Tropical cyclones facilitate recovery of forest leaf area from summer droughts in East Asia

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Abstract. Forests disturbance by tropical cyclones is mostly documented by field studies of exceptionally strong cyclones and satellite-based approaches attributing decreases in leaf area. By starting their analysis from the observed damage, these studies are biased and may, therefore, limit our understanding of the impact of cyclones in general. This study overcomes such biases by jointly analysing the cyclone tracks, climate reanalysis, and changes in satellite-based leaf area following the passage of 140 ± 41 cyclones. Sixty days following their passage, 18 ± 8 % of the cyclones resulted in a decrease and 48 ± 18 % showed no change in leaf area compared to nearby forest outside the storm track. For a surprising 34 ± 7 % of the cyclones, an increase in leaf area was observed. Cyclones resulting in higher leaf area in their affected compared to their references area coincided with an atmospheric pressure dipole steering the cyclone towards a region experiencing summer drought caused by the same dipole. When the dipole was present, the destructive power of cyclones might have been offset by their abundant precipitation enabling forest canopies in the affected area to recover faster from the drought than canopies in the reference area. This study documents previously undocumented wide-spread antagonist interactions on forest leaf area between droughts and tropical cyclones.

Main Text

Each year almost 30 cyclones, about one-third of the world's tropical cyclones, develop over the Pacific Ocean north of the equator (Landsea, 2000) where a subtropical ridge steers them mainly west and northwest towards Eastern Asia, where 90 % make landfall. The majority of the tropical cyclones in the north western Pacific basin develop between June and November (Bushnell et al., 2018) and more than half acquire typhoon strength (WMO, 2017). The four most powerful typhoons in the region since 1999, i.e., Morakot in 2009, Megi in 2010, Haiyan in 2013, and another typhoon also named Megi in 2016, claimed over 7,000 lives, left 1,700 missing, and destroyed over 10 billion USD worth of infrastructure and crops according to compilations of mostly local news sources (Yang et al., 2014; Bowen, 2016; Lu et al., 2017; OCHA, 2010). Although natural ecosystems, such as forests, have adapted to recurring high wind speeds (Eloy et al., 2017; Louf et al., 2018; Curran et al., 2008), stem breakage is almost unavoidable at wind speeds above 40 m s^{-1} (Virot et al., 2016) but has been widely reported at wind speeds well below this threshold together with other damage (Tang et al., 2003; Chiu et al., 2018; Chang et al., 2020). Despite the economic importance of forests in the region (Barbier, 1993; Vickers et al., 2010), an overall assessment of the damage of tropical cyclones on forest resources is still lacking.

By jointly analysing cyclone tracks (Joint Typhoon Warning Center ; JTWC, 2019), climate reanalysis data (ERA5-Land; ECMWF, 2019), satellite-based proxies of soil dryness (SPEIbase v2.6; Beguería et al., 2014), land cover (ESA CCI; ESA, 2017), and leaf area (ESA LAI; Martins et al., 2020), we estimated: (a) the potential forest area damaged by tropical cyclones, (b) the impact of tropical cyclones on leaf area, and (c) the main drivers of this impact. Previous studies attributed decreases in leaf area or related satellite-based indices to different disturbance agents (Ozdogan et al., 2014; Honkavaara et al., 2013; Forzieri et al., 2020), including cyclones (Takao et al., 2014). A damage-based approach is designed to identify only decreases in leaf area, thus failing to identify events in which tropical cyclones left the leaf area unaltered or even increased it. In contrast, this study starts the analysis from the actual storm tracks which allows for an unbiased assessment of the impact of cyclones on forests (Blanc and Strobl, 2016).

The land area affected was identified for each of the 580 tropical cyclones that occurred in the study region between 1999 and 2018, considering that cyclone-driven damage could only occur within the storm track at locations that experienced high wind speeds or high precipitation. Pixels within the storm track defined as 2, 3 of 4 times the diameter of the cyclone for which threshold values for wind or precipitation were exceeded were classified as affected areas, the remaining pixels in the track served as a cyclone-specific reference area. The uncertainty derived from defining the width of the storm track (Willoughby and Rahn, 2004) and determining which wind speeds and amounts of precipitation could result in damage are accounted for by an ensemble of nine related definitions with different threshold values (**Table A1**). In this report uncertainties represent the standard deviation across the nine definitions for the affected area and are accounted for in Figs 1, 2, 3, and A2, and Tables A1, A2 and A3.

Since 1999, 2,240,000 ± 690,000 km^2 of forest in the study region experienced conditions that may have resulted in cyclone-driven damage, at least once every decade (**Fig. 1a**). At decadal or longer return intervals, a single cyclone may greatly affect ecosystem functioning, forest structure and species composition of the forest (Xi, 2015; Castañeda-Moya et al., 2020). No less than 540,000 ± 260,000 km^2, including 70 % of the tropical forest in the region, experienced potentially damaging conditions at least once per year, and are thus classified as being under chronic wind stress (**Fig. 1b**). Estimates from the rain-only definitions closely matched the 700,000 km^2 yr^{-1} that was reported following a similar approach in which the affected area was defined as a 100 km buffer zone along the storm track (Lin et al., 2020).

Irrespective of the definition of the affected area, the coefficient of variation of the between-year variation in potentially damaged areas ranged from 15 to 20 % (**Fig. 1c**). Excluding the four most powerful typhoons that occurred in the region since 1999 changed the average coefficient of variation from 17 to 16 %. This suggests that the most powerful typhoons make only a small contribution to the total annually potentially affected area in the region. A recent literature review reported, however, that 66 % of the research papers in this area have examined the effects of only about 6 % of the most powerful cyclones (Lin et al., 2020). The relatively small contribution of those events to the potentially damage area suggests that in regions with frequent tropical storms, disturbance ecology would benefit from broadening its scope by examining the effects and recovery of a representative sample of tropical cyclones, rather than focusing on the most devastating events.

The impact of a tropical cyclone on leaf area was calculated based on the adjusted Hedge's effect size by comparing the change in leaf area before and after the cyclone in the affected area with the change before and after the cyclone in the reference area for each individual cyclone (**Eq. 1**). Using a reference area that is specific to each cyclone means that seasonal dynamics related to leaf phenology and seasonal monsoons are accounted for in the effect size, which is a unitless description of the mean change in leaf area normalized by its standard deviation (**Eq. 1**). Hence, a positive effect size denotes a faster increase or a slower decrease in leaf area in the affected area compared to the reference area following the passage of a tropical cyclone.

A total of 316 ± 22 tropical cyclones or 54 ± 4 % of the storm events under study could not be further analysed (**Table A1**) because leaf area index observations were missing from either the affected area, the reference area, or both, thus violating the requirements for calculating the effect size (**Eq. 1**). Of the remaining 264 ± 22 tropical cyclones, only 140 ± 41 passed the additional quality check necessary to be retained for further analysis in this study, i.e., the difference in the leaf area between the reference and affected area prior to the passage of a storm should be less than 10 % of the leaf area in the reference area. In other words, prior to the storm, the leaf area in the reference area had to be similar to the leaf area in what will become the affected area once the storm passed. Of the 580 cyclones, 31 % was less than class 1, 14 % was classified as class 1, 11 % as class 2, 10 % as class 3, 21 % as class 4, and 13 % as class 5. The distribution of the intensity classes of the sample of 140 ± 41 cyclones that could be further analysed were similar to the census of the 580 cyclones with 33 % of the retained cyclones classified below class 1, 13 % in class 1, 8 % in class 2, 9 % in class 3, 23 % in class 4, and 14 % class 5. Despite the loss of around 75 % of the 580 events, the sample analysed in this study is unbiased in terms of cyclone intensity classes (**Fig. A2**).

Tropical cyclones have been widely observed to defoliate and disturb forests because of limb breaking, uprooting, stem breakage and landslides following high wind speeds and heavy precipitation (Wang et al., 2013; Uriarte et al., 2019; Chambers et al., 2007; Douglas, 1999; Lin et al., 2011). Nevertheless, in this study, only 18 ± 8 % of the observed cyclones resulted in a detectable reduction in leaf area 60 days after their passage as a direct effect of limb breakage, uprooting, stem breakage and landslides. For 48 ± 18 % of the cyclones, the change in leaf area 60 days after a cyclone passed was so small that it could not be distinguished from the threshold representing no-change. Ecological theory predicts forest dwarfing in regions with high cyclone frequencies compared to the longevity of a tree, directly through gradual removal of taller trees over many generations (Lin et al., 2020; McDowell et al., 2020) and indirectly through the loss of nutrients (Tang et al., 2003; Lin et al., 2011). Where forest dwarfing has occurred, it might be hard to observe the short-term effects of an individual tropical cyclone on forest structure and function (Mabry et al., 1998).

For a surprising 34 ± 7 % of the cyclones an increase or given the way the effect size was calculated, a reduced decrease in leaf area was observed, leading to the question which conditions lead to an increase or a reduced decrease in leaf area between the affected and reference areas 60 days following the passage of a tropical cyclone? To answer this question, two groups of meta-data were compiled for each of the 140 ± 41 tropical cyclones that passed the quality checks, the first group consisting of five characteristics describing the land surface before the passage of a cyclone and the second group containing five characteristics of the cyclone itself (**Table A2**). Following factorial analysis to identify collinearity between the meta-data in the same group, the explanatory power of the meta-data was quantified as a decrease in the accuracy of a random forest analysis (**Fig. 2**). The random forest analysis was repeated 12 times with different combinations of largely uncorrelated meta-data (**Table A3**). Each random forest analysis included the effect sizes and meta-data for all nine definitions of affected area to account for this specific source of uncertainty.

The statistical analysis showed that accumulation of precipitation during the passage of a cyclone over land makes the largest contribution to the accuracy of the random forest analysis. Randomizing this variable decreased the accuracy of the random forest analysis by 9 to 21 % (**Fig. 2**). The Pacific Japan index for atmospheric pressure at the time of landfall was the second most important variable contributing 1 to 17 %. The other meta-data contributed relatively little (-6 to 8 %) to the accuracy of the random forest analysis with negative importance indicating that removing the variable from the model improved its performance. Subsequently, the six meta-data with the highest explanatory power were used to build a single regression tree to obtain the environmental drivers and their cut-off values that would best explain the change in leaf area following the passage of a tropical cyclone (**Fig. 3**). Note that cyclone intensity had a low explanatory power (**Fig. 3**) which is explained by the observation that positive, neutral and negative effects occurred in all five intensity classes (**Fig. A2**). The remainder of this report focusses on the mechanisms underlying the increase or reduced decrease in leaf area following the passage of a tropical cyclone.

Cyclones bringing abundant precipitation (> 32 mm) during summer months (i.e., after month 6.5) when the atmosphere was under a positive phase of Pacific Japan index (> -0.028) resulted dominantly (56 % to 69 %) in a leaf area that was 0.5 m^2 m^{-2} higher in the affected compared to the reference area (**Fig. 3**). Given that the passage of the cyclone was often preceded by a summer drought, the observed increase in leaf area should most likely be interpreted as a faster recovery from the drought in the area affected by the cyclone than in its reference area. The vegetation response was thought to be the outcome of two elements: (a) cyclones making landfall in June, July and August bring 30 to 50 % of the annual precipitation in coastal areas in the study domain (**Fig. A3**) and are thus substantial sources of precipitation. The importance of the precipitation brought by tropical cyclones is confirmed by domain-wide changes in the standardized precipitation-evapotranspiration index showing that 1006 of the 1262 (80 %) cyclones increased soil wetness, and (b) given that much of the study domain has a monsoon climate with relatively little rain in the fall and winter months (Chou et al., 2009), the implication is that summer droughts might, for evergreen vegetation, have lasting effects until the next growing season unless the drought is ended before the dry season begins.

An increase in leaf area or a reduced decrease, following the passage of a tropical cyclone, thus requires three conditions to co-occur: (a) a dry spell, (b) a cyclone making landfall in the region experiencing the dry spell, and (c) the cyclone bringing abundant precipitation to mitigate the soil dryness. At first sight, meeting all three conditions at the same time seems unlikely, however, for the mid-latitudes, including Korea, China, Taiwan, and Japan, dry summers see an increase in the number of tropical cyclones making landfall which often end the summer drought (Yoo et al., 2015). In South Korea, for example, at least 43 % but possibly as much as 90 % of the summer droughts in coastal regions were abruptly ended by a tropical cyclone (Yoo et al., 2015). Based on our analysis of the standardized precipitation-evapotranspiration index, at least 210 of the 1262 (17 %) tropical cyclones in East Asia ended a drought.

The co-occurrence of dry spells and tropical cyclones has been linked to a meridional dipole system in the mid-latitude regions of East Asia with a high pressure system in the region of 40-50 N and 150-160 E where it is causing the dry spell, and the low pressure system in the region of 20-30 N and 120-150 E. When such a dipole exists, tropical cyclones generated from the monsoon trough over the West Pacific Ocean are steered through the trough in between the high- and low-pressure systems towards and then along the coast of East Asia (Choi et al., 2010). While travelling along the edges of the high pressure system, the tropical cyclone may disturb the circulation, resulting in an unfavourable environment to sustain the dipole (Choi et al., 2011; Kubota et al., 2016) and bringing precipitation to the dry region that was under the high pressure system.

As suggested by the random forest analysis (**Fig. 2**), analysing the atmospheric pressure separately for cyclones that resulted in no change, an increase or a decrease in leaf area (**Fig. 4**) showed that tropical cyclones that were followed by an increase or reduced decrease in leaf area coincided with a meridional dipole (**Fig. 4b**). Moreover, the genesis of tropical cyclones that were followed by a decrease in leaf area, occurred under very different atmospheric conditions compared to cyclones followed by an increasing leaf area. A relationship between the atmospheric system causing summer droughts, tropical cyclones and their subsequent impact on leaf areas, suggest that whether more drought damage is to be expected in the future will not only depend on an increase in drought frequency and intensity but will in part be determined by the exact weather system that is causing the drought. Although the co-occurrence of droughts and cyclones has previously been demonstrated (Choi et al., 2011; Kubota et al., 2016), we believe to be the first to document its large-scale antagonist effect on forest leaf area.

By studying a representative sample of tropical cyclones in terms of storm intensity (**Fig. A2**), we have shown that almost half of the tropical cyclones, i.e., 48 ± 18 %, caused little to no damage to forest leaf area, suggesting that forest dwarfing is a general structural adaption in the study region. Moreover, a third, i.e., 34 ± 7 % of the cyclones in East Asia resulted in an increase or reduced decrease in forest growth, because these storms relieved water stress within their track or even ended summer droughts. The observed frequency of positive vegetation responses to cyclones suggests that the present day vision of cyclones as agents of destruction (Altman et al., 2018; Negrón-Juárez et al., 2010, 2014) should be refined toward a recognition that, depending on the environmental conditions prior to the storm and the atmospheric conditions leading to the genesis of the tropical cyclone, cyclones frequently facilitate the recovery of forest leaf area and as such dampen the effects of summer droughts.

Materials and Methods

Cyclone track and track diameter

Since 1945, tropical cyclones in the Western North Pacific Ocean have been tracked and their intensity recorded by the Joint Typhoon Warning Center (JTWC). The track data shared by the Joint Typhoon Warning Center consist of quality-controlled six-hourly geolocation observations of the centre of the storm with the diameter of the storm being a proxy for its intensity (JTWC, 2019). For the period under consideration, from 1999 to 2018, the geolocations and diameters are the output of the Dvorak model (Dvorak, 1984; Dvorak et al., 1990) derived from visible and infrared satellite imagery. Storm diameters are available starting from January 2003. Prior to this date a generic diameter of 100 km (Lin et al., 2020) is used in this study. Linear interpolation of the six-hourly track data resulted in hourly track data to fill in any gaps in the mapping of the cyclone track.

In this study, we focus on East Asia which, given the absence of natural boundaries, is defined as the land contained within the north western Pacific basin that, according to the Joint Typhoon Warning Center stretches from 100 to 150 degrees east and 0 to 60 degrees north. The Joint Typhoon Warning Center compiled track and intensity data for 580 tropical cyclones between 1999 and 2018 in the north western Pacific basin. A shorter time series (1999 to 2018) than the entire length of time available (1945 to 2018) was analysed due to the more limited availability of the leaf area index data which had to be jointly analysed with the track and intensity data to quantify the impact of cyclones on natural ecosystems.

Area affected by individual cyclones

The land area thought to be affected by a specific cyclone as well as the reference area for each of the 580 cyclones that occurred in the study area between 1999 and 2018 were identified based on nine different but related definitions (**Table A1**). Each definition comprises a combination of at least two out of three criteria, e.g., the diameter of the cyclone, the maximum wind speed at each location during the passage of the cyclone and accumulated precipitation at each location during the passage of the cyclone. Each forested pixel within each individual storm track was classified as either affected area or reference area based on these nine definitions. Differences in the results coming from differences in the definitions were used throughout the analysis to estimate semantic uncertainties. Uncertainties related to the estimated diameter of the cyclone, wind speed and precipitation data were not accounted for in the calculation of the affected and reference areas because they were thought to be smaller than the uncertainty coming from differences in the definitions themselves.

The underlying assumption behind the definitions is that forests can only be affected by a specific cyclone if they are located along its storm track. The minimum width of each storm track is the diameter of the cyclone as reported by the Joint Typhoon Warning Center. Following the observation that over the ocean, the actual wind speed exceeds the critical wind speed for stem breakage or uprooting (i.e., 17 m s^{-1} ref. Chen et al., 2018) over a distance of at least three times the diameter of the cyclone (Willoughby and Rahn, 2004), the minimum width of a storm track in which cyclone-related forest damage could occur is defined as three times the diameter recorded by the Joint Typhoon Warning Center although wind speeds drop dramatically when cyclones make land fall (Kaplan and Demaria, 2001). The minimum width of a storm track over land should, therefore, be reduced compared to the observations over the ocean. This study used three different widths to define a storm track, i.e., two, three or four times the recorded diameter (**Table A1**).

Being located within the track of a specific cyclone is essential but not sufficient for damage to occur. Within a storm track, only forested pixels that experienced high wind speeds or high precipitation were counted as in the potentially affected area. Forest pixels that were located within the storm track but did not experience high wind speeds or high precipitation were counted as in the reference area. Note that to better account for the uncertainties arising from this approach, the threshold values for wind speed and precipitation were increased as the track diameter increased (**Table A1**). For a narrow storm track it is reasonable to assume that there would be damage shown in all pixels except those where wind speed or precipitation did not exceed a relatively low threshold value. For wide storm tracks the opposite applies; it is reasonable to assume that few of the pixels would show damage except where wind speed or precipitation exceeded relatively high threshold values.

Wind speed and precipitation data were extracted from the ERA5-Land reanalysis data for land (ECMWF, 2019). The ERA5-Land reanalysis dataset has a spatial resolution of 9 km x 9 km and a time step of 1 hour. It is the product of a data assimilation study conducted with the H-TESSEL scheme by ERA5 IFS Cy45r1 and nudged by climatological observations (ECMWF, 2018). The Cy45r1 reanalysis dataset shows statistically neutral results for the position error of individual cyclones (ECMWF Confluence Wiki: Implementation of IFS cycle 45r1). The spatial representation of the reanalysis data is reported to compare favourably with observational data (Chen et al., 2021) outside the domain of this study. No reports on similar tests for the current study domain, i.e., East Asia, were found. Furthermore, land cover maps released through the European Space Agency's Climate Change Initiative (ESA, 2017) were used to restrict the analysis to forests. The Climate Change Initiative maps integrate observations from several space-borne sensors, including MERIS, SPOT-VGT, AVHRR, and PROBA-V, into a continuous map with a 300 m resolution from 1994 onwards.

Wind speed and precipitation data were spatially disaggregated and temporally aggregated to match the spatial and temporal resolution of the leaf area index product (see below). Maximum wind speed and accumulative precipitation were aggregated over time steps to match the 10-day resolution of the leaf area index product. We preserved the temporal resolution of the land cover map but aggregated its spatial resolution from 300 m to 1 km to match the resolution of the leaf area index product. During aggregation, the majority of land cover at the 300 m resolution was assigned to the 1 km pixel resolution.

Impact on leaf area of an individual cyclone

Version 2 of European Space Agency's Climate Change Initiative product was used to calculate leaf area in this study. The product has a 1 km spatial resolution, a 10-day temporal resolution, and is available from 1999 onwards. The default leaf area index product is distributed as a composite image using at least six valid observations on a pixel within a 30-day moving window (Verger et al., 2014). The composite image is drawn from satellite-based observations of the surface reflectance in the red, near-infrared, and shortwave infrared from SPOT-VGT (from 1999 to May 2014) and PROBA-V (from June 2014 to present). Gaps in missing observations are filled by the application of a relationship between local weather and leaf area index dynamics. Gap filling resulted in errors on the leaf area index estimates of less than 0.18 (Martins et al., 2017). The spatiotemporal resolution of the leaf area index products was the coarsest of all data products used and therefore determined the spatiotemporal resolution of the analysis as a whole. Moreover, the availability of the leaf area index product determined the starting date for the study.

The impact of cyclones on leaf area was calculated by comparing the change in leaf area before and after the cyclone in the affected area with changes before and after the cyclone in the reference area for each individual cyclone. In this approach, the reference area serves as the control for the affected area, given that reference area and the affected area may have a different size, the adjusted Hedge's effect size (Rustad et al., 2001) can be used to calculate the effect size of an individual cyclone on leaf area (**Eq. 1**). Using a reference area that is specific to each cyclone, seasonal dynamics such as leaf phenology, are accounted for in the effect size. Effect size is thus a unitless quantifier which describes the mean change in state, obtained by normalizing the mean difference in leaf area with the standard deviation (**Eq. 1**). A positive or negative effect size value indicates, respectively, an increase or decrease in leaf area following the passage of a cyclone:

$$ES = \frac{\left(\overline{LAI}_{bef} - \overline{LAI}_{aft}\right)_{aff} - \left(\overline{LAI}_{bef} - \overline{LAI}_{aft}\right)_{ref}}{\sigma}, \quad [1]$$

where *ES* is the event-based effect size for leaf area. The upper bar represents the mean of leaf area index in the reference (*ref*) or the affected (*aff*) area. The subscripts *bef* and *aft* denote the observation dates before and after the cyclone; σ denotes the standard deviation of all observations within the storm track. Given the 10-day frequency of the ESA leaf area index product, two leaf area index maps are used for the calculation of the effect size, one to characterize the leaf area index 1 to 10 days before the cyclone and the other to characterize the leaf area index 60 to 70 days after the cyclone. To distinguish between the affected and reference areas the effect sizes were calculated for each event using the nine definitions. After applying the quality control criteria (see below) a different number of events was available for each definition (**Table A1**).

Starting the analysis from the actual storm tracks, as was the case in this study, allows for an unbiased assessment of the impact of cyclones on forests (Blanc and Strobl, 2016), in contrast to studies that attribute decreases in leaf area or related satellite-based indices to different disturbance agents (Ozdogan et al., 2014; Honkavaara et al., 2013; Forzieri et al., 2020) including cyclones (Takao et al., 2014). By design, the latter approach is not capable of identifying neutral or positive impacts of cyclones on leaf area. As positive effects were not limited to the cyclones from a low intensity class (**Fig. A2**), the intensity class had little explanatory power (**Fig. 2**) making a systematic bias towards positive effect sizes caused by low intensity cyclones unlikely. Given the 60-day time window, our method is more likely to be biased towards detecting no changes in leaf area than detecting positive or negative changes in leaf area.

A meaningful effect size relies on the change in the reference area to evaluate whether the change in leaf area in the affected area is faster, similar or slower. The way the effect size is calculated thus accounts for phenological changes in leaf area. If the reference area would not be used in the calculation of the effect size, the change in leaf area over the affected area would mostly represent leaf phenology especially if the 60-day window includes the start or the end of the growing season, and would thus be unsuitable to address the question at hand.

As this study aims to quantify changes in leaf area index, it could not make use of gap filled leaf area index values which would level off such changes. Furthermore, calculating the effect size required leaf area index estimates before the passage of the cyclone in the reference and soon-to-be affected area and leaf area index estimates after the passage of the cyclone in the reference and affected area. The 60-day time frame was a compromise to avoid excessive data gaps in the leaf area index product when using the composite leaf area index product. Because the leaf area index product reports leaf area index values within a 60-day window, the analysis had to be refined so that this 60-day window never included the cyclone. The offset between the cyclone and a leaf area index observation from the composite leaf area index product was calculated by subtracting the date of the cyclone from the last observation date of the leaf area index composite data before the cyclone or first observation date of the leaf area index composite data after the cyclone. Pixels with a negative offset indicated that the composite data were likely to include observations from both before and after the cyclone and were therefore discarded in the calculations of the effect size.

The calculation of the effect size assumes having a similar leaf area index between the area that will become the affected area and the area that will become the reference area after the passage of a cyclone. If the absolute difference in leaf area index between the reference and the affected area was less than 10 %, the effect size calculated for this event was included in subsequent analyses. This can be formalized as:

$$\left| \frac{\overline{LAI}_{bef\,aff}}{\overline{LAI}_{bef\,ref}} - 1 \right| < 0.1 \qquad [2]$$

Where the 0.1 represents the 10 % threshold that was guided by the observed relationship between the remotely-sensed leaf area and its deviation to ground truth data for leaf areas of 5 m^2 m^{-2} or below (Fig. 26 in Jorge, 2020). This quality control criterion reflects the idea that prior to the passage of a tropical cyclone, the LAI needs to be similar in what will become the reference and affected area. If not, changes in leaf area following the passage of the cyclone cannot be assigned to its passage.

Following the passage of a tropical cyclone, a change in LAI of less than 10% before and after the passage of the cyclone was, in line with the quality control criterion, considered to be too small to be considered substantial. Such events were classified as cyclones with a neutral effect size. This classification was formalized as:

$$\left| \left(\overline{LAI}_{bef} - \overline{LAI}_{aft}\right)_{aff} - \left(\overline{LAI}_{bef} - \overline{LAI}_{aft}\right)_{ref} \right| < 0.1 * \left(\overline{LAI}_{bef}\right)_{ref} \qquad [3]$$

Multivariate analysis

Each tropical cyclone was characterized by its: (1) latitude of landfall (degrees); (2) intensity of the tropical cyclone (m s^{-1}); (3) month of landfall; (4) maximum wind speed during passage over land (m s^{-1}); (5) accumulated rainfall during passage over land (mm); (6) accumulated rainfall on land 30 days prior to landfall of the cyclone (mm); (7) affected area during passage over land (km^2); (8) leaf area 30 days prior to landfall (m^2 m^{-2}); (9) Standardized Precipitation Evapotranspiration Index (mm mm^{-1}) as a drought proxy; and (10) Pacific Japan index the month of landfall (Pa Pa^{-1}). These characteristics were calculated as the average along the trajectory of the cyclone.

Characteristics 1 to 4 were retrieved from the Joint Typhoon Warning Center database as detailed in ‘Cyclone track and track diameter’. Characteristics 5 to 6 were retrieved from the ERA5-Land reanalysis data for land (ECMWF, 2019) and characteristic 7 from the analysis combining cyclone track, cyclone diameter and ERA5-Land reanalysis, as explained in ‘Area affected by individual cyclones’. Characteristic 8 was taken from the leaf area index analysis as explained in ‘Impact on leaf area of an individual cyclone’. For characteristic 9, the Standardized Precipitation

Evapotranspiration Index was used and combined with the cyclone masks created in 'Area affected by the individual cyclone'. Characteristic 10, the Pacific Japan index, was calculated from ERA5 hourly reanalysis (Hersbach et al., 2018). Details on the calculation of characteristics 9 and 10 are provided in subsequent sections.

These ten characteristics were separated into two groups describing the condition of the land and ocean prior to the event and the characteristics of the tropical cyclone itself. The prior conditions group contained: pre-event leaf area index, pre-event drought state, pre-event accumulative rainfall, oceanic Nino index, and month. Characteristics such as maximum wind speed, accumulative rainfall, cyclone intensity, affected area, and latitude were used to describe the cyclone itself (**Table A2**).

Factor analysis (Grice, 2001) was used to reveal the collinearity among the selected variables in the prior conditions and tropical cyclone characteristic group (**Table A2**). Collinearity was used to create 12 sets (4 x 3) of mostly independent characteristics (**Table A3**) which were used as the input for a random forest tree to identify the characteristics that best explained the effect size for leaf area index. The random forest analysis was repeated for each of the 12 sets, but limited to four-layer random forest trees, to identify the importance of the environmental variables on the tropical cyclone effect size (not shown). Finally, to reduce the collinearity of the input variables, only the six variables with the highest accuracy in the random forest were used to create a single decision tree which is shown in **Fig. 3.** For this, the recursive partitioning approach was used with a maximum of four levels and a minimum of 20 samples in each node provided by the R-rpart package (Therneau et al., 2019).

Drought analysis

The standardized precipitation evapotranspiration index, is a proxy index for drought that represents the climatic water balance and was used to assess the drought of a forest soil before and after the passage of an individual tropical cyclone. The standardized precipitation evapotranspiration index data between 1999 and 2018 were retrieved from the Global Standardized Precipitation and Evapotranspiration Index Database (SPEIbase v2.6 (Beguería et al., 2014)), which is based on the CRU TS v.4.03 dataset (Harris et al., 2020). In this study, the temporal resolution of the data was preserved but the spatial resolution was regridded from the original half-degree to 1 km to match the resolution of the ESA leaf area index product. The contribution of an individual tropical cyclone to ending a drought was evaluated by comparing the standardized precipitation and evapotranspiration index from affected and reference areas through the following equation:

$$\delta SPEI = (SPEI_{imon})_{aff} - (SPEI_{imon})_{ref}, \qquad [3]$$

where δSPEI is the event-based change in standardized precipitation and evapotranspiration index. A positive or negative δSPEI respectively denotes an increase or decrease in available water resources following the passage of a tropical cyclone. The subscription *imon* represents the integration time of available water resources in the calculation of the standardized precipitation and evapotranspiration index either in the reference (*ref*) or the affected (*aff*) area which are defined in previous section. The same time window, i.e., 60-days, was applied for the calculation of δSPEI and event-based effect size for leaf area index.

Atmospheric analysis

The Pacific Japan index was calculated by comparing the difference of the 3-month running mean atmospheric pressure anomaly from Yokohama in Japan (35 N, 155 E) with Hengchun in Taiwan (22.5 N, 125 E) (Kubota et al., 2016) with the 20 year climatology from 1999 to 2019. A monthly Pacific Japan index was used in this study and the pressure data were retrieved from ERA5 (Hersbach et al., 2018).

The Pacific Japan index for the month of the passage of each tropical cyclone were stratified according to the impact (given by the effect size) of the cyclone on forest leaf area. Mean absolute atmospheric pressure field and leaf area were calculated for those cyclones with a neutral effect size on leaf area (**Fig. 4a**). Changes in pressure field and leaf area were calculated for both cyclones with a positive and negative impact on leaf area (**Fig. 4b & c**).

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Data availability

R-Scripts and data for performing the analysis and creating the plots can be found at https://github.com/ychenatsinca/LAI_STUDY_EA_V1/releases/tag/v1 and https://doi.org/10.5281/zenodo.6459795. The database of event-based effect sizes, surface properties and cyclone properties for each of the 1262 events (i.e., 140 ± 41 unique tropical cyclones analysed for nine related definitions) can be accessed at: http://YYCdb.synology.me:5833/sharing/MqA4YFBHk

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Figures and Tables

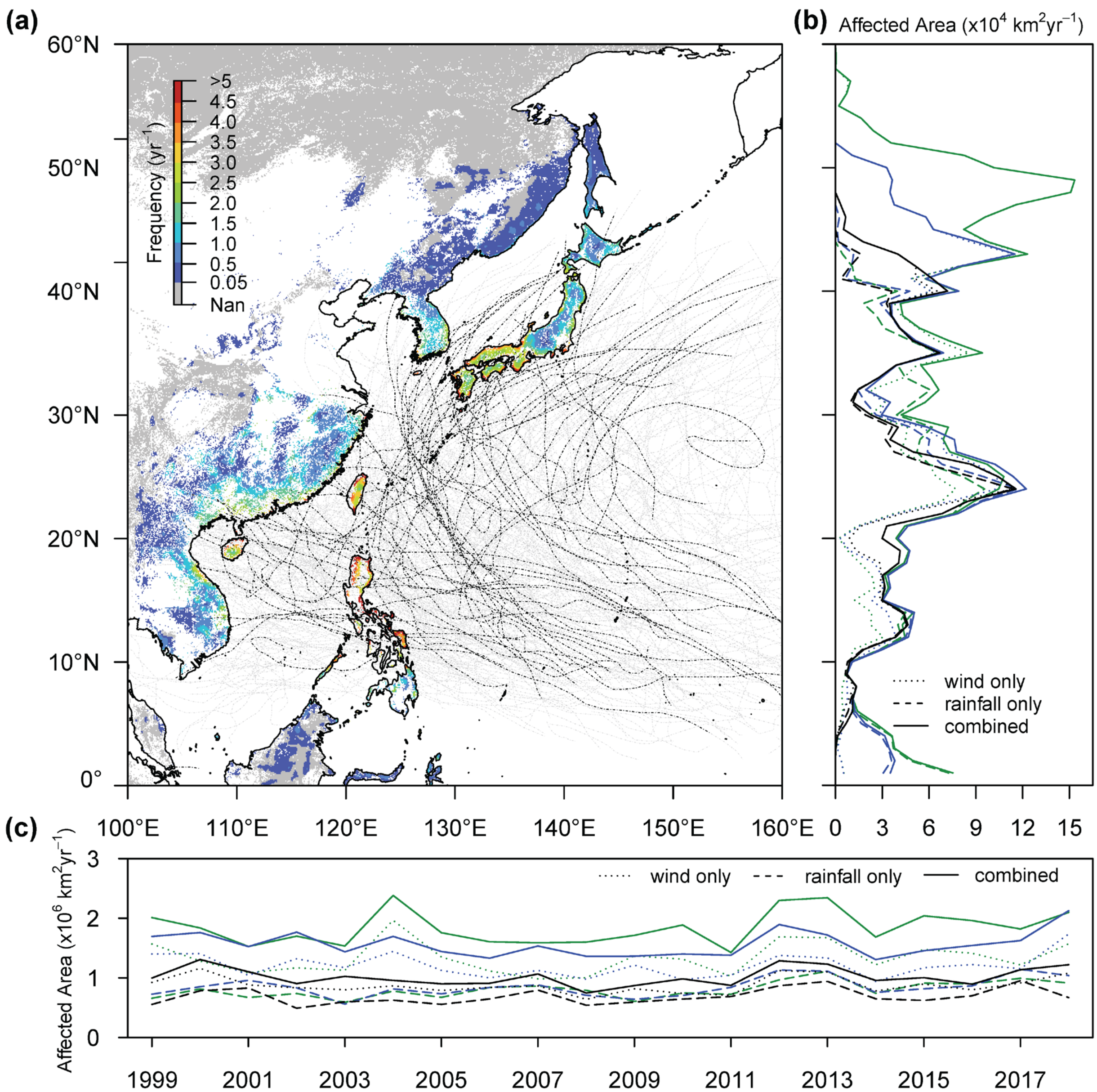

Figure 1. Spatial and temporal patterns of potential forest damage by tropical cyclones in East Asia. (**a**) Return frequency (yr^{-1}) of tropical cyclones between 1999 and 2018 following a combined wind-precipitation definition considering three diameters to define the width of the storm track (definition 3a in **Table A1**). Forests unlikely to have experienced a tropical cyclone between 1999 and 2018 are shaded in grey. For land locations shown in white, forest is not the dominant land cover. The dot-dashed lines show the cyclone tracks between 1999 and 2018. The black lines indicate the events that passed the quality control criteria used in this study. (**b**) Latitudinal gradients of potentially damaged forest area (km^2 yr^{-1}) between 1999 to 2018 for all nine definitions of affected area. Damage

potential is the outcome of an interplay between cyclone frequency, cyclone intensity, and the presence of forests. The different definitions of affected area (**Table A1**) consistently show a high potential for forest damage over island and coastal regions located between 10 and 35 degrees north. This high potential is largely driven by the frequency of tropical cyclones (**Fig. A1**), i.e., two or more cyclones making landfall per year. Depending on how the affected area is defined, there is a second region located between 40 and 50 degrees north with a high potential for storm damage. In this region, the potential damage is the outcome of the high forest cover resulting in a strong dependency on the assumed width of the storm track (**Fig. A1**). (**c**) Temporal dynamics of the total potentially damaged forest area (km^2 yr^{-1}) for all nine definitions of affected area.

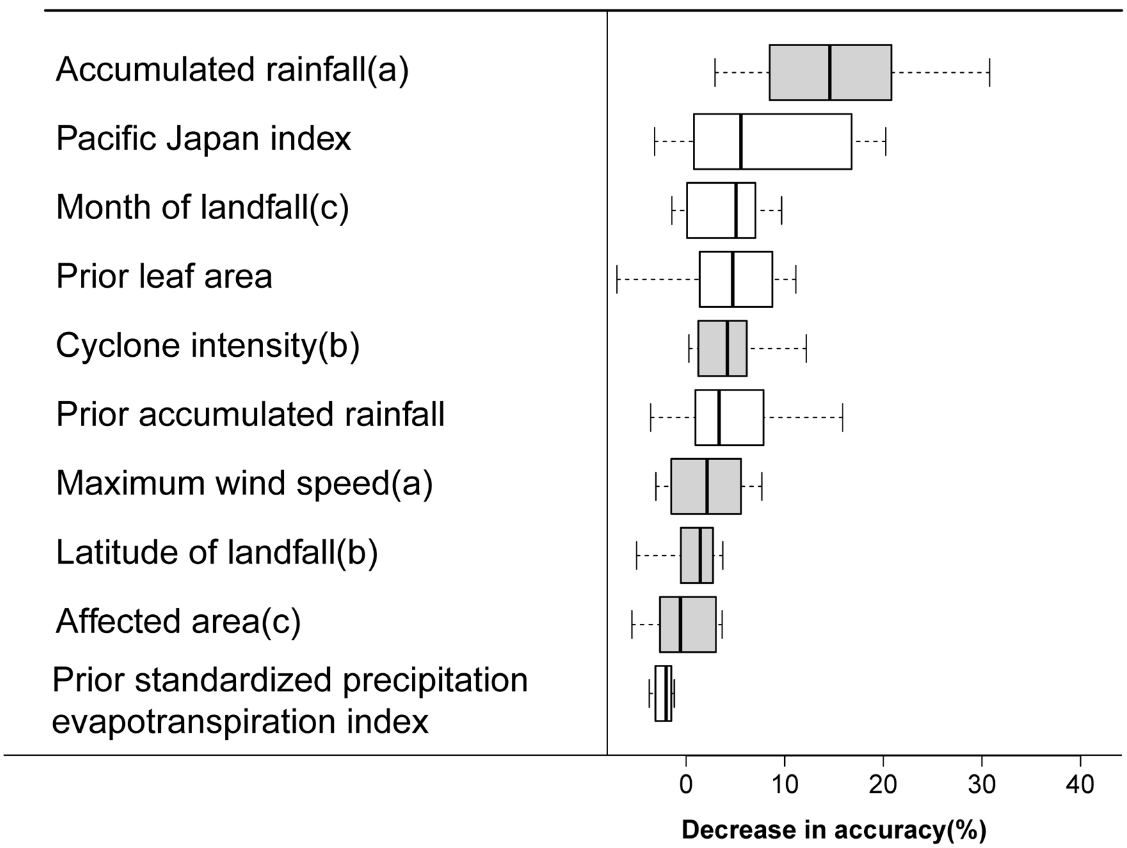

Figure 2. Importance of five surface (white) and five cyclone (grey) characteristics in explaining the leaf area response to the passage of a tropical cyclone. The boxplots show the 95, 75, 50, 25 and 5 percentiles of the decrease in accuracy. The letters a, b and c following the label of a characteristic indicate collinearity between the variables (**Table A2**). Each boxplot contains the results of 12 random forest analyses fitted with different combinations of largely uncorrelated characteristics (**Table A3**). Each random forest analysis is based on 1262 cases coming from the 140 ± 41 individual tropical cyclones for which the impact was quantified according to nine related definitions (**Table A1**). The medians were used to sort the cyclone and surface characteristics according to decreasing importance.

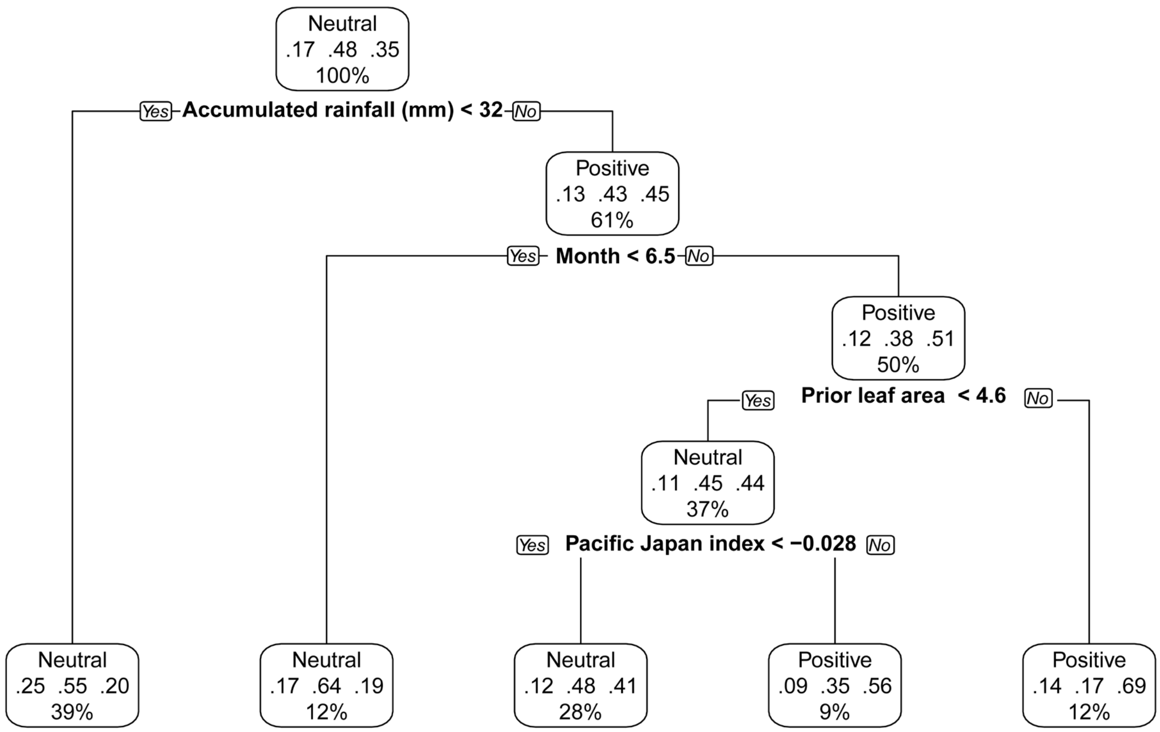

Figure 3. Environmental drivers contributing to an increase in leaf area in the affected compared to the reference area, following the passage of a tropical cyclone. The fractions of a negative (left), neutral (middle) and positive (right) effect size are shown in each box. The number of events is listed as the percentage of the total number of events in the random tree (n=1262). To reduce the collinearity of the input variables, only the six variables with the highest accuracy (**Fig. 2**) were used to create the four-layer decision tree.

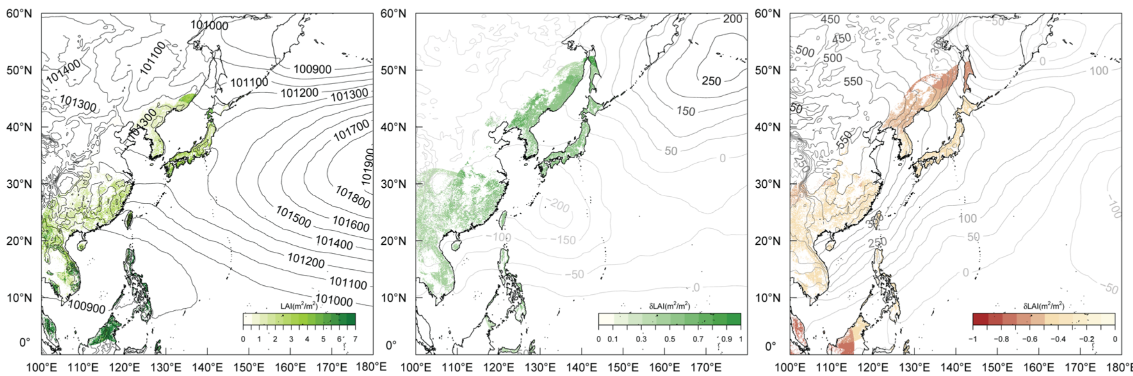

Figure 4. Pressure fields (Pa) and changes therein in the month of the passage of a tropical cyclone for cyclones that had a neutral, positive, or negative impact on the leaf area (m^2 m^{-2}) of forests. Effect sizes are based on the definition that uses three times the cyclone diameter and wind speed to identify the affected and reference areas (definition 3a in **Table A1**) (**a**) Mean atmospheric pressure and leaf area prior to the passage of a tropical cyclone that had a neutral impact on forest leaf area. (**b**) Changes in mean atmospheric pressure and leaf area between cyclones with a neutral and positive effect on leaf area. (**c**) Changes in mean atmospheric pressure and leaf area between cyclones with a neutral and negative effect on leaf area.

Appendix

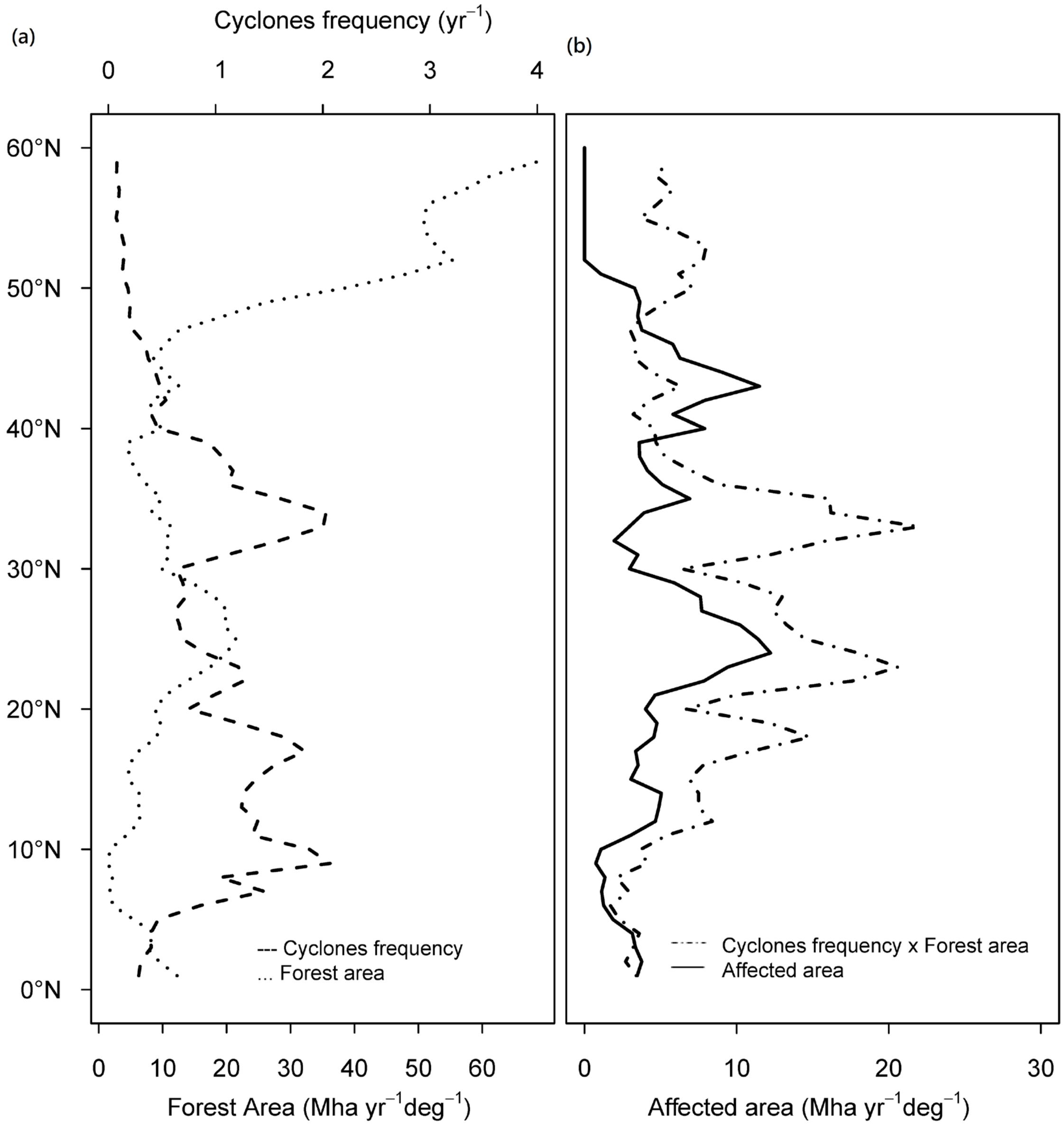

Figure A1. Contribution of return frequency and forest cover to the affected area: (**a**) zonal average of forest coverage (dotted line; km^2) and the return frequency (dashed line; yr^{-1}) of tropical cyclones from 0 to 60 degrees N averaged over Eastern Asia, as defined in this study; (**b**) Zonal average of the interaction between return frequency and forest cover, calculated by multiplying the return frequency with the forest cover (dotdash line; km^2 yr^{-1}) and the estimated zonal average of the annual affected forest area (full line; km^2 yr^{-1}). Correlations between return frequency and affected area (Pearson correlation coefficient = -0.35, p-value < 0.01, n = 60), forest cover and affected area (Pearson correlation coefficient = 0.089, p-value = 0.5, n = 60) and frequency x cover and affected area

(Pearson correlation coefficient = 0.44, p-value < 0.01, n = 60). The latter thus correlates best with the zonal variation in the affected area and was therefore shown in subplot b. Results are shown for affected areas defined as locations within an area extending to three times the cyclone width for which the wind exceeded a threshold (definition 3a in Table S1)

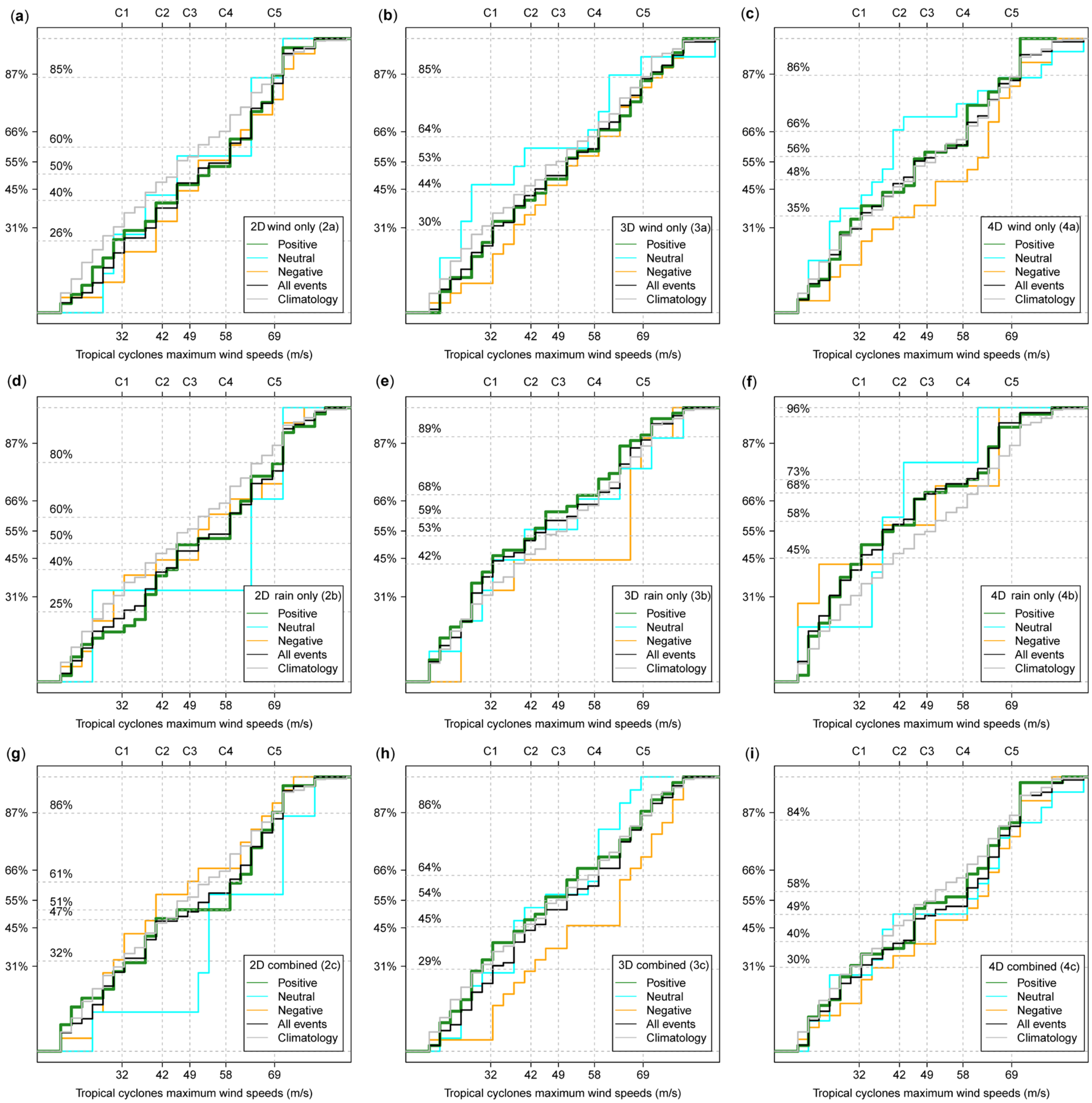

Figure A2. Cumulative distribution of tropical cyclones as a function of their maximum intensity for the nine definitions of affected area used in this study. The cumulative distribution for the census of 580 tropical cyclones recorded for the study period is shown left of the y-axis for class 1 (31%), class 2 (45%), class 3 (55%), class (4) 66% and class 5 (87%) cyclones. The numbers shown of the right of the y-axis represent the cumulative distribution of the sample of the 580 events following a specific definition. Panel (a) shows wind only for 2 diameters, (b) wind only for 3 diameters, (c) wind only for 4 diameters, (d) rain only for 2 diameters, (e) rain only for 3 diameters, (f) rain only for 4 diameters, (g) wind or rain for 2 diameters, (h) wind or rain for 3 diameters, and (i) wind or rain for 4 diameters as detailed in Table S1. The intensity distribution for tropical cyclones with a negative effect size is shown in orange, for tropical cyclones with a neutral effect size is shown in blue, and for tropical cyclones with a positive effect size in green. The black solid line shows the distribution for the specific definition (n = 140 ± 41 cyclones depending on the definition). The grey solid line shows the distribution of the 580 events that occurred between 1999 to 2018. Small deviations between the grey and the black line suggest that the sample well represented the 580 cyclones in terms of their intensity class. The maximum wind speed of category 1 cyclones is between 32 m s^{-1} and 42 m s^{-1}, between 42 m s^{-1} and 49 m s^{-1} for category 2, between 49 m s^{-1} and 58 m s^{-1} for category 3, between 58 m s^{-1} and 69 m s^{-1} for category 4, and exceeding 69 m s^{-1} for category 5. In East Asia, tropical cyclones of intensity class 3 or higher are called typhoons.

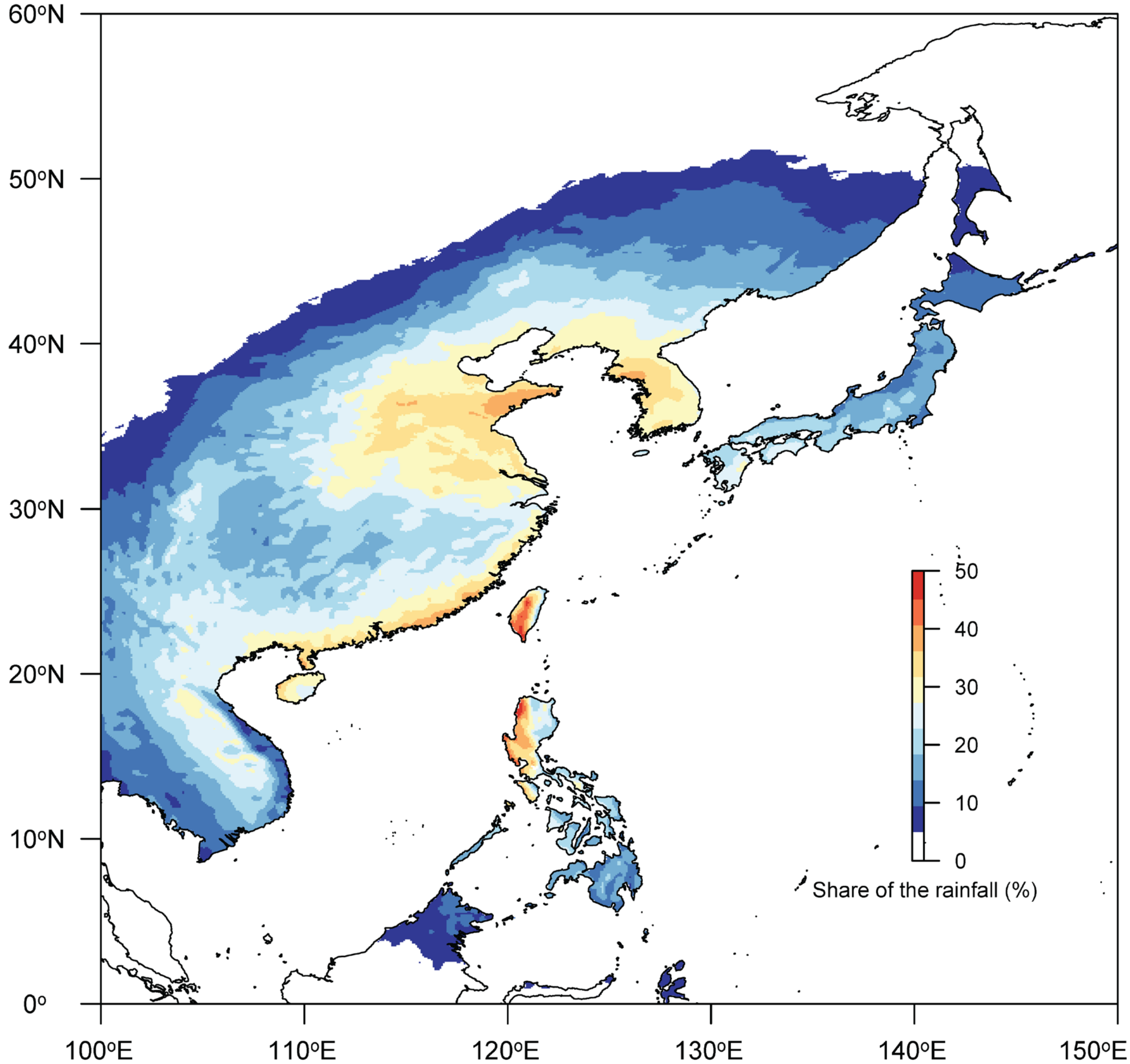

Figure A3. Share (%) of the rainfall contributed by tropical cyclones in June, July and August (JJA) to the total annual rainfall over Eastern Asia between 1999 to 2018.

Table A1. Criteria for distinguishing between the affected and reference areas following the passage of an individual cyclone and the number of events according to each specific definition. Group 1 groups definitions based on wind speed, group 2 definitions are based on precipitation and group 3 definitions are based on both wind speed and precipitation. All three definitions include an estimate of storm path based on a multiple of the reported storm diameter. Column A denotes the number of events for which data were lacking so that the effect size could not be calculated; column B denotes the number of events for which all required data were available; column C denotes the subset of B for which the data passed the quality control; ES refers to effect size. A total of 580 unique tropical cyclones were considered in this study.

Group	Affected area	Reference area	A	B	C	Negative effect size	Neutral effect size	Positive effect size
1.a	> 8 m s^{-1} and <2 diameters	< 8 m s^{-1} and <2 diameters	342	238	105	22	51	32
1.b	> 10 m s^{-1} and <3 diameters	< 10 m s^{-1} and <3 diameters	305	275	182	38	97	47
1.c	> 12 m s^{-1} and <4 diameters	< 12 m s^{-1} and <4 diameters	291	289	183	31	92	60
2.a	> 60 mm and <2 diameters	< 60 mm and <2 diameters	338	242	115	19	51	45
2.b	> 80 mm and <3 diameters	< 80 mm and <3 diameters	315	265	129	11	59	59
2.c	> 100 mm and <4 diameters	< 100 mm and <4 diameters	311	269	86	9	32	45
3.a	(> 8 m s^{-1} or > 60 mm) and <2 diameters	(< 8 m s^{-1} or < 60 mm) and < 2 diameters	352	228	103	25	45	33
3.b	(> 10 m s^{-1} or > 80 mm) and <3 diameters	(< 10 m s^{-1} or < 80 mm) and < 3 diameters	304	276	188	38	95	55
3.c	(> 12 m s^{-1} or > 100 mm) and <4 diameters	(< 12 m s^{-1} or < 100 mm) and < 4 diameters	288	292	171	35	83	53
Mean			316	264	140	25	67	48
Std			22	22	41	11	25	10
Mean (%)			54	46	24	18	48	34
Std (%)			4	4	7	8	18	7

Table A2. Loadings of each characteristic on three axes and collinearity between variables within the same group. Collinearity was used to build random forests with largely uncorrelated explanatory variables (**Fig. 2 & 3**). Factor analysis was performed separately for each group. Given the exploratory nature of this analysis, a factor loading of 0.6 was used as a cut-off and those exceeding that level are highlighted in bold face.

Group	Characteristics	FC1	FC2	FC3	Collinearity
Cyclone characteristics	Maximum wind speed during passage over land (m s^{-1})	0.01	**-0.79**	0.21	a
	Accumulated rainfall during passage over land (mm)	-0.18	**-0.83**	-0.03	a
	Latitude of landfall (degrees)	**0.83**	0.04	0.08	b
	Intensity of the tropical cyclone, gusts (m s^{-1})	**0.87**	0.14	0.06	b
	Affected area during passage over land (ha)	0.15	0.09	**0.97**	c
Surface conditions prior to the cyclone	Month of landfall	-0.35	-0.06	**0.72**	c
	Prior accumulated rainfall (30 days prior to landfall (mm))	**0.62**	**0.60**	0.17	d
	Prior leaf area index (30 days prior to landfall (m^2 m^{-2}))	**0.87**	-0.06	-0.07	e
	Prior Pacific Japan index (Pa Pa^{-1})	**-0.69**	-0.07	**0.74**	f
	Prior drought state (standardized precipitation and evapotranspiration index, 30 days prior to landfall (mm mm^{-1}))	0.01	**0.95**	0.03	g

Table A3. Sets of largely independent variables that were used as input in the random forest analysis. Details of the variables are given in the section "multivariate analysis". The justification for the groups is given by the collinearity as reported in Table S2.

Set	Group with tropical cyclone characteristics	Group with land characteristics prior to the cyclone
1	Maximum wind speed, latitude & affected area	Month & prior accumulated rainfall
2	Maximum wind speed, cyclone intensity & affected area	Prior accumulated rainfall, prior leaf area, & prior standardized precipitation and evapotranspiration index
3	Accumulated rainfall, latitude & affected area	Prior Pacific Japan index & prior standardized precipitation and evapotranspiration index
4	Accumulated rainfall, cyclone intensity & affected area	