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Implications of tropical cyclones on damage and potential recovery and restoration of logged forests in Vietnam

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Summary

Many natural forests in Southeast Asia are degraded following decades of logging. Restoration of these forests is delayed by ongoing logging and tropical cyclones, but the implications for recovery are largely uncertain. We analysed meteorological, satellite and forest inventory plot data to assess the effect of Typhoon Doksuri, a major tropical cyclone, on the forest landscapes of central Vietnam consisting of natural forests and plantations. We estimated the return period for a cyclone of this intensity to be 40 years. Plantations were almost twice as likely to suffer cyclone damage compared to natural forests. Logged natural forests (9-12 years after cessation of government-licensed logging) were surveyed before and after the storm with two years between measurements and remained a small biomass carbon sink (0.1±0.3 Mg C ha^{-1} y^{-1}) over this period. The cyclone reduced the carbon sink of recovering natural forests by an average of 0.85 Mg C ha^{-1} y^{-1}, less than the carbon loss due to ongoing unlicensed logging. Restoration of forest landscapes in Southeast Asia requires a reduction in unlicensed logging and prevention of further conversion of degraded natural forests to plantations, particularly in landscapes prone to tropical cyclones where natural forests provide a resilient carbon sink.

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Introduction

Tropical forests play an important role in the global carbon cycle (Mitchard, 2018). Degradation of forests by anthropogenic activities such as logging releases carbon to the atmosphere (Baccini et al., 2017; Erb et al., 2018). In contrast, restoration and recovery of degraded forests removes carbon from the atmosphere as forest regrowth generates a carbon sink (Philipson et al., 2020). Silvicultural treatments can enhance the rate of biomass recovery (Hu et al., 2020), whereas ongoing logging (Ngo et al., 2020) and natural disturbances such as storms can cause damage and slow recovery. Little is known about how ongoing logging and natural disturbances such as storms in combination affect the rate of biomass recovery of tropical forests, yet this understanding is vital for restoring forest landscapes, particularly in mainland Southeast Asia.

A large body of work has assessed how tropical forests recover from logging through assessment of aboveground carbon (AGC) stocks and dynamics (e.g., Berry et al., 2010; Blanc et al., 2009; Gourlet-Fleury et al., 2013; Hu et al., 2019; 2020; Mazzei et al., 2010; Philipson et al., 2020; Piponiot et al., 2016; Roopsind et al., 2018; Rutishauser et al., 2015; Sist et al., 2014; Vidal et al., 2016; West et al., 2014). Shortly after logging, forests are often a net carbon source due to high mortality of damaged trees, before returning to a carbon sink (Blanc et al., 2009; Mazzei et al., 2010). Logged forests can be a stronger carbon sink compared to unlogged forests (Berry et al., 2010; Roopsind et al., 2017), because remaining trees benefit from reduced competition (Villegas et al., 2009). Logging creates canopy openings that stimulate growth rates of remaining trees (Delcamp et al., 2008; Hérault et al., 2010; Sist and Nguyen-The, 2002) and recruitment of new stems (Delcamp et al., 2008; Sist and Nguyen-The, 2002). Logging also affects the mortality rate, directly by harvesting specific timber species and indirectly by increasing the mortality probability of injured trees (Pinard and Putz, 1996; Shenkin et al., 2015; Sist et al., 2003b; Sist and Nguyen-The, 2002). Woody debris created by logging will decay over subsequent years, impacting the total ecosystem carbon balance. In Borneo, post-logging mortality, growth and recruitment rates increased with logging intensity (Lussetti et al., 2016; Sist and Nguyen-The, 2002). The rate of post-logging AGC recovery depends on logging intensity, both in the Neotropics (Piponiot et al., 2016; Rutishauser et al., 2015; Roopsind et al., 2018) and Africa (Gourlet-Fleury et al., 2013). Overall, the time taken for tropical forests to recover pre-logging AGC stocks can take many decades (Blanc et al., 2009; Pinard and Cropper, 2002; Rutishauser et al., 2015).

Tropical cyclones are a major natural disturbance that can cause substantial damage and disturbance to forests (Lugo, 2008; Ibanez et al., 2019). Known as hurricanes in the North Atlantic and eastern Pacific Ocean and typhoons in the northwest Pacific Ocean, tropical cyclones are synoptic scale, low pressure systems resulting in strong winds and heavy rainfall (Chan and Chan, 2015). Cyclones cause defoliation (Fernandez & Fletcher, 1991; Walker, 1991; Lin et al., 2003; Turton, 2008; Murphy et al., 2008; Lin et al., 2011), a reduction in leaf area index (Herbert et al., 1999) and changes in microclimate (Turton & Siegenthaler, 2004). Damage includes snapped and wind-thrown trees and increased tree mortality (Turton, 2008; Pohlman et al., 2008; Uriarte et al., 2019), resulting in a consequent reduction of timber volume (Lugo, 2008). However, the effect of storms on the carbon balance of forests is less clear. Forests can become carbon sources after being damaged (Fisk et al., 2013; Uriarte and Papaik, 2007) before returning to a carbon sink (Lugo, 2008). Climate change is projected to increase the frequency and intensity of tropical cyclones (Kossin et al., 2014; Knutson et al., 2010; Mei et al., 2015), so quantifying their effect on tropical forests is important.

Southeast Asia contains 15% of the world's remaining tropical forests and are important for protection of biodiversity and carbon storage (Stibig et al., 2014). Rapid deforestation (Estoque et al., 2019; Feng et al., 2021; Feng et al., 2022) and widespread logging (Edwards et al., 2013) across Southeast Asia has resulted in large areas of degraded and damaged landscapes. In 2011 the Bonn Challenge was launched, aiming to restore 350 million hectares of degraded and damaged landscapes into restoration by 2030 through Forest Landscape Restoration (FLR) (Stanturf and Mansourian, 2020). FLR aims to increase the resilience of landscapes, enhancing and protecting biodiversity while also providing sustainable livelihood options for local communities (IUCN, 2022). This can be achieved through protection of remaining forest, enabling regeneration of natural forest, and also the establishment of commercial tree plantations (Sayer and Elliot, 2005). Over 65 million ha of degraded landscapes have been identified across China, Indonesia, South Korea and Vietnam (Stanturf and Mansourian, 2020), demonstrating extensive potential for restoration. Indeed, restoration of degraded forest landscapes is a key component of the climate plans of many Southeast Asian nations through their Nationally Determined Contributions (IGES, 2021). FLR projects have long time scales, and are likely to experience ongoing logging as well as natural disturbances including tropical cyclones. Remarkably, very few studies have analysed the effects of either logging or cyclones on AGC stocks or recovery in mainland Southeast Asian forests, despite the importance of both processes for FLR, managing national carbon emissions and sequestration for countries in this region.

Like much of Southeast Asia, forests in Vietnam have been degraded by logging (McElwee, 2004) with a consequent reduction in carbon stocks (Stas et al., 2020), but very few studies have assessed effects on AGC dynamics (Do et al., 2018; Nam et al., 2018). Logging in natural forests is now prohibited in Vietnam, but informal, unlicensed and unplanned selective logging still occurs and is slowing the rate of biomass recovery in degraded forests (Ngo et al., 2020). Vietnam experiences 5-6 tropical cyclones a year (Lap, 2019), but we are not aware of any studies that have assessed the effects of cyclones on Vietnam's forests. Crucially, little is known about how cyclones alter the rate at which the AGC of logged forests recovers, or whether heavily logged forests are more or less susceptible to storm damage compared to unlogged forests. In recent decades, plantations have increased in Vietnam in some cases replacing natural forests, particularly those already degraded by logging (Nambiar et al., 2021: Spracklen and Spracklen, 2021), but the relative susceptibility of natural forests and plantations to storm damage is not well understood. Better understanding of the effects of logging and tropical cyclones on forests is needed to help Southeast Asian countries conserve and manage their forest resources and to inform forest restoration and climate mitigation initiatives.

Typhoon Doksuri, one of the most powerful tropical cyclones to hit Vietnam in recent decades (Takagi, 2019), affected North-Central Vietnam during 10th to 16th September 2017. This provides the opportunity to assess, for the first time, the impact of a major tropical cyclone on plantations and natural forests in Southeast Asia. We analysed meteorological data to assess the intensity of Typhoon Doksuri and estimate the likely return period. We used satellite data to assess the effects of the cyclone on both plantation and natural forests and to assess historical logging intensity across natural forests. Data from our forest plot network, surveyed before and after the cyclone, was used to explore how logging intensity and the cyclone affected tree dynamics. We combined data from forest surveys with satellite data to assess the regional impacts of the tropical cyclone on recovery of natural forest carbon stocks.

Methods

Study area

Our study area covers Quang Binh province and southern Ha Tinh province, in the North Central Coast region of Vietnam (Fig. 1). The study area covers 719,230 ha, consisting of around 77% natural forest and 23% plantation. Selective logging as part of government-licensed operations occurs across much of the natural forests in the study area (Stas et al., 2020; Ngo et al., 2020). Since 2014, most commercial logging in Vietnam is prohibited (Vietnam Law on Forestry, 2017) although informal and unplanned logging without government permission that is therefore considered to be illegal, still persists (Ngo et al., 2020; FCPF, 2018). Plantations have been developed on non-forest land or through replacing natural forests (FCPF, 2018) and largely consist of rubber and Acacia, which is operated on 3-7 year rotations (Spracklen & Spracklen, 2021).

Tropical cyclone analysis

We used cyclone best-track estimates from IBTrACS (International Best Track Archive for Climate Stewardship), which combines data from regional meteorological centers and other agencies into one product (Knapp et al., 2010; Levinson et al., 2010). To determine the return frequency of storms of different intensities, we used 10-m wind speed from the operational analysis from the European Centre for Medium Range Weather Forecast (ECMWF) Integrated Forecasting System (IFS) model. We used data from 1983-2019 for May to December at a resolution of 0.1^{o} (~9 km) for runs commencing at 00, 06, 12, and 18 UTC. We used the operational analysis because of its smaller horizontal grid-spacing compared to the ERA-Interim reanalysis.

To derive return periods for storms of equal intensity, we used the Peaks Over Threshold (POT) Extreme Value Analysis techniques that have been used widely for the analysis of extreme wind speeds. The method is described in detail by Della-Marta et al. (2009) and outlined briefly here. A Generalised Pareto Distribution (GPD) was fitted to the time series of grid point 10-m wind speeds. A Poisson distribution was assumed for the exceedances over a certain threshold. To obtain time series that are estimated to have independent exceedances, the original time series were first declustered based on seasonal and diurnal thresholds, smoothed by spline fitting. Confidence intervals for the modelled return periods were calculated using the profile likelihood method, which was based on a likelihood ratio test.

Forest inventory plots

We analysed data from 24 forest inventory plots (0.25 ha; 50 m × 50 m) all located in lowland (< 700 m elevation) natural forest (Stas et al., 2020). Forest plots were located in an area that was designated as the Khe Nuoc Trong watershed protection forest in 2007, prohibiting government-licensed selective timber harvesting operations (Stas et al., 2020; Ngo et al., 2020).In 2020, the area was designated as a Nature Reserve (one of the highest classes of forest protection in Vietnam). Forest plots were established across a gradient of historical logging intensity, based on analysis of remote sensing data (see below); rapid decomposition means that older stumps were hard to identify in the field (Stas et al., 2020). All forest plots are located about 150 km south of the typhoon track (Fig.1). We do not have any plots in plantation forest.

All forest plots were surveyed twice, with two years in between the surveys (Supplementary Table 1). To minimize the effects of seasonal fluctuations on stem expansion and shrinkage (Sheil, 2003, 1995), plots were re-measured as close as possible to the first census date, with a maximum of one month difference. Surveys pre-typhoon were conducted between April 2016 and June 2017, and surveys post-typhoon between May 2018 and May 2019. Surveys were therefore conducted 9-12 years after cessation of government-licensed logging. Surveys followed RAINFOR and GEM protocols (Marthews et al., 2014; Phillips et al., 2016; http://www.rainfor.org/en/manuals). In the first survey, all living woody stems ≥ 10 cm diameter at breast height (dbh) were tagged, measured and species identified. Tree heights were measured for a subset of stems, else estimated using a locally derived height-diameter model. Stems ≥ 5 cm were recorded in the same way in a 4 m × 50 m transect. In the second census, the dbh of each living stem was re-measured, it was recorded if a tagged stem died and newly recruited stems (i.e. stems ≥10 cm dbh in the plot and stems 5-10 cm dbh in the belt transect) were measured as described in the first census. Information from logged stumps were used to assess recent unlicensed logging (Stas et al., 2020).

Above-ground biomass (AGB) for each stem was calculated using the allometric equation 4 of Chave et al., (2014), including dbh, tree height and wood density (Réjou-Méchain et al., 2017), and summed to retrieve plot-level AGB for both censuses. AGB stocks were converted into above-ground live carbon (AGC) assuming biomass was 47% C (IPCC, 2006). We then calculated the change in AGC (ΔC_C) between the surveys partitioned into three components: change in AGC due to dbh growth ΔC_G, AGC change due to mortality of stems ΔC_M and the AGC change due to recruitment of stems ΔC_R (Rozendaal and Chazdon, 2015; Rozendaal et al., 2017). We report annual changes by dividing observed changes over the two year measurement period by a factor of 2.

Remote sensing

We assessed logging intensity from 1988 to 2016 using Landsat images as described in detail in Stas et al. (2020). The resolution of Landsat imagery was insufficient to identify canopy gaps from selective logging, but can detect other disturbances such as skid trails and logging tracks. Changes in normalised burn ratio (NBR) between consecutive images were used to identify disturbances from selective logging. We calculated NBR as:

$$NBR = \frac{NIR - SWIR}{NIR + SWIR}$$

where NIR is Near-Infrared and SWIR is Short-wave Infrared. The logging intensity of each forest plot was related to the number of disturbances detected within 1000 m of the forest plot.

To assess storm damage, we used before and after images from European Space Agency Sentinel-1 (S-1) and Sentinel-2 (S-2) satellites. We used images as close to the dates of the storm as possible. S-1 is an active microwave system that operates in the C-band (roughly 5.6 cm) with a repeat time of about 12 days. We downloaded 20 S-1 Level-1 images from ascending orbits covering 2 adjacent granules (relative orbit number 128). These Synthetic Aperture Radar (SAR) images consist of cross polarised VH (Vertically sent and horizontally received) and co-polarised VV (Vertically sent and vertically received) bands. We downloaded images immediately before (30/07/2017, 11/08/2017, 23/08/2017, 04/09/2017) and after (16/09/2017, 28/09/2017, 10/10/2017, 15/11/2017, 02/01/2018, 19/02/2018) the typhoon. Pre-processing of all S-1 imagery consisted of orbital correction, calibration, subsetting to the study site, terrain flattening and terrain correction using Shuttle Radar Topography Mission (SRTM) data (Jarvis et al., 2008) and speckle filtering (Lee-Sigma filter).

S-2 is a visual, NIR and SWIR satellite with a resolution of 10-20 m and a repeat time of 5 days. We downloaded a total of 27 S-2 images as Level-1C Top-of-Atmosphere reflectance products, from 5 adjacent granules: T48QXD, T48QXE, T48QWE, T48QWF and T48QXF. These dated from 20/02/2017 to 15/02/2018. To calculate damage we selected the most cloud-free images before (09/08/2017; 14/08/2017; 11/09/2017; combined to give complete coverage) and after the typhoon (18/09/2017; this was the only largely cloud free image occurring for several months after the storm). All the S-2 images were then terrain and atmosphere corrected using the Sen2Cor module (Louis et al., 2016). Cloud and cloud shadow covered pixels were then manually removed from the images, by visual inspection of the RGB images. The NIR band is at a resolution of 10 m while the SWIR band has a 20 m resolution. Bicubic interpolation was used to resample the SWIR resolution to 10 m. We calculated the average NBR on areas of undamaged forest for all the before and after images and found a variation of no more than 5%, indicating that illumination conditions are even across the images used to calculate damage.

Storm damage was estimated as the change (ΔNBR, ΔVV and ΔVH) caused by the storm calculated as the value after the storm minus before the storm. Of the 24 forest plots, 4 were obscured by cloud in the post-typhoon image, leaving 20 useable plots for the S-2 imagery. Historical logging intensity and storm damage for each plot was classified as light, medium or heavy. We assessed the Pearson correlation between storm damage intensity (ΔNBR) and historical logging intensity (number of disturbances within 1 km). To explore how plot level AGC changes compare with remote sensed data we compared ΔNBR, ΔVV and ΔVH calculated for the locations of the forest plots with the plot level AGC changes (ΔC_C, ΔC_R, ΔC_M).

The impact of forest type, elevation, aspect relative to the direction of the storm (0^o windward, 180^o leeward) and distance to storm track were modelled using logistic regression. Storm track was taken from IBTrACS (Knapp et al., 2010). Elevation was taken from the SRTM (Jarvis et al., 2008) and used to calculate slope and aspect. Forest type (plantation or natural forest) was based on information from the Vietnamese Ministry of Agriculture and Rural Development (MARD). We present the results of the logistic regression as odds ratio of damage, defined as the probability of an event occurring in the presence of the specified factor, compared to the probability that it will occur in the absence of that factor.

To assess regional storm damage, we randomly selected and analysed 800 locations (natural forest and plantation) across the study area, separated by at least 250 m. At each location we manually classified the forest within a 100 m diameter circle as undamaged, lightly damaged or severely damaged, based on a visual analysis of the S-2 RGB image directly after the storm. For each location we calculated average ΔNBR, ΔVV and ΔVH. We used the Bhattacharyya coefficient (BC), a measure of overlap between distributions, to assess the overlap between classes (0: complete separation of the classes, 1: complete overlap). We defined a threshold for storm damage as the 95th percentile of ΔNBR (-0.05) or ΔVH (0.019) across the undamaged plots. Additionally, we calculated time-series of NBR, VV and VH values for all the natural forest locations. Most plantations were harvested shortly after the typhoon (likely due to damage from the storm, see discussion) and so we did not assess time series for plantations.

Results

The majority of tropical cyclones impact north-central Vietnam (18-20°N) between April and August (Fig. 2a). Based on an analysis of 10-m wind speeds, we estimate that a cyclone of the strength of Storm Doksuri has a return period of 40 years (95th confidence interval 20-600 years, Fig. 2b).

Forest plots showed net changes in live AGC ranging from -4.4 to 2.6 Mg C ha^{-1} y^{-1}, with ~40% of plots experiencing a reduction. There was no significant correlation between historical logging intensity and storm damage intensity (P=0.7). Despite being affected by a major storm, the average net AGC change across all plots was 0.1±0.3 Mg C ha^{-1} y^{-1}. We found no significant differences in AGC fluxes with historical logging intensity (Table 1). Ongoing (illegal) logging occurs across our study area (Ngo et al., 2020), but our forest plots experienced little logging during the census interval (only 2% of mortality in forest plots was due to logging). For all plots combined, diameter growth rates averaged 0.3 cm y^{-1}, recruitment rates averaged 1.5% y^{-1} and mortality rates averaged 2.3% y^{-1}, and all rates did not differ with historical logging intensity. There were significant differences in AGC fluxes with storm damage (as detected by remote sensing), with plots heavily damaged by the storm having a negative net AGC change (-1.7 Mg C ha^{-1} y^{-1}), in contrast to positive net AGC fluxes for lightly damaged plots (+1.3 Mg C ha^{-1} y^{-1}) (Fig. 3). Heavily damaged plots had significantly lower carbon gains from diameter growth and recruitment, but differences in carbon losses from mortality were not significant. There was on average 2 years between census dates including both pre-storm and post-storm periods. Slight differences in census dates meant that plots experiencing light storm damage were on average first measured slightly later compared to heavily damaged plots (Supplementary Table 1) and so the census period includes less time when they were undamaged to accrue carbon before the storm. Our conclusions about impacts of storm damage on AGC fluxes, in particular growth, are therefore likely to be conservative. ΔNBR was significantly correlated with net AGC change ΔC_C ($P=0.03$, $R^2=0.25$) as well as AGC net change from growth ΔC_G ($P=0.003$, $R^2=0.39$; Fig. 4) and recruitment of stems ΔC_R ($P=0.03$, $R^2=0.24$), but there was no significant correlation ($P=0.6$) with mortality of stems ΔC_M. For S-1, neither of the bands ΔVV and ΔVH showed any significant correlation ($P>0.05$) with any of the carbon fluxes.

Damaged forests exhibited a decrease in NBR and an increase in VH and VV following the storm (Fig. 5). Damaged forests have a mean ± standard deviation ΔNBR of -0.19±0.09, whilst undamaged forests have a ΔNBR of 0.00±0.02. The S-1 bands are less well classified, with damaged and undamaged forests have ΔVH of 0.02±0.01 and 0.00±0.01 respectively, and ΔVV of 0.02±0.05 and 0.00±0.04 respectively. The S-1 bands do not distinguish damaged from undamaged forest as well as S-2: for ΔNBR, ΔVH and ΔVV we calculate a BC for separation of damaged and undamaged forests of 0.18, 0.68 and 0.99 respectively.

Of cloud-free study area (~500 000 ha), we classified between 29% (S-1) and 39% (S-2) as having been damaged by Doksuri (Table 2). Analysis of S-1 data allows us to estimate that 26% of the total study area (cloud free and cloudy) experienced storm damage. The storm damaged 23%-36% of natural forest compared to 28%-39% of plantation. Storm damage decreased with distance from the cyclone track, with 45.9% of forest under 50 km from the track damaged, compared to 24.4% of forest over 50 km. The predicted spatial pattern of storm damage is relatively similar in S-1 and S-2 (Fig. 6), despite the larger area indicated as damaged in S-2 compared to S-1. Storm damage is greatest in the north and the east of the study area, with stronger damage to the north of the storm track than at the equivalent distance to the south.

Table 3 reports the odds ratios for storm damage to plantation and natural forest across the study area. The likelihood of damage declined with higher elevation, relative aspect and distance from Doksuri's track. Windward slopes are significantly more likely to suffer damage than leeward slopes, but the odds ratio is close to 1, so the effect is small. After accounting for elevation, aspect and distance to cyclone track, plantations were 1.8 times as likely to be damaged compared to natural forest.

Discussion

Historical Logging

Previous studies have reported that logged tropical forests have faster diameter growth rates than undisturbed forests in the first four years after logging in the Amazon (Delcamp et al., 2008; Hérault et al., 2010; Silva et al., 1995) and Borneo (Sist and Nguyen-The, 2002) and even 50 years after logging in peninsular Malaysia (Yamada et al., 2013). Recruitment rates are also generally higher in logged forests compared to undisturbed forests in the first four years after logging in Borneo (Sist and Nguyen-The, 2002) and 4-15 years after logging in the Amazon (Delcamp et al., 2008). Higher mortality rates in logged forests have been observed in Borneo two years after logging (Sist and Nguyen-The, 2002) and in the Amazon 8 years after logging (Blanc et al., 2009), likely due to a higher mortality of injured trees during logging (Sist and Nguyen-The, 2002). Thereafter, mortality rates in the logged and unlogged forests were similar (Blanc et al., 2009; Sist and Nguyen-The, 2002; Yamada et al., 2013). We found that historical logging intensity did not significantly impact growth, recruitment or mortality rates over the two-year period conducted 9-12 years after the cessation of government-licensed logging. It is possible that the tropical cyclone may have obscured any differences in vital rates with logging intensity.

Tropical cyclone

Based on an analysis of wind speeds, our best estimate of the return period for a storm of similar intensity to Typhoon Doksuri was 40 years. This is potentially a conservative estimate, since of all typhoon landfalls in Vietnam between 1977 and 2017, Doksuri had the strongest intensity (Takagi, 2019). In terms of rainfall, a Doksuri-intensity typhoon has a shorter return interval, estimated at 2-3 years (S. Fig. 2). The strong winds but moderate rainfall of Doksuri, is likely to influence the damage caused to the forest. Landslide frequency in other tropical forest regions has been linked to rainfall intensity and duration (Larsen and Simon, 1993).

Analysis of S-2 images shows little evidence of landslides after Doksuri, possibly due to the low rainfall during this storm. Future work is needed to assess the impacts of storms with heavy rainfall on forests in Vietnam.

Tree mortality rates in our plots were greater than other logged forests in the region (Do et al., 2018; Nam et al., 2018) and greater than the 1-2% y^{-1} mortality rates that are typical of wet tropical forests (Phillips and Gentry, 1994). Tree mortality in plots that were heavily damaged by the storm (2.75% y^{-1}) was significantly higher than mortality in lightly damaged plots. The mortality rate we observed was similar to that experienced in forests in the Philippines after a strong typhoon (2.27% y^{-1}) (Yap et al., 2016) but substantially less than the 10-20% mortality experienced after a Hurricane María in Puerto Rico that combined extreme precipitation and strong winds (Uriarte et al., 2019).

Biomass

The mean AGC change in our forest plots was 0.1 Mg C ha^{-1} y^{-1} with confidence intervals bracketing zero, and did not differ with historical logging intensity (Table 1). Negative AGC net change has been observed in some tropical forests in the first years after logging (Mazzei et al., 2010; Sist et al., 2014; Roopsind et al., 2018), before typically becoming positive (Berry et al., 2010; Roopsind et al., 2017, Gourlet-Fleury et al., 2013; Roopsind et al., 2018). Considerably higher positive AGC net change rates have been observed in recovering logged forests elsewhere in Vietnam (3.0 Mg C ha^{-1} y^{-1}, Nam et al. (2018); 5.4 Mg C ha^{-1} y^{-1}; Do et al., 2018), Borneo (0.3 – 4.3 Mg C ha^{-1} y^{-1}; Berry et al., 2010; Galante et al., 2018) and the Amazon (ranging from 0.04–2.96 Mg C ha^{-1} y^{-1}, mean of 1.33 Mg C ha^{-1} y^{-1}; Rutishauser et al., 2015). In our study, forest plots with light storm damage had net AGC change of 1.3 ± 1.1 Mg C ha^{-1} y^{-1}, significantly more than heavily damaged plots and more consistent with previous studies of recovering logged forests. We suggest the lower average biomass recovery in our plots is likely related to the damage caused by the tropical cyclone. The short time period of our study (plots were surveyed on average 390 days after the storm) means we are unable to assess the full impact of the tropical cyclone on recovery of aboveground biomass.

Logging has reduced AGC stocks in natural forests in Vietnam, with heavily logged forests containing only 50% of the biomass carbon of lightly logged forests, 9-12 years after government-licensed logging ceased (Stas et al., 2020). Previous work has shown recovery to pre-logging AGC stocks occurs more quickly if lower logging intensities (Blanc et al., 2009) or improved logging practices (West et al., 2014) are implemented but still take several decades to recover after logging finishes (Blanc et al., 2009; Pinard and Cropper, 2002; Rutishauser et al., 2015, Hu et al., 2019; 2020). In our study, forest plots with light storm damage recovered AGC at a rate of 1.3 ± 1.1 Mg C ha^{-1} y^{-1}; at this rate they would take an additional 45-50 years for our forests to recover pre-logging biomass. Additional silvicultural treatments could promote faster forest recovery (Peña-Claros et al., 2008; Hu et al., 2020).

Regional damage

We used both optical and SAR remote-sensed data to analyse storm damage at the regional scale. Most previous remote sensing studies have relied on optical imagery (Aosier et al., 2007; Guo et al., 2015; Hall et al., 2020; Hu and Smith, 2018; Lee et al., 2008; Peereman et al., 2020; Wang and Xu, 2018; Zhang et al., 2013; Hoque et al., 2016). Cloud cover, which is extensive in tropical forest regions, obscures optical images and prevents assessment of forest damage. Despite combining multiple optical images taken over a period of months, only 70% of our study area was visible in optical imagery (Table 1).

SAR is less affected by cloud cover and is sensitive to the physical characteristics of the vegetation such as moisture content and surface roughness that are affected by the storm. Forests damaged by the storm exhibited increased backscatter, likely due to leaf loss which exposes canopy branches to which C-band SAR is most sensitive (Asbridge et al., 2018; Fransson et al., 2002; Kovacs et al., 2013). In a similar manner, leaf-fall in deciduous forests also leads to an increase in backscatter (Frison et al., 2018; Rüetschi et al., 2018). We found higher sensitivity to the VH (cross-polarized) band that is more sensitive to volume scattering, compared to the VV (co-polarised) band that is more sensitive to surface scattering, further suggesting the storm mainly caused loss of leaves and limited mortality of live trees. Where storms cause substantial tree mortality, the co-polarized HH and VV bands are more affected (Wang et al., 2010), due to a decrease in surface scattering (VV band) and an increase in double-bounce scattering (HH) caused by reflection between the ground and fallen tree trunks.

We find that both VH and VV bands return to pre-storm values within 5 months (S. Fig. 1), consistent with storm-caused defoliation rather than mortality and suggesting that the impacts of storms may be relatively short lived and may not be measurable in future censuses. Similar to our study, Tanner et al. (2014) also reported lower diameter growth rates in forests damaged by a hurricane in Jamaica. Hall et al. (2020) found that the change in non-photosynthetic vegetation observed by S-2 was related to the proportion of AGC lost due to the storm.

Typhoon Doksuri damaged 29-39% of our study area (approximately 200,000 ha of forest) similar to the area damaged in Puerto Rico by Hurricanes María and Irma (290,000 ha) (Hall et al., 2020). In forests with detectable storm damage, the reduction in carbon storage was estimated as 2.3 Mg C ha^{-1} y^{-1}, similar to the reduction we measured in our forest plots (2.9 Mg C ha^{-1} y^{-1}). Across our study area, we estimate the storm reduced carbon uptake of natural forests (across both damaged and undamaged forests) by 0.85 Mg C ha^{-1} y^{-1}, equivalent to a reduction in carbon uptake of 0.6 Tg C over a two-year period. Future measurements of biomass carbon storage are needed to assess any longer term impacts of storm damage.

Storm damage typically decreases with distance from the cyclone track (Zhang et al., 2013) with damage observed at distances of up to 120 km for a cyclone in Australia (Turton, 2008). Our forest plots are all located ~150 km from the cyclone track, where damage was smaller than in areas closer to the track. However, 93% of the 0.6 Tg reduction in carbon uptake across our study area was a result of minor storm damage, defined as a ΔNBR of between -0.05 and -0.25, which is well captured by our forest plot data (moderate and severe storm damage only caused 7% of the total reduction in carbon uptake).

Other tropical storms have resulted in a larger reduction in carbon storage compared to Doksuri. Hall et al. (2020) estimated that a hurricane in Puerto Rico reduced AGC storage by 10.4±2.3 Tg C equivalent to 30 Mg C ha^{-1} or 23% of pre-storm stocks over 312,000 ha of forest. A tropical cyclone in southern China resulted in biomass losses equivalent to 12.2 Mg C ha^{-1} (Ni et al., 2021). A single squall line reduced Amazon forest AGC storage by 140 Tg C due to minor damage (0.3 MgC ha^{-1}) over a very large area (4.5×10^6 km^2) of forest (Negrón-

Juárez et al., 2010). Hurricane Katrina resulted in one of the largest impacts on forest carbon, reducing storage across forests of the southern United States by 105 Tg C (Chambers et al., 2007). Further work is required to understand why forest damage is so variable and how it depends on storm intensity and forest type.

Plantations

Plantations, largely monocultures consisting of acacia or rubber, now cover more than 4 million hectares of Vietnam (Nambiar et al., 2021), 25% of total forest area. In Vietnam, plantations have successfully contributed to increased canopy cover at the regional and national scale (Nambiar et al., 2021), in contrast to Northern India where canopy cover has not increased despite large tree planting schemes (Coleman et al., 2021).

We found plantations were more susceptible to storm damage compared to natural forests. In our analysis, the majority of plantations that exhibited storm damage in remote sensed images were harvested shortly after the storm, suggesting there was an immediate need to salvage the timber. Plantation surveys conducted directly after a storm and before any salvage logging occur are required to verify damage detected by remote sensing. In many situations, storm damage and tree mortality increases with elevation, due to stronger winds and thinner soils that occur in the mountains (Mitchell, 2013). In contrast, we found forest damage decreased with elevation, likely due to the decline in cyclone intensity with distance inland and higher elevations being further from the coast (Lu et al., 2020). Tree plantations in Vietnam are mostly located at lower elevations, placing them at substantial risk to storm damage. We found minimal difference in storm damage between windward and leeward slopes, likely due to frequent directions in wind direction that can occur in a tropical cyclone (Li et al., 2013). This means that locating plantations on slopes facing away from the ocean and the predominant direction of storm tracks is unlikely to provide much protection (Lu et al., 2020).

Implications for restoration

We show that degraded natural forests recovering from logging are an important carbon sink even over a period when they are impacted by a major tropical cyclone. Unlicensed logging, which is pervasive across natural forests of North-Central Vietnam leads to much larger carbon losses, estimated as 60 Mg C ha^{-1} over the 40 year return period of a major tropical cyclone (Ngo et al., 2020). Logging of natural forests across Central Vietnam has even caused a reduction in carbon stocks over the 2005 to 2015 period (Paudyal et al., 2020), highlighting the need to find sustainable solutions to reduce unlicensed logging.

Monoculture acacia plantations have expanded in Vietnam in recent decades, sometimes at the expense of natural forests (Spracklen and Spracklen, 2021). Plantations are needed to provide timber, but they typically store less carbon (Lewis et al., 2019; Hua et al., 2022) and deliver less environmental services such as sediment retention, soil erosion control and biodiversity provision compared to natural forests (Paudyal et al., 2020; Wang et al., 2021; Hua et al., 2022). Our analysis demonstrates that acacia plantations are also more likely to experience storm damage compared to natural forests. This provides additional motivation to prevent conversion of natural forests to plantation and prioritise restoration of degraded natural forests in cyclone-prone areas of the tropics. Natural forests of ‘poor quality’, defined in Vietnam as forests with timber volumes of less than 100 m^3 ha^{-1}, are often considered to be low value and consequently are preferentially converted to plantations (FCPF, 2018; FCPF, 2021). A greater recognition of the substantial potential of ‘poor quality’ forests for carbon removal, resilience from storm damage and other ecosystem services is needed.

Operating plantations over longer rotations would produce higher quality timber and increase financial returns (Maraseni et al., 2017) as well as increasing the carbon storage and sequestration potential (Sang et al., 2012), but would further increase risk of typhoon damage (Zhunusova et al., 2019). Mixed or native species plantations may be more resilient to storms and other disturbances (Jactel et al., 2017; Crowther et al., 2020) and should be investigated. Plantations can contribute to local livelihoods (Malkamäki et al., 2018; Van Khuc et al., 2020) and may reduce pressure on natural forests, but these benefits need to be better understood.

Vietnam has committed to reduce further loss and degradation of natural forests and restore large areas of degraded natural forest (Law on Forestry, 2017). The Forest Carbon Partnership Facility (FCPF) Carbon Fund, which covers the North Central Coast region of Vietnam, aims to achieve emission reductions through reducing unlicensed logging and restoring degraded natural forests (FCPF, 2018). Achieving this will require stronger forest governance and law enforcement combined with development of sustainable livelihoods for forest dependent communities (FCPF 2018; 2021). Remote sensed methods of detecting unplanned selective logging and conversion of natural forest to plantation (Spracklen and Spracklen, 2021) are needed to improve enforcement and to monitor the success of these new policies and interventions.

Policy makers need to consider trade-offs between the wood production from plantations versus the greater environmental services (Hua et al., 2022) and climate resilience provided by degraded natural forests. Careful forest planning is needed to identify where new plantations can be developed without further loss of degraded natural forest or high quality agricultural land.

Conclusion

We studied the impact of a major tropical cyclone on natural forests recovering from logging in Vietnam. Government-licenced logging ceased 9-12 years before our study. Forest plots were surveyed before and after the storm with two years between measurements. We used 10-m wind speeds to estimate the storm had a return period of 40 years. Despite being impacted by this storm, degraded natural forests remained a small biomass carbon sink of 0.1 Mg C ha^{-1} y^{-1}. Net changes in aboveground biomass did not differ with historical logging intensity but were negatively related to cyclone damage. Natural forests with minimal storm damage increased biomass carbon storage by 1.3 ± 1.1 Mg C ha^{-1} y^{-1} compared to a 1.7 ± 1.1 Mg C ha^{-1} y^{-1} reduction in carbon storage in more damaged forest plots. On average, the cyclone slowed recovery of natural forests by 0.85 Mg C ha^{-1} y^{-1} over the two-year measurement period, resulting in a reduction in carbon sink of 0.6 Tg C across our study area. The reduction in carbon sink was largely down to reduced growth rates, which our remote sensed analysis suggests may be due to defoliation. The reduction in carbon sink due to this major tropical cyclone is less than the carbon loss due to pervasive illegal logging which is the major driver slowing recovery of carbon stocks in logged forests of North-Central Vietnam. Even though plantations are managed on very short rotations in an attempt to reduce storm damage, they were almost twice as likely as natural forests to suffer cyclone damage. Our results indicate that large tropical cyclones slow the recovery of above-ground biomass in logged natural forests, but that natural forests in Vietnam are remarkably resilient to storm damage. Preventing further conversion of degraded natural forests to plantation and reduction of illegal logging in degraded natural forests is needed to facilitate forest restoration in Vietnam.

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Tables

Table 1. Above-ground carbon (AGC) fluxes for each logging and storm class. Values represent the mean ± standard deviation calculated from forest inventory plots for stems ≥5 cm diameter at breast height (dbh). Differences between classes were tested using ANOVA or, when distributions within groups were not normally distributed, the Kruskal-Wallis rank sum test, with significant p-values annotated by *.

AGC fluxes	Logging intensity			p	Storm Damage intensity			p
	Light	Medium	Heavy		Light	Medium	Heavy	
AGC net change (Mg C ha^{-1} y^{-1})	-0.5 ± 2.3	0.2 ± 1.6	0.6 ± 1.2	0.434	1.3 ± 1.1	0.2 ± 1.7	-1.7 ± 1.4	0.007*
AGC dbh growth (Mg C ha^{-1} y^{-1})	1.4 ± 1.4	1.2 ± 1.6	1.5 ± 0.7	0.968	2.4 ± 0.2	1.1 ± 1.1	0.5 ± 1.6	0.033*
AGC recruitment (Mg C ha^{-1} y^{-1})	0.2 ± 0.2	0.2 ± 0.1	0.2 ± 0.1	0.265	0.1 ± 0.1	0.1 ± 0.1	0.3 ± 0.2	0.048*
AGC mortality (Mg C ha^{-1} y^{-1})	-2.1 ± 1.9	-1.3 ± 0.8	-1.1 ± 1.0	0.330	-1.2 ± 1.0	-1.0 ± 0.8	-2.5 ± 2.4	0.300

Table 2. Area of natural forest and plantation damaged by the cyclone. Results are shown for cloud-free from Sentinel-1 (S-1) and Sentinel-2 (S-2) and total study area for S-1. The percentage of natural forest, plantation and total area that experienced cyclone damage is indicated in brackets.

	Study area (cloud-free)				Total study area			
S-1	Area (ha)		Damaged area (ha)		Area (ha)		Damaged area (ha)	
	502,174		143,546 (28%)		719,228		185,831 (26%)	
	Natural	Plantation	Natural	Plantation	Natural	Plantation	Natural	Plantation
	355,829	146,345	93,242 (26%)	50,304 (34%)	554,721	164,507	129,695 (23%)	56,136 (34%)
S-2	Area (ha)		Damaged area (ha)		Area (ha)		Damaged area (ha)	
	502,174		196,893 (39%)		----		----	
	Natural	Plantation	Natural	Plantation	Natural	Plantation	Natural	Plantation
	355,829	146,345	130,227 (37%)	66,666 (46%)	----	----	----	----

Table 3. Odds ratios for variables affecting chances of typhoon damage for natural forest, plantation and natural forest and plantation combined based on analysis of Sentinel-2 data. All results significant ($p < 0.001$).

	Elevation (100 m)	Aspect (10^o)	Distance to storm track (10 km)	Plantation
Natural forest	0.838	0.984	0.878	-----
Plantation	0.832	0.988	0.933	-----
Combined	0.836	0.985	0.892	1.830

Figures

Figure 1. Study area (boundary indicated with orange line) and path of Doksuri typhoon (blue line). Elevation ranges from green (0 m) to white (1500 m).

Figure 2. Frequency and return period of tropical cyclone in Vietnam **a)** Frequency of tropical cyclones shown according to latitude and by month of year. b) Return period of tropical cyclones calculated based on 10-m wind speeds (m s^{-1}). Typhoon Doksuri is indicated. Dashed lines indicate 5^{th} and 95^{th} percentile uncertainty range.

Figure 3. Carbon fluxes for forest plots experiencing light (L), moderate (M) and heavy (H) storm damage as identified by analysis of S-2 ΔNBR.

Figure 4. Mean ΔNBR from Sentinel-2 imagery plotted against the net change in above ground carbon (ΔC_C) from the forest plots. Results from the linear regression are shown, with a solid line showing line of best fit, shaded area showing 95% confidence limits for the slope and dotted lines showing 95% prediction limits.

Figure 5. Identification of storm damage based on Sentinel-2 (S-2) and Sentinel-1 (S-1) data. The mean change in normalised burn ratio (ΔNBR) from S-2 is plotted against (a) mean ΔVH and (b) ΔVV from S-1 for 800 randomly selected forest locations across the study area, manually classified by storm damage (no/light, moderate and severe damage). ΔNBR, ΔVH and ΔVV are calculated as post-storm minus pre-storm values. Results from the linear regression are shown, with a solid line showing line of best fit, shaded area showing 95% confidence limits for the slope and dotted lines showing 95% prediction limits.

Figure 6. Map of forest damage across study area caused by Typhoon Doksuri for (a) Sentinel-2 and (b) Sentinel-1 imagery. Little or no damage (green) is classified as ΔNBR > -0.05 (S-2) or ΔVH < 0.019 (S-1). Hatched areas indicate non-forest areas or for (a) areas of cloud cover on date of post-typhoon S-2 image for which no assessment of damage was possible.

Additional Information

Data Accessibility

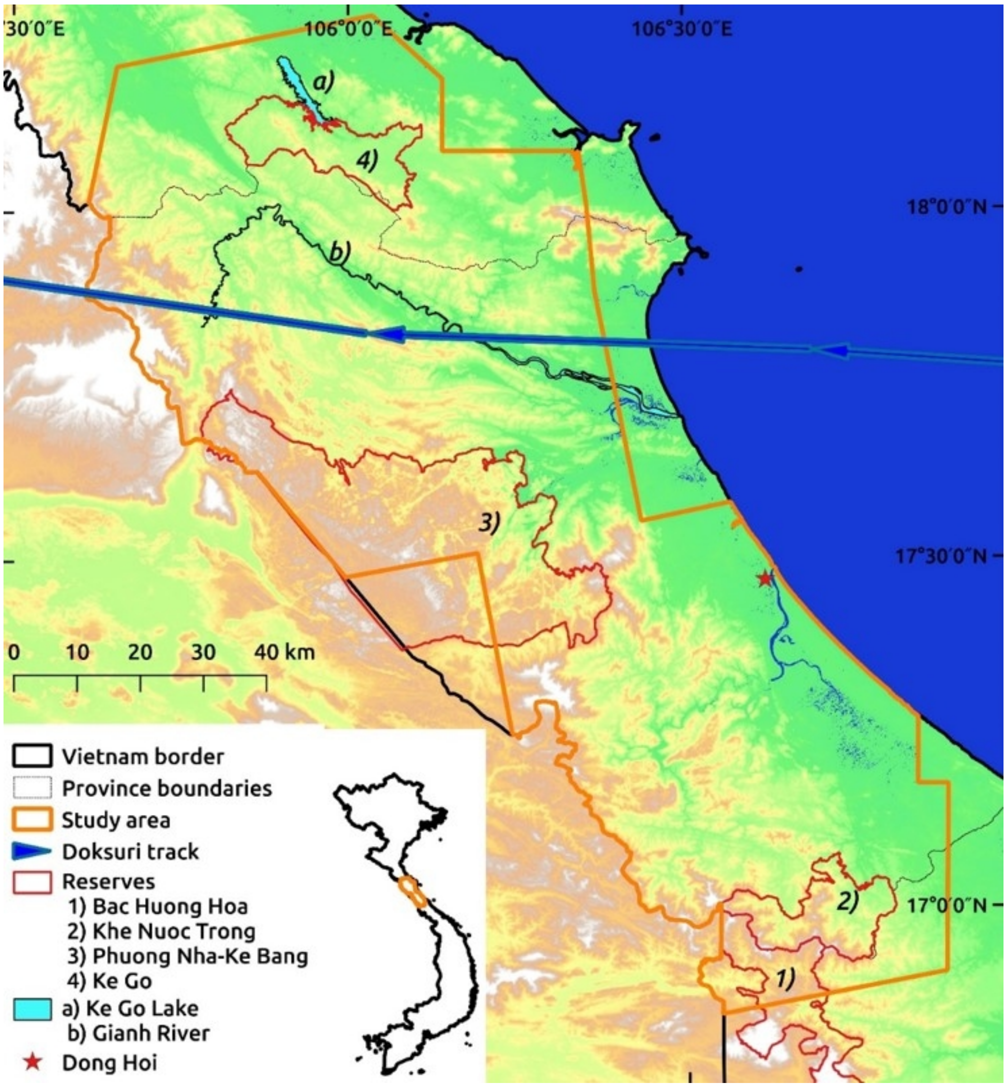
Data from forest plots is archived at https://www.forestplots.net/. Sentinel data is available from https://scihub.copernicus.eu/. ECMWF data is available from https://www.ecmwf.int/en/forecasts.

Authors' Contributions

Study design was led by SMS, BDS, MK, EJ, OLP and DVS. SMS, BDS, PDW led the data analysis. TCL, HDT, TTL, DTN, HTL and AVL contributed to data collection and analysis. All authors discussed data interpretation and contributed to drafting the submitted manuscript.

Competing Interests

We have no competing interests.



Study area (boundary indicated with orange line) and path of Doksuri typhoon (blue line). Elevation ranges from green (0 m) to white (1500 m).

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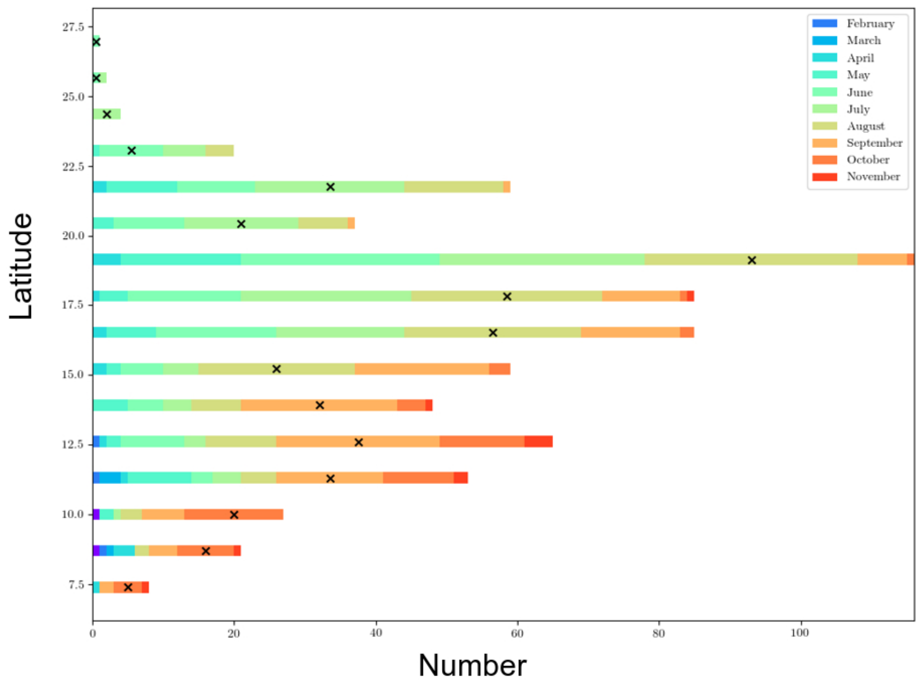
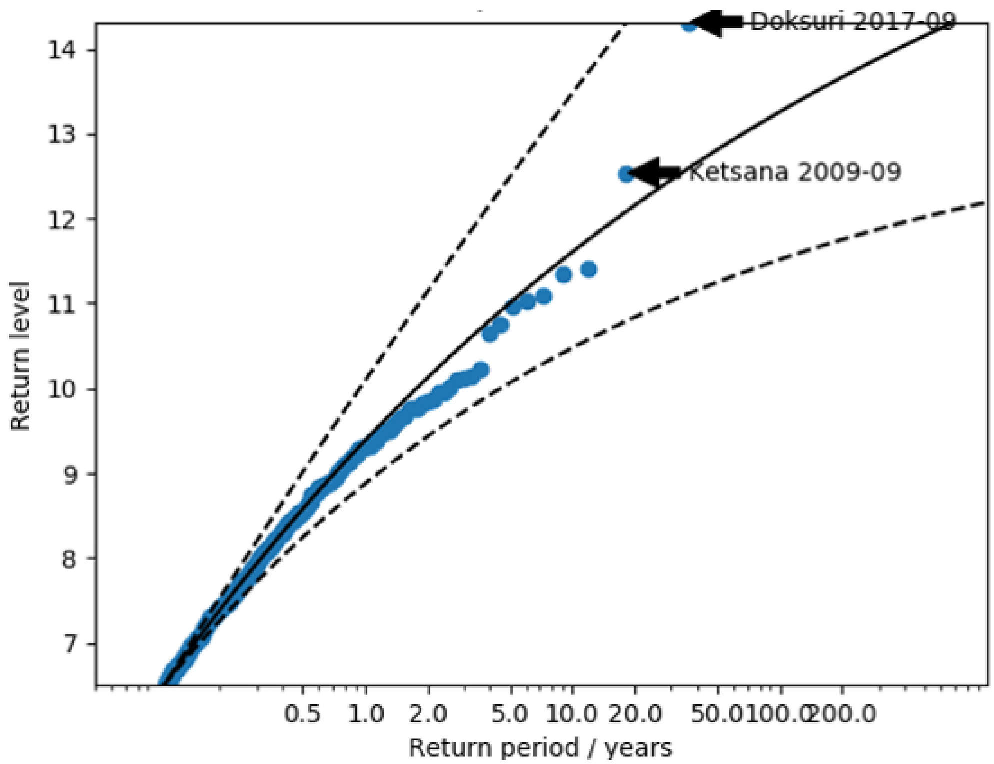


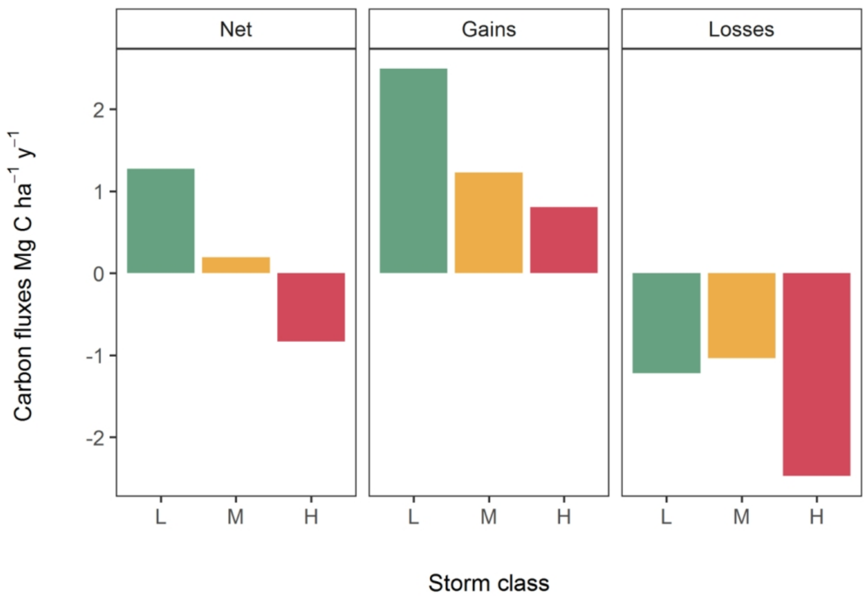
Frequency and return period of tropical cyclone in Vietnam a) Frequency of tropical cyclones shown according to latitude and by month of year. b) Return period of tropical cyclones calculated based on 10-m wind speeds (m s-1). Typhoon Doksuri is indicated. Dashed lines indicate 5th and 95th percentile uncertainty range.

351x272mm (72 x 72 DPI)



Frequency and return period of tropical cyclone in Vietnam a) Frequency of tropical cyclones shown according to latitude and by month of year. b) Return period of tropical cyclones calculated based on 10-m wind speeds (m s-1). Typhoon Doksuri is indicated. Dashed lines indicate 5th and 95th percentile uncertainty range.

381x286mm (37 x 37 DPI)



Carbon fluxes for forest plots experiencing light (L), moderate (M) and heavy (H) storm damage as identified by analysis of S-2 ΔNBR.

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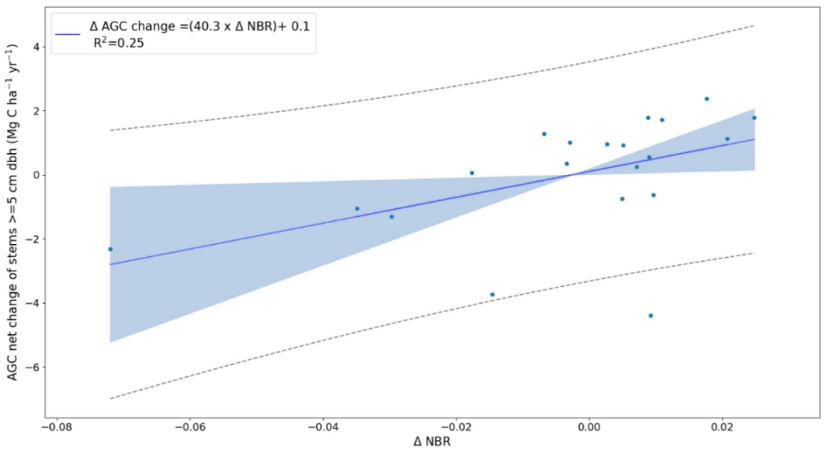
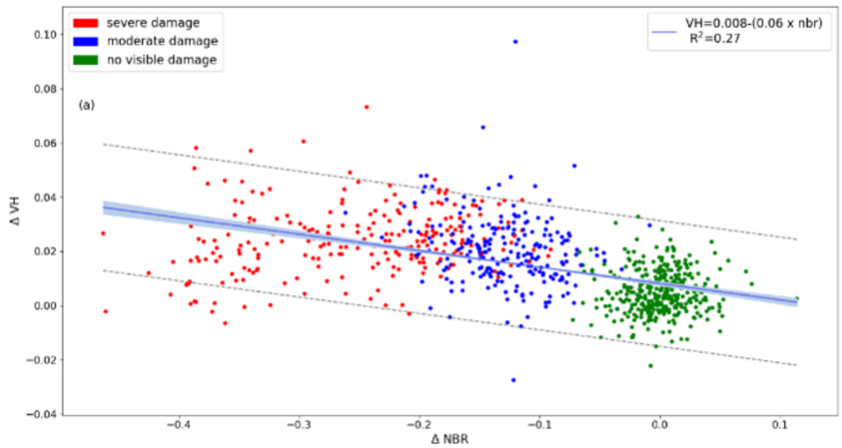


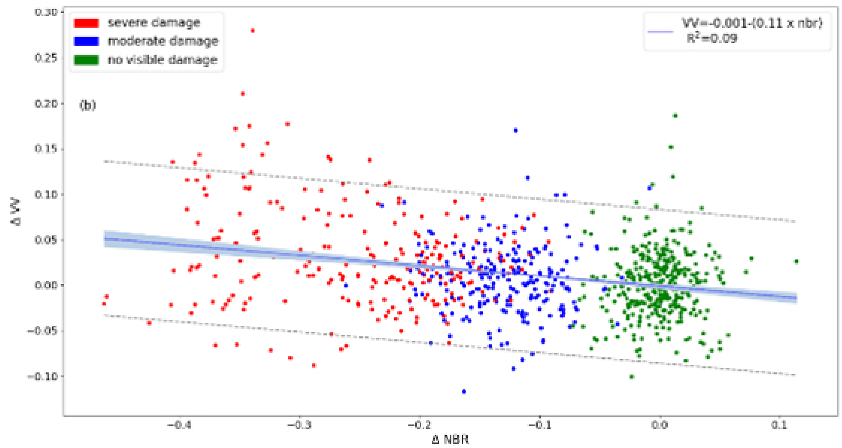
Mean ΔNBR from Sentinel-2 imagery plotted against the net change in above ground carbon (ΔCC) from the forest plots. Results from the linear regression are shown, with a solid line showing line of best fit, shaded area showing 95% confidence limits for the slope and dotted lines showing 95% prediction limits.

811x423mm (43 x 44 DPI)



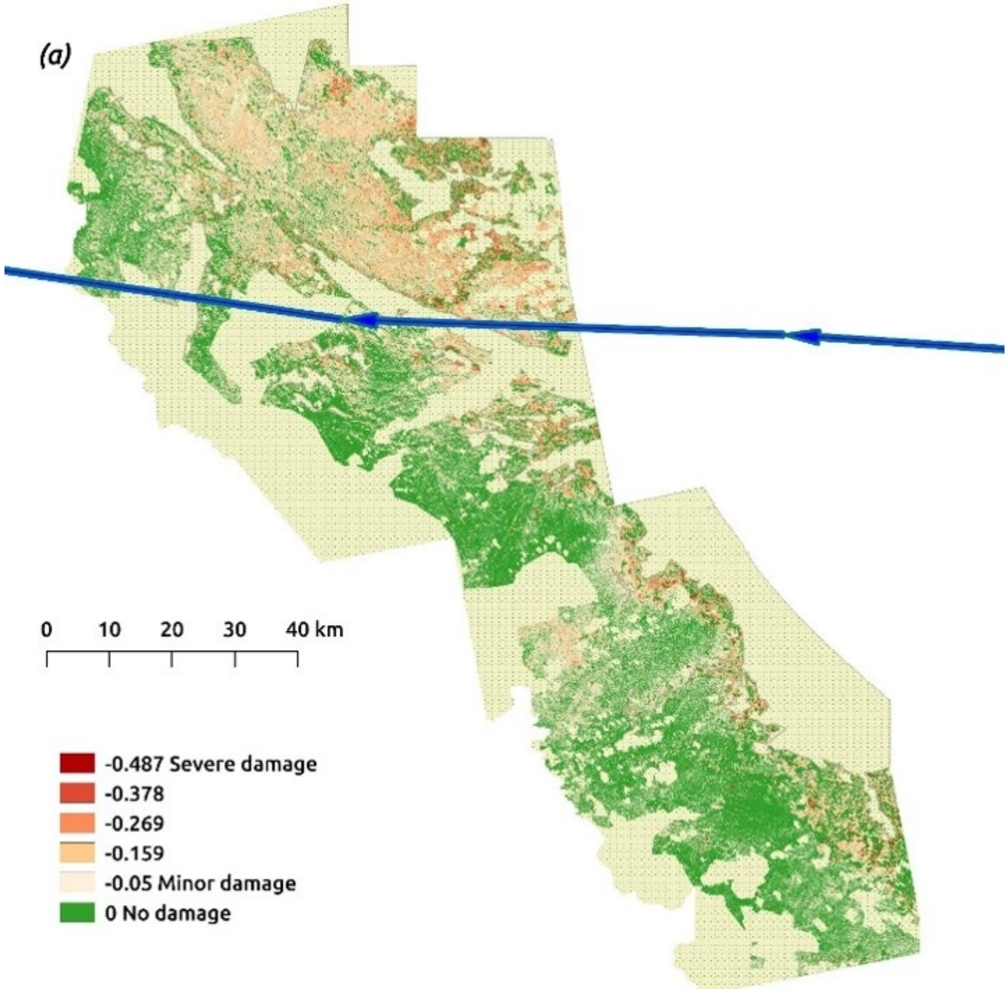
Identification of storm damage based on Sentinel-2 (S-2) and Sentinel-1 (S-1) data. The mean change in normalised burn ratio (ΔNBR) from S-2 is plotted against (a) mean ΔVH and (b) ΔVV from S-1 for 800 randomly selected forest locations across the study area, manually classified by storm damage (no/light, moderate and severe damage). ΔNBR, ΔVH and ΔVV are calculated as post-storm minus pre-storm values. Results from the linear regression are shown, with a solid line showing line of best fit, shaded area showing 95% confidence limits for the slope and dotted lines showing 95% prediction limits.

452x240mm (45 x 45 DPI)



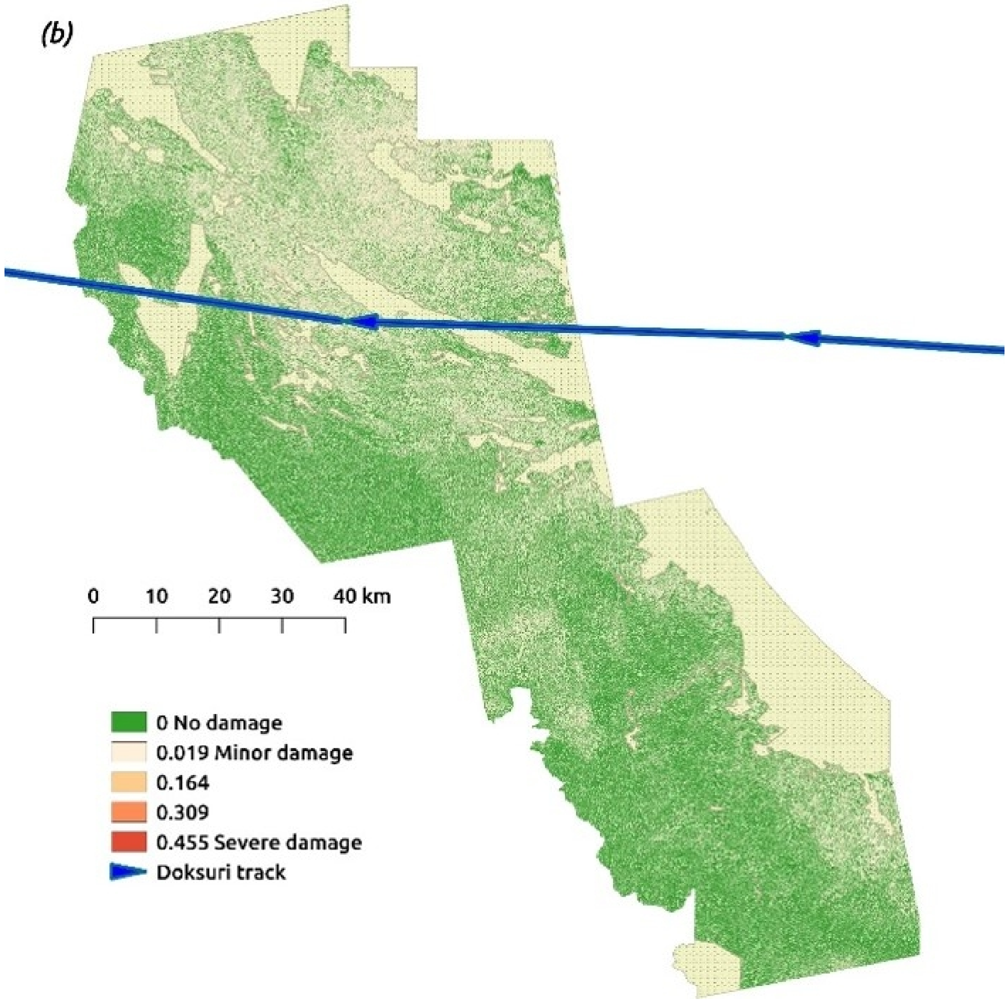
Identification of storm damage based on Sentinel-2 (S-2) and Sentinel-1 (S-1) data. The mean change in normalised burn ratio (ΔNBR) from S-2 is plotted against (a) mean ΔVH and (b) ΔVV from S-1 for 800 randomly selected forest locations across the study area, manually classified by storm damage (no/light, moderate and severe damage). ΔNBR, ΔVH and ΔVV are calculated as post-storm minus pre-storm values. Results from the linear regression are shown, with a solid line showing line of best fit, shaded area showing 95% confidence limits for the slope and dotted lines showing 95% prediction limits.

458x243mm (37 x 37 DPI)



Map of forest damage across study area caused by Typhoon Doksuri for (a) Sentinel-2 and (b) Sentinel-1 imagery. Little or no damage (green) is classified as ΔNBR > -0.05 (S-2) or ΔVH < 0.019 (S-1). Hatched areas indicate non-forest areas or for (a) areas of cloud cover on date of post-typhoon S-2 image for which no assessment of damage was possible.

162x162mm (112 x 112 DPI)



Map of forest damage across study area caused by Typhoon Doksuri for (a) Sentinel-2 and (b) Sentinel-1 imagery. Little or no damage (green) is classified as ΔNBR > -0.05 (S-2) or ΔVH < 0.019 (S-1). Hatched areas indicate non-forest areas or for (a) areas of cloud cover on date of post-typhoon S-2 image for which no assessment of damage was possible.

162x163mm (110 x 110 DPI)