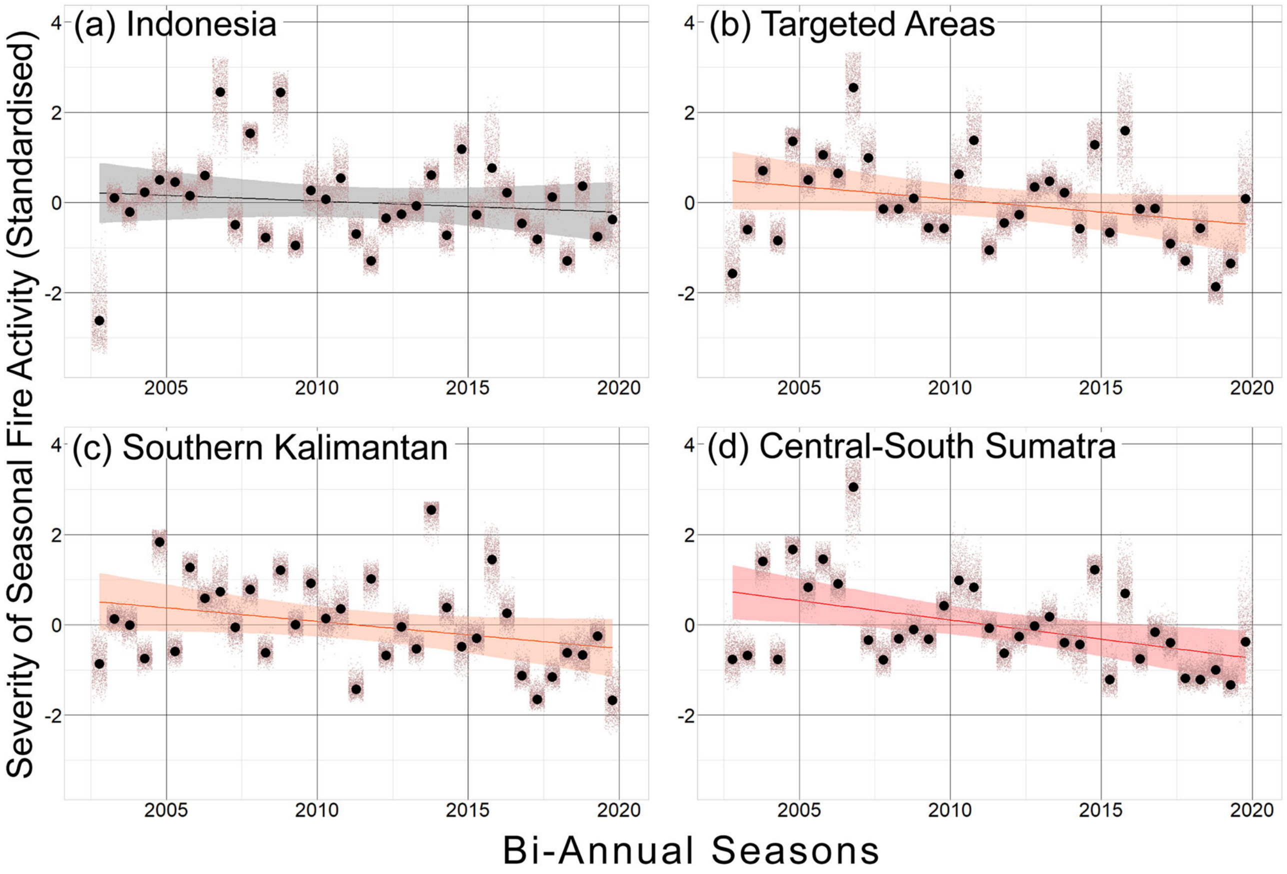


Fig. 3 Declining severity of seasonal fire activity, controlling for precipitation, for Indonesia, Targeted Areas, Southern Kalimantan, and Central-South Sumatra. Trends describe skewness of seasonal fire-event severity, controlling for precipitation, standardised per region. The cloud of points around each datum denotes the spread of bootstrapped model residuals. Red and orange trend lines and 95% confidence envelopes indicate trend significance, at $p < 0.05$ for **d** and $p < 0.1$ for **b**, **c**.

prone lands degraded by agriculture[1] (Table 1). We find evidence for such shifts upon determining robust trends (Table 2; Fig. 2e, f) to the relative frequencies of annually-observed land uses/covers of varied management intensities (Table 1; Fig. 2d) amongst AFDs of fire events, severe fire events, and their ignitions, controlling for national fire activity (Supplementary Note 2, Supplementary Note 3). Ignition(s) are defined as the earliest AFD(s) per fire event. Consistent with attenuation due to land management, over 2002–2019 fire activity became significantly less-prevalent across mosaic lands incorporating >50% agriculture/plantations (*mosaic cropland*), but not across mosaic lands incorporating <50% agriculture/plantations (*mosaic vegetation*) (Table 2). This uneven trend is despite each mosaic class accounting for an equal one-fifth share of overall national fire activity (Table 1), being spatially integrated with one another (Supplementary Fig. 5), and having comparable rates of fire activity (Table 1), total extents, and proportional extents under active land use (Supplementary Fig. 4).

Mosaic cropland became significantly less prevalent amongst ignitions of severe fire events (Table 2b blue cells) and of all fire events (Table 2d) in all regions of Table 2 but Peatland. (Hereafter, Peatland denotes the regional extent of peatlands of varied land uses in Fig. 2c). In Central-South Sumatra and Southern Kalimantan, *mosaic cropland* declined in prevalence amongst ignitions of severe fire events in these regions, at a rate of ~−0.5% yr^{-1} of such ignitions in these regions (Table 2b). Accordingly, over 2002–2019, 9–10% of ignitions of severe fire events in these two fire-affected regions transitioned away from *mosaic cropland*, as did 11% of such ignitions nationally. *Mosaic cropland* decreased in prevalence more markedly amongst ignitions of all fire events (Table 2d), especially in Central-South Sumatra (−0.75% yr^{-1}). In Peatland, *forest*, rather than *mosaic cropland*, significantly declined in prevalence amongst ignitions (Table 2b, d).

Land use/cover trends observed for whole fire events (Table 2a, c) reflect those for ignitions but also extend to forests. As with ignitions, *mosaic cropland* became less prevalent amongst all fire events in the fire-affected regions (-0.5% yr^{-1}) (Table 2c). Also as with ignitions, *forest*, rather than *mosaic cropland*, declined in prevalence amongst severe and all fire events in Peatland (Table 2a, c). However, severe fire events exhibited land-use/cover shifts departing from those of ignitions or all fire events generally. *Forest*, not *mosaic cropland*, declined in prevalence amongst severe fire events nationally and in most regions (Table 2a). Nationally, 11% of AFDs of severe fire events shifted away from *forest* over 2002–2019. Differences between the land use/cover shifts observed for severe fire events (Table 2a) and their ignitions (Table 2b) partly reflect sampling differences that raise the minimum fire-event severity of the former relative to the latter (Supplementary Note 2). In this light, Table 2 suggests that declining fire activity across *mosaic cropland* (Fig. 2e) translated into reduced extreme fire activity across *forest* (Fig. 2f).

Attenuating fire-activity extremes and peatland. Shifting associations between fire activity and land use/cover over Peatland (Fig. 2c) were distinct from those of the surrounding fire-affected regions (Fig. 2f). As noted, severe fire events and their ignitions over Peatland experienced a declining incidence of *forest*, rather than *mosaic cropland* (Table 2a, b), underscoring peatlands'

Table 1 Land use/cover classes and respective fractions of fire activity in the fire-affected regions of Indonesia.

Management intensity	Land-use/cover	Class description	Fire-affected regions	
			% Fire activity (2018)	Relative fire occurrence (ratio of % fire activity to % class area, 2018)
High	Cleared/Cultivated Lands	Intensive agriculture, paddy fields, and associated herbaceous covers, as typically observed surrounding urban centres and across densely settled areas	19.4	1.8
Medium	Mosaic Cropland with Vegetation (>50% agri./plantation)	Mosaic croplands (>50%), including plantations, amongst trees and shrubs of natural, degraded, or managed states	24.7	1.1
Low	Mosaic Vegetation with Cropland (<50% agri./plantation)	Mosaic trees or shrubs (>50%) of natural, degraded, or managed states amongst croplands, including plantations	20.7	1
Negligible	Mosaic Shrubland	Mosaics of trees, shrubs, and herbaceous covers, without cropland/plantation; mostly natural vegetation formations in Papua	0.1	4.7
Negligible	Forest	Natural broadleaf evergreen tree cover of >15% coverage	21.1	0.6
Negligible	Low/Sparse Vegetation	Trees, shrubs, and herbaceous cover of <15% coverage	6.8	4.7
Negligible	Flooded Vegetation	Trees, and occasional shrubs, subject to recurrent flooding by fresh or brackish water; generally peatland, especially that >2 m deep and/or relatively intact	6.3	0.7

High relative fire occurrence measures for mosaic shrubland and *low/sparse vegetation* are qualified by the relatively limited area of these land covers. The seven classes above combine the 22 original classes of the Copernicus Climate Change Initiative Land-Cover Product (Supplementary Table 5). Class descriptions above reflect the relative frequencies of the original classes in Indonesia. The description of *flooded vegetation* also reflects visual interpretation using high-resolution satellite imagery and comparisons of its spatial distribution (Supplementary Fig. 5) against peatswamp forest degradation mapped by Nikonovas et al.[30]. Percentage fire activity is with respect to MODIS active-fire detections.

unique role in the attenuation of severe fire activity. The upshot of such distinctive land-use trends amidst burning and/or distinctive fire regimes on peatlands is that they may retard, or even offset, a generalised attenuation of severe fire activity, consistent with the long-term concentration of Indonesian fire activity on peatlands[37]. Our data support this possibility of retardation or offset while also recognising attenuation over peatlands, as detailed below.

Regarding concentrated burning on peatlands, very severe fire events across Peatland accounted for 76% of the total severity for all fire events nationally over 2002–2019 (Fig. 2a–c). This fraction greatly qualifies previous reports of ~30–60% of national fire activity on peatlands based on aggregate observations of BAs or AFDs[18,30,35–37]. Relatively severe fire activity in Peatland compared to mineral soils (Fig. 2a–c) reflects myriad historical and geographic factors, including greater and more frequent extremes of fire-event severity in Peatland (Supplementary Fig. 7). Notably, severe fire events in Peatland are characterised by relatively energetic burning, that is, greater fire radiative power indicative of greater biomass consumption[46], as opposed to larger fire events with relatively many AFDs or having longer durations. On Peatland, total FRP per fire event accounted for 51–52% of the scale of severe and very severe fire events when controlling for AFD quantity per event, compared to only 30–33% on mineral soils ($p < 0.01$, log-log partial correlations weighted by severity; Supplementary Table 7). Fire-event scale, in turn, accounted for 97% and 93% of fire-event severity on Peatland and mineral soils, respectively (r^2 of log–log correlation weighted by severity, $p < 0.01$).

Regarding attenuation over peatlands, declining fire activity across *mosaic cropland* and/or *forest* coincided with significant increases to the prevalence of *flooded vegetation* amongst fire events and ignitions, regionally and nationally (Table 2 orange cells). *Flooded vegetation* describes peatswamp forest fringed by agriculture but which remains relatively unmanaged and intact (Fig. 2c, d). *Flooded vegetation* so encompasses virtually all remaining primary peatland forest[30] and half of peatlands >2 m deep (Supplementary Fig. 5, Supplementary Table 6). Amongst ignitions of severe fire events (Table 2b), increases to the prevalence of *flooded vegetation* were generally less than or comparable to decreases in the prevalence of *mosaic cropland* or *forest*, including for Peatland, consistent with attenuation. Nationally, 6% of ignitions of severe fire events shifted towards *flooded vegetation* over 2002–2019, or about half the corresponding 11% shift away from *mosaic cropland* (Table 2b). In contrast, amongst severe fire events (Table 2a), increases to the prevalence of *flooded vegetation* were generally much greater than decreases to the prevalence of *mosaic cropland* or *forest*, as in the fire-affected regions, though crucially the Peatland region is exceptional in this respect. There, shifts towards *flooded vegetation* remained comparable to shifts away from *forest*, suggesting relatively concerted, if distinctive, local processes of fire prevention across peatlands.

Discussion

Previously, fire abatement driven by intensifying land management in the developing world was observed virtually exclusively in naturally fire-prone savannah biomes, such as northern Africa[1,11]. We extend such abatement dynamics to the humid tropics for the first time upon disaggregating overall fire activity into discrete fire events and quantifying their severity for Equatorial Asia, describing ultimately an *attenuation* of the severe fire activity that has arisen largely since ca.1970. We report significant declines in the rate of severe fire events across Indonesia and its fire-affected regions over the last two decades (Fig. 1), as well as significant declines in the severity of seasonal fire activity, particularly in Sumatra (Fig. 3).

Table 2 Estimated percentage annual change in land uses/cover frequency across fire events or ignitions, based on annual observations of land use/cover and fire activity over 2002–2019, by region, for either active-fire detections of severe fire events, ignition active-fire detections of severe fire events, active-fire detections of all fire events, and ignition active-fire detections of all fire events.

	Land Use/Cover 2002-2019													
	Management Intensity			Largely Unmanaged				Management Intensity			Largely Unmanaged			
	High	*Medium*	*Low*					*High*	*Medium*	*Low*				
Region	*Cleared/ Cultivated*	*Mosaic Cropland*	*Mosaic Veg.*	*Forest*	*Mosaic Shrubland*	*Low/Sparse Vegetation*	*Flooded Vegetation*	*Cleared/ Cultivated*	*Mosaic Cropland*	*Mosaic Veg.*	*Forest*	*Mosaic Shrubland*	*Low/Sparse Vegetation*	*Flooded Vegetation*
	(a) Active-Fire Detections of Severe Fire Events							***(b) Ignition Active-Fire Detections of Severe Fire Events***						
Indonesia	–0.18	–0.47	0.03	–0.60	0.11	0.10	0.84	–0.02	–0.61	–0.21	0.12	0.16	0.20	0.35
Southern Kalimantan	0.05	–0.33	–0.22	–0.59	0.01	0.23	0.87	–0.06	–0.55	–0.15	0.23	0.01	0.23	0.29
Central-South Sumatra	–0.65	–0.13	0.45	–0.47	0.00	–0.15	0.98	–0.04	–0.52	–0.27	0.03	0.00	0.19	0.59
Elsewhere	0.38	–1.46	–0.52	–0.03	0.64	0.11	0.50	0.12	–0.74	–0.29	0.08	0.41	0.21	0.17
Peatland	–0.15	0.01	0.15	–0.95	0.00	–0.03	0.98	–0.09	–0.20	0.12	–0.65	0.00	0.18	0.64
Mineral Soil	–0.11	–1.94	–0.49	0.77	0.46	0.44	0.35	–0.05	–0.91	–0.28	0.60	0.26	0.20	0.13
Targeted Areas	0.01	–0.01	0.04	–0.84	–0.01	–0.10	0.99	–0.05	–0.42	0.03	–0.27	–0.00	0.15	0.57
	(c) Active-Fire Detections of All Fire Events							***(d) Ignition Active-Fire Detections of All Fire Events***						
Indonesia	–0.19	–0.55	–0.03	–0.01	0.07	0.13	0.52	–0.18	–0.63	0.01	0.26	0.07	0.13	0.27
Southern Kalimantan	–0.12	–0.52	–0.05	0.04	0.01	0.21	0.42	–0.21	–0.61	0.07	0.36	0.01	0.16	0.20
Central-South Sumatra	–0.47	–0.54	–0.04	0.02	0.00	0.07	0.93	–0.22	–0.75	–0.12	0.28	0.00	0.12	0.64
Elsewhere	0.04	–0.67	–0.13	0.09	0.22	0.13	0.17	–0.04	–0.48	0.04	0.06	0.13	0.10	0.09
Peatland	–0.27	–0.19	0.16	–0.74	0.00	0.08	0.96	–0.34	–0.41	0.10	–0.45	0.01	0.18	0.92
Mineral Soil	–0.16	–0.88	–0.09	0.58	0.15	0.14	0.13	–0.15	–0.73	0.03	0.48	0.10	0.11	0.08
Targeted Areas	–0.14	–0.30	0.10	–0.55	–0.00	0.04	0.87	–0.26	–0.62	0.13	–0.06	0.00	0.17	0.65

Blue and orange shading denote significant decreasing and increasing trends in land use/cover frequency amongst fire events/ignitions, respectively (dark, $p < 0.001$; medium, $p < 0.01$; light, $p < 0.05$). Shading denotes at least moderate significance without Bonferroni correction. Values are estimated annual changes to the relative frequency of a land use/cover class, expressed as percentages of a given set of active-fire detections (AFDs) panels **a** & **c** or ignition AFDs panels **b** & **d** per region, over 2002–2019. For example, the value of −0.59 for the *forest* class of Southern Kalimantan in panel **a** indicates that the incidence of *forest* decreased across all AFDs of severe fire events across this region at −0.59% yr^{-1} of such AFDs on average. Interpretation favouring dark and medium shaded cells is favoured, according to Bonferroni adjustments. Row totals do not sum to 0 due to the exclusion of coefficients for a land-cover comprised of settled and/or bare areas host to <3% of fire activity nationally (Supplementary Table 6). Java and the Lesser Sunda Islands are excluded for all regions.

Such attenuation of severe fire activity departs from the prior anthropogenic amplification of fire activity[20], which commenced in the 1960s with a rapid expansion of degraded vegetation[39,47,48]. Crucially, this attenuation, underlain by changing land-use/cover amidst burning, also appears contrary to projections of increased regional fire activity due to climate change[49,50]. In this respect, our findings affirm earlier conjecture for Equatorial Asia that "land manager responses to expected shifts in tropical precipitation may critically determine the strength of climate–carbon cycle feedbacks during the 21st century"[45]. The observed attenuation further qualifies previous reports of non-significant downward trends in overall fire activity in Southeast Asia[1], as it does reports of no trend whatsoever for Indonesia[6,16,29]. Correspondingly, a similar attenuation of severe fire activity is conceivable for other tropical regions, particularly South America, where previously reported trends in overall fire activity were similarly non-significant downward[1] and for which major countries (i.e., Brazil) have similarly attempted to depress fire activity with some success[10,51].

Our observations elaborate dynamics possibly underlying a recently-reported divergence between burned area, which has been declining regionally and pantropically over the last two decades, and fire emissions, which have remained steady or even increased per unit burned area, as in equatorial and northern Africa[10]. In Southeast Asia (including Indonesia), total burned area of 2010–2019 declined by ~5% relative to 2000–2009, yet fire CO_2 emissions per unit burned area remained constant[10]. Such a divergence would arise if, as we observe, the attenuation of fire-event severity manifests widely over mosaic agricultural areas yet not in comparable but higher-biomass, less managed mosaic lands, even if still extending to forests in the case of extreme fire activity. Such a divergence would also arise if, as we observe, severe fire activity remained stable or ascendent across carbon-dense *flooded vegetation*, consistent with a concentration of Indonesian burning on peatlands since the 1990s[37] following historical agricultural expansion[30,33,52]. Such selective attenuation, favouring lands of relatively moderate carbon stock (*mosaic cropland*) or limited extent within epicentres of severe fire activity (*forest;* Fig. 2a, d), supports explanations of the divergence in question citing an increasing fraction of burning in forest-dominated, high-carbon areas[10].

The Indonesian case further clarifies dynamics underlying the divergence in question in terms of modes of fire abatement and emission reduction. Heightened fire activity during 2019 in Indonesia, Amazonia, Australia, and Russia resulted in the greatest global discrepancy between fire emissions and burned area of the last two decades[10]. In Indonesia, the significance of the increasing prevalence of *flooded vegetation* amongst severe fire events over 2002–2019 was, in fact, conditional on heightened burning during late 2019 and late 2015 to a lesser degree (Supplementary Note 2). This conditionality underscores the centrality of recurrent, drought-driven, relatively brief, and largely predictable[47,53] periods of extreme burning to the divergence between burned area and fire emissions. In turn, this conditionality suggests that recent, targeted fire prevention across Indonesian peatlands[17], which reduced fire activity by ~30% in 2019[17], may gradually diminish this divergence and, further, that such interventions must feature prominently in emission-reduction efforts in similar contexts punctuated by periodic extreme burning. In contrast, the declining prevalence of *mosaic cropland* and nearby *forest* amongst severe fire activity was more robust over our time series (Supplementary Note 2), indicating an alternative, relatively constant, incremental, and generalised mode of land management yielding less intensive emission reductions.

Drought reoccurred throughout our time series (Fig. 1c) and was accounted for, both as a variable in our models and by variations to our time-series observations. Therefore, non-climatic factors, namely land management, must underlie the attenuation of severe fire activity. Conceptually, land management has been characterised as progressive agricultural capitalisation[1], typified by agricultural investment, intensification, modernisation, and commercialisation. Capitalisation doubtless plays a role in fire abatement, as for instance amongst Indonesian smallholders, who progressively replaced swidden practices with oil-palm permaculture since the 1990s[54,55]. Yet capitalisation is ultimately a crude determinant of fire abatement and has an uncertain, seemingly nuanced role here. Consistent with the expected role of capitalisation, fire activity declined widely across *mosaic cropland*, but not the less cultivated and capitalised *mosaic vegetation* (Table 2). On the other hand, the literature is clear that the relatively capitalised Indonesian agro-industrial sector has a relatively *high* association with the extensive burning of disused lands, compared to less capitalised land users[17]; that Indonesian agro-industrial investment has been *declining*[56], as described below; and that the vast majority of such investment has occurred *prior to or during* agricultural establishment[57], which has been ongoing decades. Some clarity of the role of capitalisation may be offered by the fact that fire activity declined *rarely* and relatively *moderately* across intensively-farmed *cleared/cultivated lands* (Table 2), which also have a relatively *high* fire-occurrence rate (Table 1). Conceptually, therefore, transitioning from *mosaic vegetation* to *mosaic cropland* to *cleared/cultivated lands* as per the presumed course of progressive land management would perversely *increase* overall fire activity, likely due to more frequent agricultural fires, while simultaneously reducing severe fire activity generally, as per our observations.

This model of attenuation resonates with recent developments in Indonesia suppressing severe fire activity in managed lands, summarised below:

(i) AGRICULTURAL INTENSIFICATION AND VEGETATION CONVERSION IN MANAGED LANDSCAPES HAS REDUCED BIOMASS SUBJECT TO AGRICULTURAL BURNING. Sumatra experienced much greater in-situ agricultural intensification and related vegetation conversion than Kalimantan, as indicated by Sumatra's larger and growing rate of agro-industrial expansion over farmed or cleared lands rather than forest since 2000[43,58]. This concords with Sumatra's greater decline in seasonal fire-activity severity (Fig. 3d) and susceptibility to burning[42] despite its relatively severe droughts (Fig. 1c)[44].

(ii) AGRICULTURAL PLANNING AND FIRE MANAGEMENT ARE GAINING EFFICACY AND URGENCY. A growing reticence to license peatland conversion by 2010[59] led to moratoria on agro-industrial plantation concessions in 2011 and 2016[60–62]. These promoted intensified, rather than expansionary, agro-industrial production and were relatively protective of peatlands. Further, following economically and politically costly burning during 2013–2015[22,63], the central government intensified fire prevention, principally in mosaic agricultural Target Areas (Supplementary Fig. 1), depressing fire activity[17,31]. The eager and arguably novel cooperation of the agro-industrial sector[32,64] was integral to this effort. Cooperation was motivated by major losses of financial investment and planted stock due to 2013–2015 burning, both for oil palm[65] and pulp-and-paper interests, apparently limiting burning across plantations by 2019[18].

(iii) OIL-PALM EXPANSION HAS SLOWED. The drastic slowdown to oil-palm expansion since 2012[56] would have reduced extensive burning on peripheral degraded lands, given agro-industrial activities' disproportionate influence on the same[17]. Slowed oil-palm expansion reflected downward commodity-price trends, reducing investment accordingly[56], a trend compounded by tightening oil-palm concession licencing and allowing greater opportunity for fire-prevention initiatives. The slowdown to oil-palm expansion overall is seemingly more relevant to attenuation than the slowdown to related forest conversion[12], which was relatively recent and moderate[30,56].

The preceding characterises attenuation via land management as an active, if serendipitous, convergence of political forces and economic trends where and when fire prevention becomes feasible and urgent. Such a dynamic complements and extends conceptualisations of passive fire abatement via agricultural capitalisation. Initial capitalisation typically foments additional agricultural development and burning[2] and, in time, degraded-land conversion (item i above), greater monitoring and regulation (item ii), and greater political and economic costs for uncontrolled burning (items ii & iii), all of which gradually tip towards attenuation in semi-cultivated mosaic lands. Such a nuanced linkage between attenuation and capitalisation would resolve the apparent contraction whereby fire abatement proceeds from capitalised lands to less capitalised peripheries while attenuation proceeds from the most severe burning to the least.

Materials and methods

Experimental design. We observed trends in severe Indonesian fire activity relative to variable precipitation and land-management intensity over 2002–2019, nationally and regionally. To this end, we parsed overall, aggregate fire activity observed as MODIS AFDs into spatio-temporally discrete fire events and their respective ignitions (Section "Fire events and ignitions"). In turn, we estimated the severity of these fire events, both individually as a function of their scale, thermal intensity, and duration, and collectively as a function of their severity frequency distribution (Section "Fire-event severity"). Finally, we statistically determined robust declining trends in the annual rate of severe fire events and to the severity of seasonal fire activity over 2002–2019, controlling for precipitation respectively during the traditional fire season (July–December) or either bi-annual season (January–June, July–December) (Section "Trends in fire-activity severity"). For a given region, we similarly determined highly uneven trends in severe fire events and their ignitions amongst constituent agricultural land uses and vegetative land covers of varying management intensity, also observed continuously over 2002–2019 (Section "Land use/cover shifts and fire-activity severity").

Fire events and ignitions. Fire events are defined as spatio-temporal clusters of MODIS Collection 6 MCD14ML AFDs[66,67] observed across Indonesia between 1 July 2002 and 31 December 2019[68] (Fig. 4). Each AFD denotes one or more fires per ~1-km MODIS pixel, observed four times daily, and is represented by a latitude-longitude coordinate point at the pixel's centre. We clustered a given AFD into a given fire event when (i) the AFD occurred within a 1-km^2 grid cell that was the same as or adjacent to a cell hosting AFDs already in the fire event (Fig. 4 Events 1 & 3–4; A, D); and (ii) the AFD occurred within four days of AFDs already incorporated by the fire event and in the same or an adjacent cell (Fig. 4F), following Sloan et al.[17] and Cattau et al.[69]. The 1-km^2 grid cells reflect the ~1-km pixel resolution underlying the MODIS AFD data. July 2002 is the earliest date when both MODIS instruments aboard the Terra and Aqua satellites were

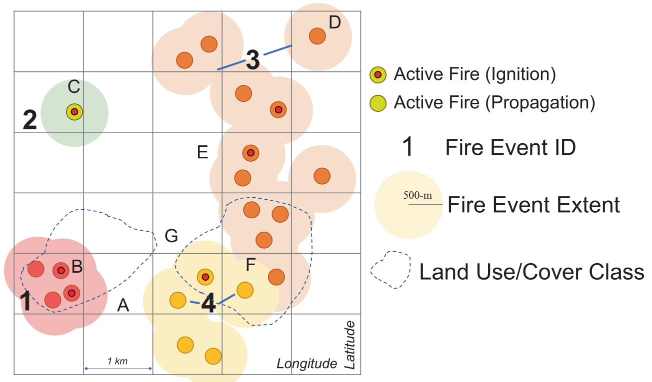


Fig. 4 Fire events as clusters of active-fire detections. After Sloan et al.[17]. **A** Fire Events 1 and 4 are distinct, regardless of any similarity of their respective active-fire detection (AFD) dates, because their AFDs are separated by at least one 1-km^2 grid cell. **B** Multiple AFDs of the same earliest date per fire event are all considered ignition AFDs. **C** For fire events defined by a single AFD, the AFD is always an ignition AFD. **D** The 500-m buffer surrounding an AFD is relevant only for comparisons with burned area maps in Supplementary Note 4. **E** AFDs of adjacent cells must be detected within four days of each other to belong to the same fire event, regardless of the total duration of the fire event, which may be up to many weeks. **F** Spatially proximate AFDs belong to different fire events when they are separated from each other by more than four days. **G** For analysis of fire activity by land-management intensity (Table 2), the incidence of a land-use/cover class amongst a given set of fire activity is given by the overlap of the class and eligible AFDs, not the whole fire event.

operational. Partial temporal coverage for 2002 is inconsequential since virtually all fire activity occurs during July–December[17,70]. The four-day threshold accounts for upper MODIS AFD omission-error rates for Indonesia[71]. Comparisons of our fire events against those defined using more conservative two-day or three-day thresholds indicate minimal to negligible differences in terms of fire-event number, duration, ignition pattern, and size inequality[69,72]. For each fire event, its ignition(s) are those AFD(s) with the earliest detection date (Fig. 4). For very large events, such as events formed by the coalescence of multiple nodes of burning, ignitions represent the earliest amongst a likely more diverse set.

The AFDs and related fire events are best understood as an intensive sample of total fire activity. Cloud cover or smoke haze invariably limit MODIS AFDs, probably selectively[73], such as on peatlands, where smouldering fire may be insufficiently hot for satellite detection or where abundant haze may obscure fire activity despite the high overpass rate of the MODIS sensors. AFD omission rates are low, typically at ~5–8%[67,71,74,75], but can be higher, particularly when burning is small scale and the land cover is mixed[69,76,77]. Also, the ~1 km resolution of our MODIS data, inherent to our fire events (Fig. 4), may conflate the AFDs of proximate but distinct burning within a single fire event. Such considerations mean that fire events, their ignitions, and their durations as defined here are ultimately approximations. These issues are unlikely to cause significant bias here, however, given our focus on severe, relatively large, and so relatively well-captured fire events[71,74]. The use of finer-grain VIIRS AFD data[78] would address the issue of conflation, but not of cloud/haze, and would preclude observation before 2012 of interest here. The use of MODIS MCD64a1 burned area (BA) data[79], which are theoretically less affected by cloud cover, would still result in greater omission rates overall[6,80] due to their lesser sensitivity, albeit probably amongst smaller-scale burning[18,81]. The online supplement provides validations of our fire events, including comparisons against burned areas (Supplementary Note 4) and a comparison of our fire-event severity measure to one based on MODIS BA data (Supplementary Note 5).

Fire-event severity. We described the severity of a fire event by incorporating the spatial, thermal, and temporal characteristics of its AFDs:

$$\text{Fire-Event Severity}_i = \sum\text{FRP of AFDs of Fire Event}_i \times \text{Duration of Fire Event}_i \qquad (1)$$

where, for the i^{th} fire event, *ΣFRP* describes fire-event scale as the total FRP of all constituent AFDs, in Megawatts, and *Duration* is the number of days between the earliest (ignition) and latest AFD of the fire event (minimum = 1 day). Severity scores are thus high for fire events with relatively many AFDs, denoting greater fire magnitude and intensity[82]; higher where burning is also relatively energetic, denoting even greater intensity, as due to greater biomass consumption[46]; and higher still where fire activity is also relatively persistent, as it tends to be during drought conditions[45]. Fire-event scale and duration in Eq. (1) are correlated significantly but moderately ($r = 0.27$, $p < 0.01$), such that their interaction integrates complementary attributes of fire activity. The sum of severity scores across all fire events of a given period is referred to as the total severity for that period.

Various factors recommend describing fire-activity severity as per Eq. (1) based on MODIS AFD-derived fire events (Supplementary Note 5). Compared to an analogous fire-event severity index defined for Global Fire Atlas fire events[83,84] based on MODIS MCD64a1 500-m BA data[79] (Eqn. S2), being the only alternative fire-event data for our region and most like it, Eq. (1) represents the scale of large, intense fire events more comprehensively while capturing relatively greater extremes of fire activity amongst individual events. Significant differences in the extremes of fire-event severity frequency distributions between our study and the analogous severity index for the Global Fire Atlas support this view (Supplementary Fig. 9, Supplementary Note 5).

The severity of seasonal fire activity is given as the degree to which a frequency distribution of fire-event severity scores (Eq. 1) for a given season is skewed by extreme values:

$$\text{Fire-Event Severity Skewness}_t = N_t\sum\left(X_{it} - \overline{X}_t\right)^3 / S_t^3(N_t - 1)(N_t - 2) \qquad (2)$$

where, for the tth bi-annual season (January–June, July–December) in our time series, N_t is the number of all fire events, X_{it} is the severity of the ith fire event as per Eq. (1), $\bar{X}_t$ is the sample mean for season t, and S_t is the sample standard deviation for season t. Equation (2) is highly correlated with the total magnitude of seasonal fire-event severity (Supplementary Fig. 2), given as the sum of deviations of all seasonal fire-event severity scores relative to the mean score for 2002–2019. Equation (2) does however more aptly capture seasonal variations to fire-activity extremeness and extensiveness (Supplementary Note 1).

Trends in fire-activity severity. Precipitation is the primary factor affecting fire activity in Equatorial Asia at regional and inter-annual scales[2,15,37,85], accounting for up to 80% of Indonesian fire risk, AFD frequency, and fire-related carbon emissions at monthly-to-annual intervals[17,85–87]. A highly non-linear relationship between precipitation and fire activity[45] underlies a profound inter-annual variability characterising Indonesian burning[29,37]. This variability frustrates the confident determination of trends to absolute fire activity, except perhaps over very long observation periods (e.g., >30 years) beyond the scope of all but very course historical AVHRR satellite fire data[2]. We therefore control for the effects of precipitation to describe trends to fire activity attributable to human activity, as described below. Ultimately, we describe an *attenuation* of certain measures of severe fire activity, that is, their decline over 2002–2019 for a given level of precipitation, which we attribute to changing human activities such as land management. This approach follows from other studies that similarly observe and attribute shifting relationships between Indonesian burning and precipitation[17,42]. It is a confident assumption that attenuation reflects neither an increasing trend to precipitation nor shifts to the bioclimatic nexus of drought and burning, e.g., the degree to which burning concentrates in droughts. There is no clear evidence for either possibility (Fig. 1d)[37,44] and our modelling would be robust to them.

We modelled changes to fire-activity extremes over 2002–2019 in terms of changing annual rates of severe fire events (Fig. 1) as well as changing severity of seasonal fire activity (Fig. 3). The annual rates of severe and very severe fire events are given respectively as the proportions of fire events per annum that are ≥75th or ≥90th the national fire-event severity-score percentile of 2002–2019 (≥60.4 and ≥216). For Indonesia (excluding Java and the Lesser Sunda Islands), two key fire-affected regions (Central-South Sumatra, Southern Kalimantan; Fig. 2e), and predominantly agricultural areas recently targeted for fire suppression (Targeted Areas, Supplementary Fig. 1), we regressed annual rates of severe fire events on total fire-season precipitation (July–December) per annum and time elapsed since 2002 (Fig. 1). For Indonesia and the same regions, we similarly regressed the severity of seasonal fire activity (Eq. 2) on total seasonal precipitation (January–June, July–December) and the number of seasonal intervals elapsed since July 2002 (Fig. 3). The consideration of bi-annual seasons separately in the latter set of regressions recognises the occasionally elevated severity of seasonal fire activity outside the usual fire season, as in 2005 and 2014 (Supplementary Fig. 2a). The bi-annual intervals concord with the seasonality of Indonesian fire activity[17,70] as well as intervals over which precipitation and burning strongly correlate[2,15,85]. A significant negative effect of the temporal variables in the two sets of regressions above indicates a declining rate of severe or very severe fire events or a declining severity of seasonal fire activity over 2002–2019, respectively, controlling for precipitation. Precipitation was observed according to NASA's IMERG v06B data product[88], which estimates monthly precipitation at 0.1° resolution via half-hourly satellite microwave observations calibrated daily with rain gauges. IMERG data are the successor to coarser-resolution TRMM Multi-Satellite Precipitation Analysis (TMPA) data[89] used in earlier regional fire modelling[37,45] and are highly correlated with the recently developed CHIRPS satellite-derived precipitation data[90]. A comparison of IMERG and CHIRPS data against gridded rain-gauge data across 2001–2019 for Taiwan indicated slightly greater accuracy on the part of IMERG data, including relatively stable monthly and seasonal measures[91]. Compared to TMPA data, IMERG data generally better approximate rain-gauge data and more accurately capture temporal variations to precipitation[92–95]. An occasional over-estimation of total precipitation by IMERG in select, often wetter conditions[92,96,97] was also common and generally more acute for TMPA data[98], not observed for Taiwan 2001–2019[91], and unlikely to bias our observations given their focus on drought.

All regression models were bootstrapped 1000 times to generate reliable significance estimates robust to data distributions[99], as per Field et al.[85]. The 1000 bootstrapped samples also collectively approximated a time series that could be expected if our 2002–2019 time series were shifted slightly earlier or later in time or otherwise lengthened, as by varying the number, timing, and magnitude of droughts observed during 2002–2019. In this way, we avoid reporting spurious trends attributable to the particular timing of drought and severe burning during 2002–2019. Since certain years host fire activity disproportionately due to drought (Fig. 1), a set models for severe fire-event rates were also weighted according to national annual AFD frequencies. Models of the severity of seasonal fire activity were unweighted because weights exacerbated heteroskedasticity and posed a conceptual redundancy, given strong correlations between AFD frequency and seasonal severity-score skewness ($r = 0.76$–0.86 depending on region, $p < 0.001$), attenuating significance. The two fire-affected regions are epicentres of Indonesian fire activity and consistent with similar studies of Indonesian fire trends[42,85]. These regions encompass most peatlands, described by Miettinen et al.[36], as well as most Targeted Areas, described by Sloan et al.[17]. A fire event is deemed as occurring in a given region and seasonal or annual interval where at least one of its AFDs and its ignition AFDs occurred therein, respectively.

Land use/cover shifts and fire-activity severity. Declines in extreme fire activity are conceptually underpinned by changing land management and should vary according to land-use/cover management intensities[1]. To clarify the role of land management, we regressed land uses/cover relative frequencies amongst fire-event AFDs or ignition AFDs against time elapsed over 2002–2019, with land uses/covers varying by management intensity (Table 1) and fire events varying by severity (Table 2). Regressions were fitted for four sets of fire activity: (a) AFDs of severe fire events, (b) ignition AFDs of severe fire events, (c) AFDs of all fire events, and (d) ignition AFDs of all fire events, as per Table 2 panels a–d. Significant negative/positive trends indicate a decreasing/increasing prevalence of a land use/cover amongst the fire events or ignitions of a given set.

We determined the land uses/covers of AFDs annually over 2002–2019 based on AFDs' spatial overlap with the annual 300-m Copernicus Climate Change Initiative Land-Cover Product[100,101] (Table 1, Fig. 4). These Copernicus data provide relatively stable, accurate, annual land-use/cover classifications[102] and, crucially, greater differentiation between and amongst land uses and degraded land covers (Supplementary Table 6) compared to other land-cover data used to explore Equatorial Asian burning[27,36,69,103]. In particular, our data observe three agricultural classes along a spectrum of management intensity (Table 1). Verification of these classes against land use visually interpreted using high-resolution imagery across 8 Mha of the fire-affected regions affirm the classes' nominal management intensities (Supplementary Note 3). Annual land-use/cover observations account for all land-use/cover transitions over 2002–2019. We do not however focus on the particular role of transitions in shifting severe fire activity, nor on the degree to which a shift in land-use/cover class prevalence amongst fire events or ignitions reflects class expansion or contraction. The influence of transitions and class expansion/contraction is considered secondary to negligible over our observation period, relative to the influence of generalised trends in the use and management of a land use/cover class overall, considering the conservative change-detection algorithm of the Copernicus data and the relatively very small area of expansion/contraction relative to total class extent.

For Indonesia and each of its regions, severe fire events for fire-activity sets (a) and (b) in Table 2 were defined respectively as the top 25% of AFDs and ignition AFDs with respect to the severity scores of corresponding fire events of 2002–2019 (Supplementary Note 2). This definition reflected our use of the 75th fire-event severity percentile threshold above (Fig. 1) while recognising AFDs as units of analysis here.

Models were bootstrapped and weighted as above. Complementing bootstrapping, we tested models for sensitivity to widespread burning late in our time series by experimentally omitting all observations for 2019 or 2015. Models for the two resultant partial time series were largely consistent with those for the full time series in Table 2 (Supplementary Note 2), affirming the progressive and robust nature of the observed land-use/cover shifts underlying fire abatement.

Data availability

All data used in this paper are available via their respective cited online repositories or otherwise via request to the corresponding author. The unique fire-event data created for this study, including fire-event severity and ignitions, are available at https://doi.org/10.5061/dryad.msbcc2g1t.

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References

1. Andela, N. et al. A human-driven decline in global burned area. *Science* **356**, 1356 (2017).
2. Sloan, S., Locatelli, B., Wooster, M. J. & Gaveau, D. L. A. Fire activity in Borneo driven by industrial land conversion and drought during El Niño periods, 1982–2010. *Glob. Environ. Change* **47**, 95–109 (2017).
3. Kelley, D. I. et al. How contemporary bioclimatic and human controls change global fire regimes. *Nat. Clim. Change* **9**, 690–96 (2019).
4. Jolly, W. M. et al. Climate-induced variations in global wildfire danger from 1979 to 2013. *Nat. Commun.* **6**, 7537 (2015).
5. Ward, D. S., Shevliakova, E., Malyshev, S. & Rabin, S. Trends and variability of global fire emissions due to historical anthropogenic activities. *Glob. Biogeochem. Cycles* **32**, 122–42 (2018).
6. Earl, N. & Simmonds, I. Spatial and temporal variability and trends in 2001–2016 global fire activity. *J. Geophys. Res. Atmos.* **123**, 2524–36 (2018).
7. Giglio, L., Randerson, J. T. & van der Werf, G. R. Analysis of daily, monthly, and annual burned area using the fourth-generation Global Fire Emissions Database (GFED4). *J. Geophys. Res. Biogeosci.* **118**, 317–28 (2013).
8. Doerr, S. H. & Santín, C. Global trends in wildfire and its impacts: perceptions versus realities in a changing world. *Philos. Trans. R. Soc. B Biol. Sci.* **371**, 20150345 (2016).
9. van Lierop, P., Lindquist, E., Sathyapala, S. & Franceschini, G. Global forest area disturbance from fire, insect pests, diseases and severe weather events. *Forest Ecol. Manag.* **352**, 78–88 (2015).
10. Zheng, B. et al. Increasing forest fire emissions despite the decline in global burned area. *Sci. Adv.* **7**, eabh2646 (2021).
11. Andela, N. & van der Werf, G. R. Recent trends in African fires driven by cropland expansion and El Niño to La Niña transition. *Nat. Clim. Change* **4**, 791–95 (2014).
12. Van der Werf, G. R. et al. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). *Atmos. Chem. Phys.* **10**, 11707–35 (2010).
13. Balch, J. K. et al. Negative fire feedback in a transitional forest of southeastern Amazonia. *Glob. Change Biol.* **14**, 2276–87 (2008).
14. Cochrane, M. A. & Laurance, W. F. Synergisms among fire, land use, and climate change in the Amazon. *Ambio* **37**, 522–27 (2008).
15. Gaveau, D. L. A. et al. Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires. *Sci. Rep.* **4**, 6112 (2014).
16. Vadrevu, K. P. et al. Trends in vegetation fires in South and Southeast Asian countries. *Sci. Rep.* **9**, 7422 (2019).
17. Sloan, S., Tacconi, L. & Cattau, M. E. Fire prevention in managed landscapes: recent successes and challenges in Indonesia. *Mitig. Adapt. Strateg. Glob. Change* **26**, Article 32 (2021).
18. Gaveau, D. L. A., Descales, A., Salim, M. A., Shields, D. & Sloan, S. Refined burned-area mapping protocol using Sentinel-2 data increases estimate of 2019 Indonesian burning. *Earth Syst. Sci. Data*, https://doi.org/10.5194/essd-2021-113, (2021).
19. Randerson, J. T., Chen, Y., van der Werf, G. R., Rogers, B. M. & Morton, D. C. Global burned area and biomass burning emissions from small fires. *J. Geophys. Res. Biogeosci.* **117**, G04012 (2012).
20. Field, R. D., van der Werf, G. R. & Shen, S. S. P. Human amplification of drought-induced biomass burning in Indonesia since 1960. *Nat. Geosci.* **2**, 185–88 (2009).
21. Huijnen, V. et al. Fire carbon emissions over maritime Southeast Asia in 2015 largest since 1997. *Sci. Rep.* **6**, 26886 (2016).
22. Tacconi, L. Preventing fires and haze in Southeast Asia. *Nat. Clim. Change* **6**, 640–43 (2016).
23. Koplitz, S. N. et al. Public health impacts of the severe haze in Equatorial Asia in September–October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure. *Environ. Res. Lett.* **11**, 094023 (2016).
24. Kiely, L. et al. Air quality and health impacts of vegetation and peat fires in Equatorial Asia during 2004–2015. *Environ. Res. Lett.***15**, 094054 (2020).
25. Crippa, P. et al. Population exposure to hazardous air quality due to the 2015 fires in Equatorial Asia. *Sci. Rep.* **6**, 37074 (2016).
26. Glauber, A. J. & Gunawan, I. The Cost of Fire: An Economic Analysis of Indonesia's 2015 Fire Crisis. (The World Bank, Washington, D.C., (2016).
27. Tan, Z. D., Carrasco, L. R. & Taylor, D. Spatial correlates of forest and land fires in Indonesia. *Int. J. Wildland Fire* **29**, 1088–99 (2020).
28. Marlier, M. E. et al. Fire emissions and regional air quality impacts from fires in oil palm, timber, and logging concessions in Indonesia. *Environ. Res. Lett.* **10**, 085005 (2015).
29. Vetrita, Y. & Cochrane, M. A. Fire frequency and related land-use and land-cover changes in Indonesia's peatlands. *Remote Sens.* **12**, 5 (2020).
30. Nikonovas, T., Spessa, A., Doerr, S. H., Clay, G. D. & Mezbahuddin, S. Near-complete loss of fire-resistant primary tropical forest cover in Sumatra and Kalimantan. *Commun. Earth Environ.* **1**, 65 (2020).
31. Field, R. *Biomass burning in Indonesia: Signs of Progress in 2019?*, http://www.columbia.edu/~rf2426/index_files/20200128.Field.GSFC.NoOz.pdf, January, NASA Goddard Space Flight Center, (2019).

32. Watts, J. et al. Incentivising compliance: evaluating the effectiveness of targeted village incentives for reducing forest and peat fires. *Forest Policy Econ.* **108**, 101956 (2019).
33. Wijedasa, L. et al. Carbon emissions from peat forests will continue to increase despite emission-reduction schemes. *Glob. Change Biol.* **24**, 4598–613 (2018).
34. Sloan, S., Meyfroidt, P., Rudel, T. K. & Bongers, F. & Chazdon Robin, L. The forest transformation: Planted tree cover and regional dynamics of tree gains and losses. *Glob. Environ. Change* **59**, 101988 (2019).
35. Albar, I., Jaya, I. N. S., Saharjo, B. H., Kuncahyo, B. & Vadrevu, K. P. Spatio-temporal analysis of land and forest fires in Indonesia using MODIS active fire dataset, in *Land-Atmospheric Research Applications in South and Southeast Asia* (eds K P Vadrevu et al.), p. 105-27 (Springer International Publishing, 2018).
36. Miettinen, J., Shi, C. & Liew, S. C. Fire distribution in Peninsular Malaysia, Sumatra and Borneo in 2015 with special emphasis on peatland fires. *Environ. Manage.* **60**, 747–57 (2017).
37. Fanin, T. & van der Werf, G. R. Precipitation–fire linkages in Indonesia (1997–2015). *Biogeosciences* **14**, 3995–4008 (2017).
38. Wiggins, E. B. et al. Smoke radiocarbon measurements from Indonesian fires provide evidence for burning of millennia-aged peat. *Proc. Natl. Acad. Sci. USA* **115**, 12419 (2018).
39. Page, S. E. et al. The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* **420**, 61–65 (2002).
40. Lohberger, S., Stängel, M., Atwood, E. C. & Siegert, F. Spatial evaluation of Indonesia's 2015 fire-affected area and estimated carbon emissions using Sentinel-1. *Glob. Change Biol.* **24**, 644–54 (2018).
41. van der Werf, G. R. et al. Global fire emissions estimates during 1997–2016. *Earth Syst. Sci. Data* **9**, 697–720 (2017).
42. Field, R. D. et al. Indonesian fire activity and smoke pollution in 2015 show persistent nonlinear sensitivity to El Niño-induced drought. *Proc. Natl Acad. Sci. USA* **113**, 9204–09 (2016).
43. Austin, K. G. et al. Shifting patterns of oil palm driven deforestation in Indonesia and implications for zero-deforestation commitments. *Land Use Policy* **69**, 41–48 (2017).
44. Pan, X., Chin, M., Ichoku, C. & Field, R. Connecting Indonesian fires and drought with the type of El Niño and phase of the Indian Ocean Dipole during 1979–2016. *J. Geophys. Res. Atmos.* **123**, (2018).
45. van der Werf, G. R. et al. Climate regulation of fire emissions and deforestation in Equatorial Asia. *Proc. Natl Acad. Sci. USA* **105**, 20350–55 (2008).
46. Wooster, M. J., Roberts, G., Perry, G. L. W. & Kaufman, Y. J. Retrieval of biomass combustion rates and totals from fire radiative power observations: FRP derivation and calibration relationships between biomass consumption and fire radiative energy release. *J. Geophys. Rese. Atmos.* **110**, (2005).
47. Spessa, A. et al. Seasonal forecasting of fires over Kalimantan, Indonesia. *Nat. Hazards Earth Syst. Sci.* **15**, 429–42 (2015).
48. Siegert, F., Ruecker, G., Hinrichs, A. & Hoffmann, A. A. Increased damage from fires in logged forests during droughts caused by El Niño. *Nature* **414**, 437–40 (2001).
49. Fernandes, K. et al. Heightened fire probability in Indonesia in non-drought conditions: the effect of increasing temperatures. *Environ. Res. Lett.* **12**, 054002 (2017).
50. Herawati, H. & Santoso, H. Tropical forest susceptibility to and risk of fire under changing climate: a review of fire nature, policy and institutions in Indonesia. *Forest Policy Econ.* **13**, 227–33 (2011).
51. Nepstad, D. et al. Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science* **344**, 1118–23 (2014).
52. Dennis, R. *A Review of Fire Projects In Indonesia, 1982-1998*. (CIFOR, Bogor, Indonesia, 1999).
53. de Groot, W. J., Field, R. D., Brady, M. A., Roswintiarti, O. & Mohamad, M. Development of the Indonesian and Malaysian fire danger rating systems. *Mitig. Adapt. Strateg. Glob. Change* **12**, 165 (2006).
54. Clough, Y. et al. Land-use choices follow profitability at the expense of ecological functions in Indonesian smallholder landscapes. *Nat. Commun.* **7**, 13137 (2016).
55. Bissonnette, J.-F. & De Koninck, R. The return of the plantation? Historical and contemporary trends in the relation between plantations and smallholdings in Southeast Asia. *J. Peasant Stud.* **44**, 918–38 (2017).
56. Gaveau, D. L. A. et al. Slowing deforestation in Indonesia follows declining oil palm expansion and lower oil prices. *PLOS ONE* **17**, e0266178 (2022).
57. Svatoňová, T., Herák, D. & Kabutey, A. Financial profitability and sensitivity analysis of palm oil plantation in Indonesia. *Acta Univ. Agric. Silvic. Mendelianae Brunensis* **63**, 1365–73 (2015).
58. Gaveau, D. L. A. *et al.* Rapid conversions and avoided deforestation: examining four decades of industrial plantation expansion in Borneo. *Scientific Reports* **6**, (2016).
59. Simamora, A. P. Govt says no to converting peatland into plantations, *The Jakarta Post*. August (2010).
60. Satriastanti, F. E. Jokowi bans new oil palm and mining concessions, *Mongabay.com* April (2016).
61. Sloan, S., Edwards, D. P. & Laurance, W. F. Does Indonesia's REDD+ moratorium on new concessions spare imminently-threatened forests? *Conserv. Lett.* **5**, 222–31 (2012).
62. Busch, J. et al. Reductions in emissions from deforestation from Indonesia's moratorium on new oil palm, timber, and logging concessions. *Proc. Natl Acad Sci USA* **112**, 1328–33 (2015).
63. Forsyth, T. Public concerns about transboundary haze: a comparison of Indonesia, Singapore, and Malaysia. *Glob. Environ. Change* **25**, 76–86 (2014).
64. Carbon Conservation. Fire Free Village Program - Review 2017. (Carbon Conservation, Singapore, (2017).
65. Gaveau, D. L. A. et al. Overlapping land claims limit the use of satellites to monitor no-deforestation committments and no-burning compliance. *Conserv. Lett.* **10**, 257–64 (2017).
66. EarthData. *MODIS Collection 6 Active-Fire Detections standard scientific data (MCD14ML)*, NASA EarthData, https://earthdata.nasa.gov/firms (2019).
67. Giglio, L., Schroeder, W. & Justice, C. O. The Collection 6 MODIS active fire detection algorithm and fire products. *Remote Sens. Environ.* **178**, 31–41 (2016).
68. Sloan, S., Cattau, M.E. *Discrete Fire Events, their Severity, and their Ignitions, as Derived from MODIS MCD 14ML Active-Fire Detection Data for Indonesia, 2002-2019*. Sean Sloan and Megan E. Cattau, Datadryad.org. (2022).
69. Cattau, M. E. et al. Sources of anthropogenic fire ignitions on the peat-swamp landscape in Kalimantan, Indonesia. *Glob. Environ. Change* **39**, 205–19 (2016).
70. Wooster, M. J., Perry, G. L. W. & Zoumas, A. Fire, drought and El Niño relationships on Borneo during the pre-MODIS era (1980–2000). *Biogeosciences* **9**, 317–40 (2012).
71. Tansey, K., Beston, J., Hoscilo, A., Page, S. E. & Paredes Hernández, C. U. Relationship between MODIS fire hot spot count and burned area in a degraded tropical peat swamp forest in Central Kalimantan, Indonesia. *J. Geophys. Res.* **113**, (2008).
72. Oom, D., Silva, P. C., Bistinas, I. & Pereira, J. M. C. Highlighting biome-specific sensitivity of fire size distributions to time-gap parameter using a new algorithm for fire event individuation. *Remote Sens.* **8**, 663 (2016).
73. Schroeder, W. et al. Validation of GOES and MODIS active fire detection products using ASTER and ETM plus data. *Remote Sens. Environ.* **112**, 2711–26 (2008).
74. Hantson, S., Padilla, M., Corti, D. & Chuvieco, E. Strengths and weaknesses of MODIS hotspots to characterize global fire occurrence. *Remote Sens. Environ.* **131**, 152–59 (2013).
75. Tanpipat, V., Honda, K. & Nuchaiya, P. MODIS hotspot validation over Thailand. *Remote Sens.* **1**, 1043–54 (2009).
76. Liew, S. C., Shen, C., Low, J., Lim, A. & Kwoh, L. K. *The 24th Asian Conference on Remote Sensing and 2003 International Symposium on Remote Sensing (ACRS2003)*. p. 671-73 (Asian Association on Remote Sensing), November 3–7.
77. Fornacca, D., Ren, G. & Xiao, W. Performance of three MODIS fire products (MCD45A1, MCD64A1, MCD14ML), and ESA Fire_CCI in a mountainous area of northwest Yunnan, China, characterized by frequent small fires. *Remote Sens.* **9**, 1131 (2017).
78. Schroeder, W., Oliva, P., Giglio, L. & Csiszar, I. A. The New VIIRS 375m active fire detection data product: algorithm description and initial assessment. *Remote Sens. Environ.* **143**, 85–96 (2014).
79. Giglio, L., Boschetti, L., Roy, D. P., Humber, M. L. & Justice, C. O. The Collection 6 MODIS burned area mapping algorithm and product. *Remote Sens. Environ.* **217**, 72–85 (2018).
80. Roy, D. P., Boschetti, L., Justice, C. O. & Ju, J. The Collection 5 MODIS burned area product — Global evaluation by comparison with the MODIS active fire product. *Remote Sens. Environ.* **112**, 3690–707 (2008).
81. Miettinen, J., Langner, A. & Siegert, F. Burnt area estimation for the year 2005 in Borneo using multi-resolution satellite imagery. *Int. J. Wildland Fire* **16**, 45–53 (2007).
82. Luo, R., Hui, D., Miao, N., Liang, C. & Wells, N. Global relationship of fire occurrence and fire intensity: a test of intermediate fire occurrence-intensity hypothesis. *J. Geophys. Res. Biogeosci.* **122**, 1123–36 (2017).
83. Andela, N. et al. The Global Fire Atlas of individual fire size, duration, speed, and direction. *Earth Syst. Sci. Data* **11**, 529–52 (2019).
84. Andela, N., Morton, D. C., Giglio, L. & Randerson, J. T. *Global Fire Atlas with Characteristics of Individual Fires, 2003-2016*, ORNL Distributed Active Archive Center, https://doi.org/10.3334/ORNLDAAC/1642, https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1642 (2019).
85. Field, R. D. & Shen, S. S. P. Predictability of carbon emissions from biomass burning in Indonesia from 1997 to 2006. *J. Geophys. Res. Biogeosci.* **113**, G04024 (2008).

86. Fuller, D. O. & Murphy, K. The ENSO-fire dynamic in insular Southeast Asia. *Clim. Change* **74**, 435–55 (2006).
87. Field, R. D. et al. Development of a global fire weather database. *Nat. Hazards Earth Syst. Sci.* **15**, 1407–23 (2015).
88. Huffman, G. J. *GPM IMERG Final Precipitation gridded data, L3 1 month 0.1 degree x 0.1 degree, version 06B*. NASA Precipitation Processing System, Goddard Earth Sciences Data and Information Services Center (GES DISC). https://storm-pps.gsfc.nasa.gov/storm/; https://pmm.nasa.gov/data-access/downloads/gpm (2019).
89. Huffman, G. J. et al. The TRMM Multisatellite Precipitation Analysis (TMPA): quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *J. Hydrometeorol.* **8**, 38–55 (2007).
90. Funk, C. et al. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Sci. Data* **2**, 150066 (2015).
91. Hsu, J., Huang, W.-R., Liu, P.-Y. & Li, X. Validation of CHIRPS precipitation estimates over taiwan at multiple timescales. *Remote Sens.* **13**, 254 (2021).
92. Rozante, J. R., Vila, D. A., Barboza Chiquetto, J., Fernandes, A. D. A. & Souza Alvim, D. Evaluation of TRMM/GPM blended daily products over Brazil. *Remote Sens.* **10**, 882 (2018).
93. Prakash, S., Mitra, A. K., Pai, D. S. & AghaKouchak, A. From TRMM to GPM: how well can heavy rainfall be detected from space? *Adv. Water Resour.* **88**, 1–7 (2016).
94. Ma, Q. et al. Performance evaluation and correction of precipitation data using the 20-year IMERG and TMPA precipitation products in diverse subregions of China. *Atmos. Res.* **249**, 105304 (2021).
95. Nwachukwu, P. N., Satge, F., Yacoubi, S. E., Pinel, S. & Bonnet, M.-P. From TRMM to GPM: how reliable are satellite-based precipitation data across Nigeria? *Remote Sens.* **12**, 3964 (2020).
96. Popovych, V. F. & Dunaieva, I. A. Assessment of the GPM IMERG and CHIRPS precipitation estimations for the steppe part of the Crimea. *Meteorol. Hydrol. Water Manage* **9**, (2021).
97. Navarro, A. et al. Assessment of IMERG precipitation estimates over Europe. *Remote Sens.* **11**, 2470 (2019).
98. Dezfuli, A. K. et al. Validation of IMERG precipitation in Africa. *J. Hydrometeorol.* **18**, 2817–25 (2017).
99. Efron, B. & Tibshirani, R. J. *An Introduction to the Bootstrap*. (Chapman and Hall, Boca Raton, FL, USA, 1993).
100. Pérez-Hoyos, A., Rembold, F., Kerdiles, H. & Gallego, J. Comparison of global land cover datasets for cropland monitoring. *Remote Sens.* **9**, 1118 (2017).
101. ESA. *Annual land-cover product, 1992 to 2019/present, based on MERIS 300-m and ancillary SPOT, AVHRR, Sentinel-3 and PROB-V satellite data*. European Space Agency (ESA) European Centre for Medium-Range Weather Forecasts (ECMFW) Copernicus Climate Change Service (C3S) Climate Change Initiative (CCI), https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-land-cover?tab=overview; http://maps.elie.ucl.ac.be/CCI/viewer/download.php; http://www.esa-landcover-cci.org/ (2020).
102. Defourny, P. Product User Guide and Specification: ICDR Land Cover 2016 to 2019 (Version 2.1.1 of ESA Copernius Climate Change Intitiative Annual 300-m Land-Cover Classifications). (Universitie Catholique du Lovain, Louvain, Belgium, (2020).
103. Vetrita, Y. & Cochrane, M. A. *Annual Burned Area from Landsat, Mawas, Central Kalimantan, Indonesia, 1997-2015*, ORNL Distributed Active Archive Center, https://doi.org/10.3334/ORNLDAAC/1708, https://daac.ornl.gov/CMS/guides/Annual_Burned_Area_Maps.html; https://daac.ornl.gov/cgi-bin/dataset_lister.pl?p=33 (2019).

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Additional information

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