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Impact assessment of a super-typhoon on Hong Kong's secondary vegetation and recommendations for restoration of resilience in the forest succession

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ABSTRACT

Typhoons of varying intensities severely impact ecosystem functioning in tropical regions and their increasing frequencies and intensities due to global warming pose new challenges for effective forest restoration. This study examines the impact of a super-typhoon (Mangkhut) on the regenerating native secondary forest and exotic monocultural plantations in the degraded tropical landscape of Hong Kong. The super typhoon, which hit Hong Kong on 16 September 2018 lasted for 10 h (09:40–19:40) and was the most severe storm affecting Hong Kong over the past 100 years. Hong Kong's secondary forest is a mosaic of forest patches recovering through natural succession since 1945, and plantation stands of exotic monocultural species. We determine the loss in biomass by performing NDVI (Normalized Difference Vegetation Index) difference analysis using two Landsat-8 multi-spectral images acquired before and after the typhoon. This the assessment of typhoon impacts according to successional age group, structural stages of vegetation, landscape topography, and on stands of exotic plantations. Results indicate that hilltops, open shrubland and grassland were hard hit, especially on southwest and southeast facing slopes, and almost 90% of the landscape showed abnormal change. Patches of exotic monoculture plantation (*Lophostemon confertus, Melaleuca quinquenervia, and Acacia confusa*) were the most severely damaged by the typhoon, showing more than 25% decrease in NDVI, followed by young secondary forest. Field observations confirmed that in exotic plantations, almost the entire canopy was destroyed and there is no generation of young under story trees to replace those lost. The affected young forests and shrublands are mainly dominated by fast growing, soft wooded early successional species such as *Mallotus paniculatus or Machilus chekiangensis* as well as weak, multi-trunked, fungus infected, or other structurally deficient trees, which were uprooted or seriously damaged by typhoon gusts. The net effect of typhoons in Hong Kong's degraded landscape, appears to reinforce the arrested succession of dense, less diverse stands of weaker early successional species due to the absence of late and middle successional species and native dispersal agents. In order to obtain a stronger, more resilient forest, it would be necessary to enhance biodiversity by artificially planting a species mix, which resembles primary forests in the region. This could be achieved by thinning of young secondary forest followed by enhancement planting of pockets of high diversity forest.

1. Introduction

1.1. Background

Typhoons are tropical storms with wind speeds greater than or equal to 33 m/s (Elms and Neumann, 1993). They are usually accompanied by torrential rain, severe inundation and extreme wind speeds, causing damage to both human and natural structures, and may affect ecological processes in tropical forests (Mcdowell, 2001). The magnitude of ecological damage from a typhoon is associated with wind speed, prevailing wind direction, topographic position in the landscape and successional structure of vegetation (Lee et al., 2008).

Strong winds can cause uprooting of trees, snagging of tree boles and breaking of branches, significantly reducing the green biomass in the landscape (Lin et al., 2011). Defoliation and reduction in leaf area are also among the significant impacts of typhoons on vegetation. The

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decrease in leaf area and opening of the canopy can directly influence fauna and flora living under the canopy, as the alteration of ambient light may not be suitable, especially for shade-loving species. Moreover, torrential rainfall associated with strong winds can wash away seedlings, thus impeding forest recovery in regenerating tropical landscapes (Wang et al., 2008).

Typhoons of varying intensities regularly pass over Hong Kong bringing strong wind gusts and torrential rainfall. These threaten the recovering secondary forest by washing away seedlings and uprooting or breaking mature trees in patches (Corlett, 1999). Accurate and rapid mapping of the impacts of extreme climate events on forests can facilitate our understanding of restoration ecology. The types and spatial distribution of damage sustained and interruptions to forest succession following such impacts can indicate impediments to biomass accumulation and species recruitment. This is especially true in many of today's disturbed landscapes where decades or centuries of deforestation have resulted in severe soil erosion and loss of species pool. Satellite remote sensing, with its regular broad-scale coverage gives opportunity to monitor such changes by comparing images acquired before and after an event.

The tropical cyclone warning system was implemented in Hong Kong after the establishment of the Hong Kong Observatory in 1883. Twelve super-typhoons have hit Hong Kong since records began in 1946, but only two since Ellen in 1983, namely Hato in 2017 and Mangkhut in 2018. Super-typhoon Mangkhut which hit Hong Kong on 16 September 2018 was the most severe storm to ever hit Hong Kong. It lasted for 10 h (09:40–19:40) and was the second longest after typhoon York in 1999 which lasted 11 h. The maximum sustained wind near the centre was recorded at 250 km/h, with maximum gust peak speed at 256 km/h in an ENE direction. The maximum 60-min mean wind speeds recorded were 166 Km/h at Tates Cairn in Ma On Shan Country Park (HKO, 2018).

1.2. Impacts of disturbances on forest succession

Generally, tropical forest ecosystems support high species diversity even though soils have low fertility due to high rates of chemical leaching and high temperatures (Huston, 1980; Peña-Claros et al., 2012; Tilman et al., 1996). This is because all the nutrients are stored in the biomass of the vegetation causing high nutrient turnover rates. Once the primary vegetation is cleared all the nutrients are lost, and recovering vegetation has to re-establish the nutrient cycle on poor soils, which often is very slow and sometimes impossible (Huston, 1979). The limited amounts of nutrients available for recovering vegetation after clear cuts cause a significant resource competition among early successional species which weakens all trees and makes them susceptible to disturbances such as typhoons. In any case, competition between species is driving succession, whereby early successional species are replaced by mid-successional species with stronger roots and stems which can better resist external impacts. This increase in biodiversity and stem size is accompanied by a process of forest thinning and stem exclusion, and may take decades to centuries depending on tree life expectancies (Ashton et al., 2001), as well as the available species pool. In areas with too impoverished soils and/or which lack a source of mid-successional species, this process may never occur. The succession would be arrested at an early stage, where large numbers of weak stems compete, resulting in deficiencies such as multi-trunking (Crausbay and Martin, 2016), fungus infections, or other structurally deficiencies, thus causing greater susceptibility to damage by typhoon gusts

Therefore suggestions that intermediate disturbances such as typhoons, can increase species richness by facilitating the recruitment of early-successional and light-demanding species, (Bellingham et al., 2018; Crausbay and Martin, 2016; Tanner and Bellingham, 2006) may not apply in today's highly disturbed landscapes. The succession is often arrested at this stage following disturbance, due to unavailability of mid- and late-successional species (Ashton et al., 2001; Hubbell et al., 1999), resulting in persistence of dense, less diverse stands of weaker early successional species (Lawton and Lawton, 2010). As this type of species restriction is typical of Hong Kong's forests, disturbances to these successions may be supposed to have greater impacts. This fact is well illustrated by a severe frost event in 2016, which caused severe damage to Hong Kong's forests (Abbas et al., 2017). The exotic species and especially monoculture plantations showed to be more susceptible to frost because they are not as adapted to these events, as native species would be. Monocultural stands are also susceptible to disease, as illustrated by complete destruction of Hong Kong's plantations of a native species *Pinus massoniana* by a nematode during the 1970s (Abbas et al., 2016). On the other hand, areas not under plantation had succeeded naturally to young secondary forest. Lee et al. (2008) also emphasized the greater adaptability of native forest in central Taiwan to natural disturbances, as the native species have evolved under the prevailing local climate conditions including extreme events such as super-typhoons.

Tropical forest succession is generally thought to be accompanied by decreased fire risk after a few years, and in normal conditions it is very rare for forests and woodlands to catch fire (Chau, 1994; Herawati and Sentoso, 2011). However, in Hong Kong, forest fires initiated in nearby grasslands are common in the dry season, and have been recognized as the main impediment to structural succession from grassland to shrubland and forest (Dudgeon and Corlett, 2011; Lee et al., 2005). Such fires within the secondary forests would be enhanced by the large amounts of woody debris left after a typhoon.

Since the typhoon of September 2018 was intense and of much longer duration than any typhoon event recorded over the last 100 years, the current study documents its impacts on Hong Kong's vegetation at landscape level. Implications for enhancing the resilience of the regenerating forest are presented, based on observations of typhoon impacts on the forest successional age classes, structure and species composition over the landscape.

2. Materials and methods

2.1. Study site

Hong Kong is a special administrative region of Mainland China, located on the eastern shore of the Pearl River Estuary, having an area of ~ 1100 km^2. It shares a border to the north with Guangdong province of China and is surrounded by the South China Sea on east, west and south. Hong Kong is situated between 22° 09′ and 23° 37′ latitudes and 113°52′ and 114°30′ longitudes on the northern margins of Asian tropics (Fig. 1). The study area comprises the Tai Mo Shan and Shing

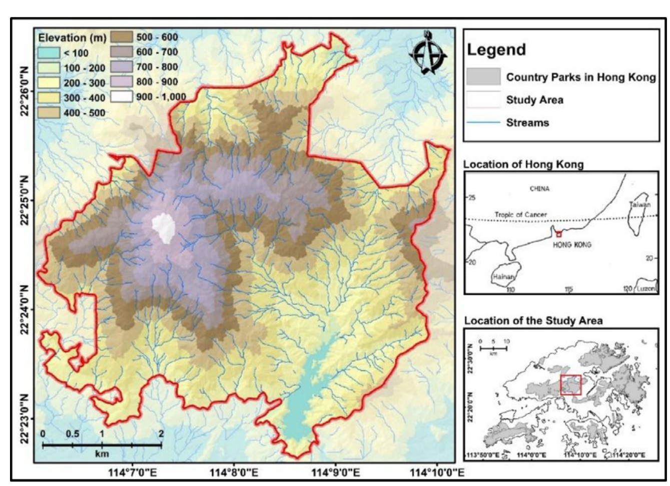

Fig. 1. Location and topography of the Study area.

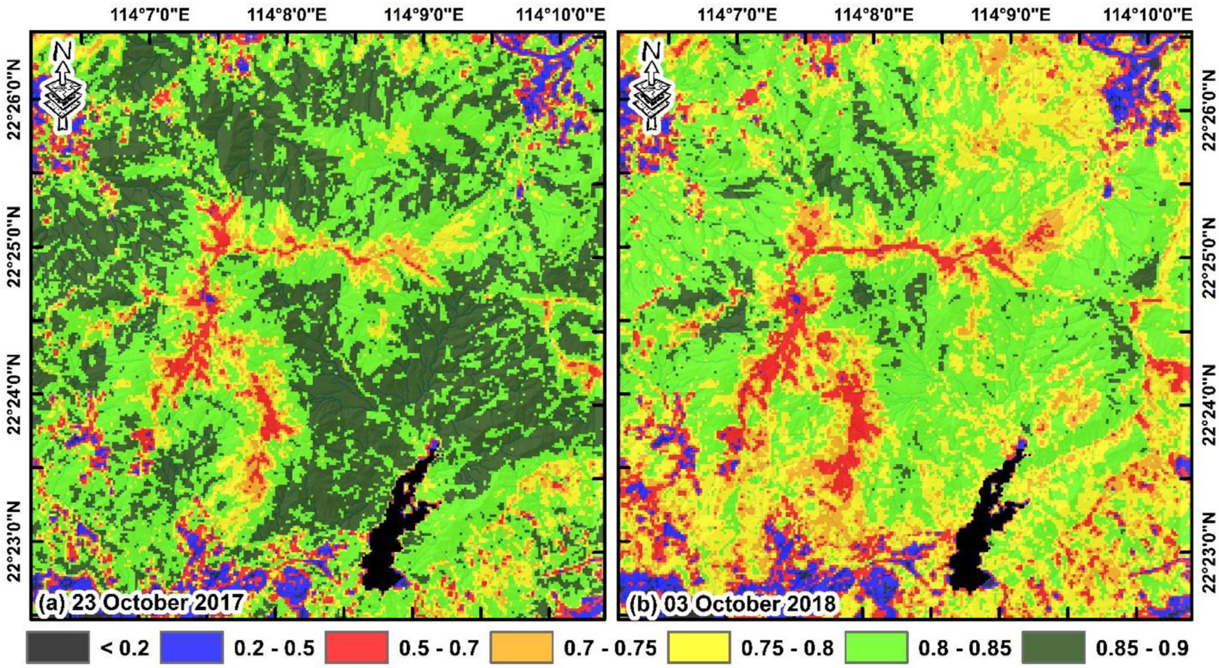

Fig. 2. NDVI images of the study area acquired on 23rd October 2017 (a - control image) and 3rd October 2018 (b - post-typhoon image).

Mun country parks in New Territories of Hong Kong (Fig. 1). The topography of the area is rugged characterized by convex slopes rising to the tallest peak (957 m) Tai Mo Shan and steep-sided slopes around Shing Mun reservoir. Upper valleys are covered with fire-maintained grasses and lower elevations are covered with patches of secondary forest and plantations (Delang and Hang, 2009), which have regenerated since WW2 following clearance thousands of years ago for farming, accompanied by massive soil erosion (Dudgeon and Corlett, 2011). Only a few small patches of old forest remain, and the regenerating forests are nothing like Hong Kong's original forests (Abbas et al., 2016). Temperature falls below zero above 400 m elevation several times in a decade, and rainfall increases with elevation (Dudgeon and Corlett, 2011; Weir and Corlett, 2006). The Hong Kong region is generally a low wind environment except during typhoon events which occur mainly in the late summer rainy season.

2.2. Data used

2.2.1. Typhoon meteorological data

Typhoon Mangkhut originated over the western North Pacific, made a landfall on Luzon (Philippines) and continued across the South China Sea towards the coast of Guangdong (China). It became a severe Typhoon in the morning of 16 September 2018, making landfall 100 km south-southwest of Hong Kong in the afternoon. The typhoon's wind speed, gust and direction data, obtained from the Hong Kong Observatory were recorded every minute and acquired for the three days – 15th September (the day prior to the typhoon), 16th September (typhoon day) and 17th September (the day after the typhoon). The data obtained were primarily from the Tai Mo Shan station, which is the highest weather station in Hong Kong and located in the study area. As the data recording at the Tai Mo Shan station failed after 4:52 pm on the day of the typhoon, data from nearby Lau Fau Shan station were also used. Typhoon Mangkhut brought about 383.3 mm of rain, about 17 percent above the average monthly total of 327.6 mm. The overall rainfall for the first nine months of 2018 was 12% lower than normal, with 1973.3 mm, compared to 2233.1 mm average. September 2018 was also 0.3 °C. above the normal of 27.7°. It is also notable that the 15th September 2018, was the hottest day of the month, at 35.1 °C, and second highest ever recorded for the month (HKO, 2018)

2.3. Remote sensing data

To evaluate the severity and spatial patterns of Mangkhut's impacts on the natural secondary forest and exotic plantations in the study area, two Landsat 8 images with a spatial resolution of 30 m were acquired, for a before and after comparison. These were on-demand terrain corrected surface reflectance images from the Earth Explorer (http://earthexplorer.usgs.gov/). which are application-ready products to support monitoring and assessment of land cover change (Vermote et al., 2016). The post-typhoon image was acquired on 3rd October 2018, 16 days after the event and the control image was acquired on 23rd October 2017. Both images are cloud-free and with less than one month difference in calendar dates, hence minimizing phenological differences. Furthermore, a general phenology curve of vegetation types in the study area indicates a decline in greenness from early October to late October, which would further reduce the bias due to any phenological change.

2.3.1. Land cover and successional age classes of forest

A detailed map of vegetation structural classes. was prepared in a previous study (Abbas et al., 2016) by using a multi-scale object-based approach with three dates of aerial photographs (1945, 1963 and 1989) and two high-resolution satellite images (2001 and 2014). Six different vegetation structural classes (Forest, Open Forest, Shrubland, Open shrubland, Grassland and Plantation) were extracted from the most recent land cover map of 2014. From this, another layer of forest age classes was produced by sequential overlapping of the 5 land cover maps. The median age of the forest patches on each layer (7, 20, 39, 61 and 70 years) was estimated based on the time since recovery, (0–14], (14–26], (26–52], (52–70] and >70yrs, respectively (Fig. 2-c).

2.3.2. Topographic variables

Habitat patterns in mountainous terrain are influenced by the regional climate coupled with micro-climatic conditions induced by topographic factors (Leempoel et al., 2015). Therefore, a very high resolution (2 m) Digital Elevation Model (DEM) was obtained from the Lands Department of Hong Kong, to determine the damage done by the typhoon according to the topography of the study area. Three distinct topographic characteristics, namely elevation, aspect, and landforms

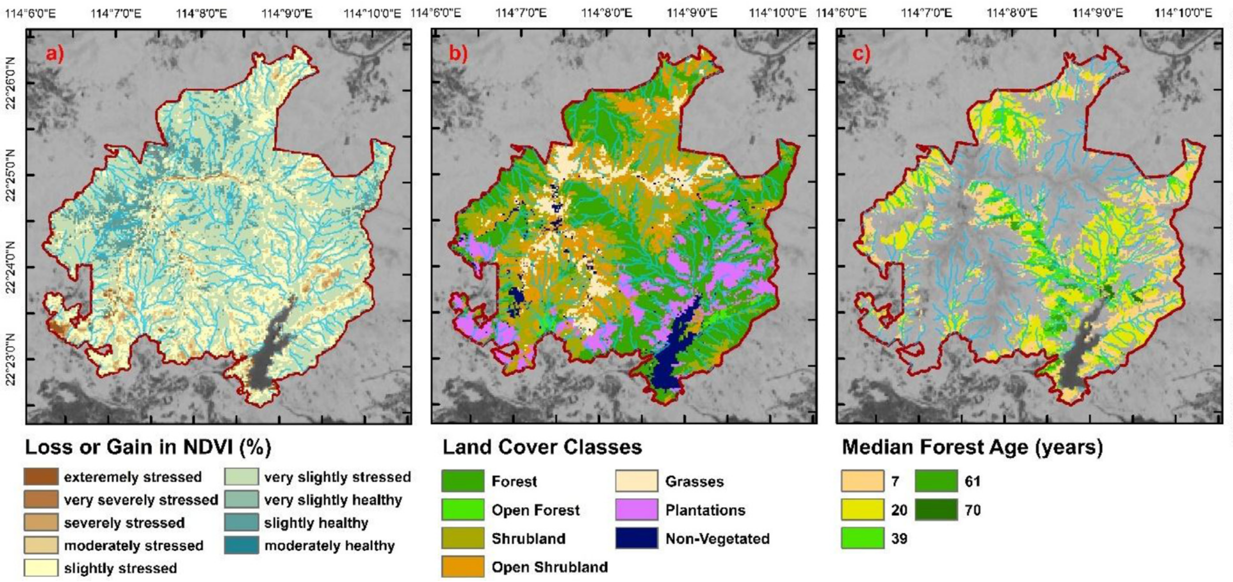

Fig. 3. a) percentage loss or gain in NDVI values ($\frac{\text{post tyhoon NDVI image} - \text{pre typhon NDVI image}}{\text{pre typhon NDVI}} \times 100$) - representing extremely stressed (< −25%], very severely stressed (−25% to −20%], severely stressed (−20% to −15%], moderately stressed (−15% to −10%], slightly stressed (−10% to −5%], very slightly stressed (−5% to 0%], very slightly healthy (0% to 5%], slightly healthy (5% to 10%], and moderately healthy (10% to 15%], b) land cover map of the study area (bare areas, built-up area and water classes are merged into non-vegetated class), and c) spatial distribution of median forest age classes.

were computed using the topographic position index with the 2 m resolution DEM.

2.4. Data analysis

The Red and Near Infra-Red (NIR) surface reflectance wavebands were used to derive a commonly used vegetation health monitoring index, the Normalized Difference Vegetation Index (NDVI) (Eq. (1)). The NDVI is based on absorption of visible light by chlorophyll pigments for photosynthesis, and strong reflectance in the NIR region linked with cell structure of leaves. However, if vegetation in under stress, absorption of red light is reduced due to disturbed photosynthesis, while the reflectance in the NIR region also decreases due to destruction of the leaf cell structure, thus reducing the value of NDVI. Since the collapse of the mesophyll layer occurs earlier than a decline in chlorophyll, and before any visible changes, the NDVI is an earlier and effective indicator of plant stress. NDVI values range from −1 to +1, with values above 0 generally representing vegetation and values below zero indicate non-vegetated areas or stressed vegetation (Tucker and Sellers, 1986). Positive values of the NDVI area highly correlated with green biomass and vegetation productivity (Pettorelli et al., 2005).

$$NDVI = \frac{NIR_\sigma - Red_\sigma}{NIR_\sigma + Red_\sigma} \tag{1}$$

$$Loss\ or\ Gain\ (\%) = \frac{NDVI_t - NDVI_c}{NDVI_c} \times 100 \tag{2}$$

where, NIR_σ and Red_σ represents the reflectance in NIR and Red wavebands, respectively, $NDVI_t$ and $NDVI_c$ represents post-typhoon and control NDVI images, respectively.

The loss in vegetation biomass or stress in vegetation was calculated by dividing the NDVI difference between the control and the post-typhoon image with the NDVI of in the control image (Eq. (2)). Positive values show normal conditions while negative values indicate the stress or reduction in green biomass. Therefore severity of the typhoon impact on the vegetation would be indicated by lower loss or gain values (Fig. 2-a). The resulting image loss or gain values ranging from −50% to 15% and were divided into nine classes with equal intervals, representing extremely stressed (< −25], very severely stressed (−20 to −15], severely stressed (−25 to −20], moderately stressed (−15 to −10], slightly stressed (−10 to −5], very slightly stressed (−5 to 0], very slightly healthy (0–5], slightly healthy (5–10], and moderately healthy (10–15].

All datasets were resampled to the lowest resolution (30 m) for subsequent analysis. The 'loss or gain (%)' image was superimposed over the layers of land cover classes, forest age classes, elevation, aspect, and the classified topographic position index, and the area statistics of damage severity classes were calculated using area tabulation in ArcGIS.

2.5. Post-typhoon field observations

Eight full day field surveys were carried out during late September and early October in 2018 to observe the damage done by the typhoon event. Trails crisscrossing the study area were walked and the typhoon damage was visually assessed for the different vegetation types along the trails. Visual observations included vegetation type (plantation or different age classes of natural forest), origin of species (native or exotic) and extent of damage (leaves only, branches, trunk or die back to roots), and overall habitat observations such as amounts of typhoon debris covering the soil and damage of understory vegetation. Observations were noted in a descriptive way for the different areas visited and whenever significant impacts were detected, photos for documentation were taken (see Fig. 5a–d). No quantitative data were collected.

3. Results

The NDVI images acquired on 3rd October 2018, following the typhoon event and control image acquired on 23rd October 2017 are shown in Fig. 2. Due to the senescing phenology of vegetation in Hong Kong, the NDVI in late October should normally be lower than NDVI in early October, therefore, any observed reduction in NDVI on 3rd October 2018 is likely to be affected by the typhoon. Most of the area with very high NDVI (0.85–0.90) before the typhoon had decreased to high NDVI (0.80–0.85). Hilltops, open shrubland and grassland were hard hit, especially on SW and SE facing slopes. Additionally, there are some severely affected patches of vegetation which show a larger fall in NDVI

Fig. 4. Distribution of NDVI loss or gain by land cover classes.

(from 0.85–0.90 to 0.70–0.75). These areas, distributed around the Shing Mun Reservoir and the South West, North East and East parts of the study area, have changed from dark green on Fig. 2a to orange and yellow on Fig. 2b. Overall these areas show a significant reduction of more than 15% in NDVI (dark brown and pale brown areas on Fig. 3-a). Overall, only 12% of the landscape shows positive change (which could be due to the earlier time of the month, of the pre-typhoon image) while the remaining 88% shows negative changes which are likely due to storm-damage.

3.1. Impacts on different land cover classes in the landscape

Following devastation during WW2, the present flora in the study area is now composed of habitat patches of natural vegetation at different successional stages (forest, open forest, shrubland, open shrubland, and grasses) and patches of exotic monocultural plantations (Fig. 3-b). The plantation patches shown in purple colour, are distributed around the Shing Mun reservoir and in the South and South West of the study area (Fig. 3-b). Forest comprises 36.44% of the landscape while exotic plantations cover ~12% of the study area (Abbas et al., 2016). Fig. 4-a shows percentage loss or gain in NDVI between the two images, and its distribution among the land cover classes (Fig. 4-b). A very small portion of the landscape (~12%) did not experience any abnormal change due to the typhoon (Fig. 3-a). On the other hand, all the land cover types show very slight to moderate loss in NDVI (> -15 to 0) which is proportional to the areal coverage of each type. However, patches of exotic monoculture plantation (*Lophostemon confertus, Melaleuca quinquenervia, and Acacia confusa*) appear to be the most severely damaged by the typhoon, as indicated by a significant loss in NDVI (Fig. 4-b). These patches can be seen as dark brown colour in the loss or gain images (Fig. 3-b). It is interesting to note that the exotic plantations in Hong Kong are reported to have limited or poor regeneration of native understory vegetation, compared to the natural forest (Lee et al., 2005). Thus, once the upper canopy is damaged by the typhoon very little standing vegetation remains in the plantation patches (Fig. 5a). Field observations show that in the *Lophostemon confertus* plantations, almost the entire canopy was destroyed by the typhoon and there is no young generation of trees to replace those lost, due to limited recruitment in the plantation understory (Fig. 5a). Thus plantation patches showed a significant drop in NDVI, compared to the natural forest which appears more adapted to storms. Despite lower overall damage compared to exotic species plantations, all the stages of natural secondary forest succession appear susceptible to damage caused by typhoon gusts, as highlighted by the decrease in NDVI in all land cover classes. The young forests and shrublands are mainly dominated by fast growing, soft wooded and therefore less wind resistant early successional species such as *Mallotus paniculatus or Machilus chekiangensis.* As observed in different parts of the study area especially weak trees such as multi-trunked, fungus infected, or other structurally deficient trees were knocked over or seriously damaged by typhoon gusts (Fig. 5c, d). Healthy trees remained upright but lost small branches, twigs and up to one third of the leaves. In many parts of the study area thick layers of debris can be observed covering the soil smothering seedlings and understory plants such as ferns. Large amounts of woody debris significantly increase the forest fire risk by providing more fuel than usual (Fig. 5b).

3.2. Damage to the successional age classes of forest (stand age)

Fig. 6 illustrates the typhoon damage among the five successional age classes of forest in the study area. The pattern of severity, and area damaged is inversely proportional to the median age of the forest patches. The results show that the intermediate (median age 39 and 61 years) and old growth forest (greater than 70-year-old) remained stable under the typhoon. However, the early successional forest was severely affected by the storm. High competition for resources in young forests indicated by high stem densities weakens individual trees and makes them more vulnerable to gusts. Pathogen infected and structurally deficient trees for example with poor root systems or co-dominant crowns are particularly affected by strong wind (Fischer pers. observ.).

3.3. Impact by topographic position (aspect, landform, elevation)

In addition to stand age or the structural stage of the vegetation, the topography of a landscape also plays a significant role in determining the stability of vegetation to withstand a wind storm (Ashton et al., 2001). The distribution patterns of varying magnitudes of typhoon damage along aspect, landforms and elevation are shown in Figs. 7–9.

The typhoon slightly impacted all types of vegetation along all aspects (Fig. 7). Nevertheless, the severest typhoon-induced loss in NDVI appears on the South, South East and East facing slopes, while cooler north facing slopes appear least affected by the typhoon, and even show a positive change in NDVI. Mapping of vegetation communities along aspects indicate that the youngest forests grew along southern aspects in later years of succession (Abbas et al., 2016). Thus the effects of forest stand age, direction of typhoon and distribution of very early successional forest along southern slopes combined to produce the severest effects of the typhoon.

Analysis of typhoon damage according to landform indicates that exposed ridges and hilltops were more severely affected than mid-slopes and sheltered places in valleys and deep ravines, with more than 600 ha above 500 m elevation suffering some damage (Fig. 8). These findings are not surprising as Tai Mo Shan is one of the highest coastal mountains in South China making the study area fully exposed to extreme weather approaching from the sea such as typhoons. However, some severe damage was seen at lower elevations, with approximately

Fig. 5. In-situ photographs of the landscape a) Lophostemon confertus plantation at the foothills of Tai Mo Shan near Kap Lung. The canopy is almost leafless, many trees are broken or severely damaged. The understory is very sparse naturally, which explains the massive reduction in NDVI, b) Damaged canopy of 20 years old natural secondary forest dominated by Machilus chekiangensis. Large amounts of branches and leaves cover the forest floor significantly increasing the fire risk, c) Co-dominant crowns make a tree structurally deficient, allowing it to break easier in typhoon gusts & d) At the contact point of two co-dominant stems bark inclusion creates a weak point, which is the main breaking point of the co-dominant trunk.

10 ha between 200 and 400 m. elevation showing more than 15% decrease in NDVI Field observations confirmed that many of these correspond to forests still dominated by exotic species, which were originally planted in lower areas.

4. Discussion

The study found that only 12% of the landscape appeared unaffected by the typhoon, and although younger forests were most severely damaged, all age classes of forest were affected in some way. This is because all secondary forests up to 70 years are not appreciably different in structure and species composition due to the limited species pool which is able to recolonize the open, mostly grassy areas. As pointed out by Abbas et al. (2019) old growth species are largely absent from recovering forests. The reasons are manifold, including environmental factors such as poor soil conditions after centuries of soil erosion, as well as biological factors such as limited dispersal of large fruited climax species. The limited species pool causes strong competition between individuals of a few species such as *Machilus chekiangkensis* or *Mallotus paniculatus*. An unusual number of competing individuals of the same species, which have similar functional traits such as soft wood, same crown shape and same maximum tree height, stresses the forest stand and makes individual trees more vulnerable to pests and environmental damage caused by typhoons. In contrast a species rich, complex, irregular and multilayered canopy of primary forest shows a much higher resilience to stress and environmental damage (Zimmerman et al., 1994).

Thus, rather than typhoon damage helping to increase diversity by creating opportunities of space and resources, as mentioned in Section 1.2, the succession is arrested at this stage due to lack of a viable species pool of mid-to late-successional species. Weakened by competition for the same resources, large numbers of the same species are heavily damaged by severe typhoon impacts creating large forest gaps. In Hong Kong's forests such gaps are recolonized by the same few species, again creating a cycle whereby the same species replace themselves, and there is no evidence that, with progression, new late successional species are arriving as reported for other areas (Shiels et al., 2014; Wang et al., 2008). Such a situation has been considered the ‘new normal’ (Zhang et al., 2016), in which winners and losers emerge. In our study area, *Machilus chekiangensis* and *Mallotus paniculatus* are winners, as they occupy much more space than they would have under primary forest conditions. In order to obtain a stronger, more resilient forest, it would be necessary to enhance biodiversity by artificially planting a species mix which resembles primary forests in the region. This could be achieved by thinning of young secondary forest followed by enhancement by planting pockets of high diversity forest.

Although the most severe and extensive damage was observed at higher elevations in the landscape due to greater wind exposure, significant damage was also seen at lower levels, especially within patches of exotic monoculture plantations. The severe loss of NDVI here is due to the absence of native tree seedlings and of native understory vegetation, and once the upper canopy of exotic trees is damaged by the typhoon very little standing vegetation remains in the plantation patches. Unlike the natural forest which appears more adapted to storms, the upper canopy of these plantation patches comprises tree species not adapted to a typhoon climate. Furthermore, the poor understory would suggest low fire susceptibility, but the dead trees and debris following a typhoon provide enhanced fuel supply for fire, and a higher fire frequency than usual is observed on archived images (Abbas et al.,

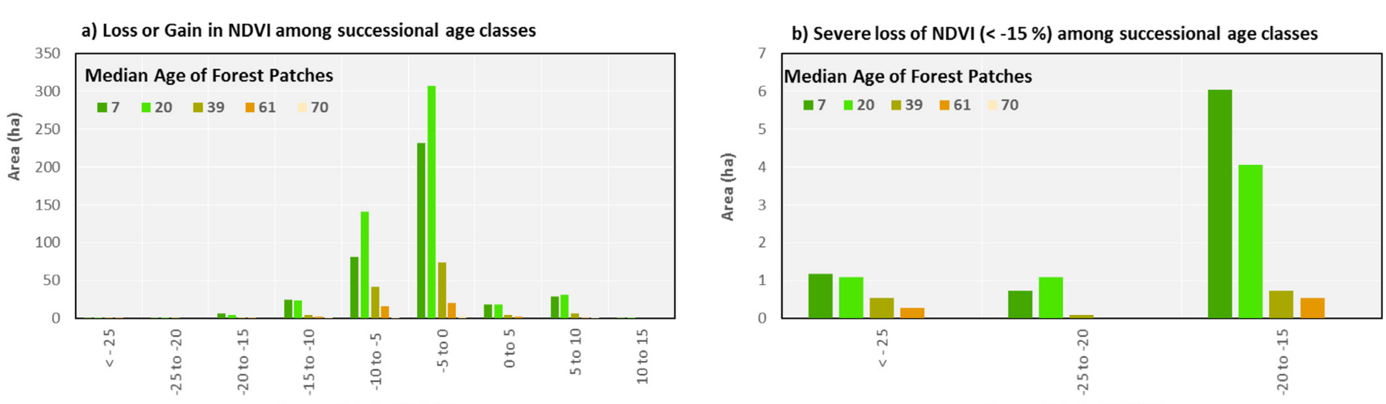

Fig. 6. Distribution of typhoon damage intensities among median stand ages of forest in the landscape.

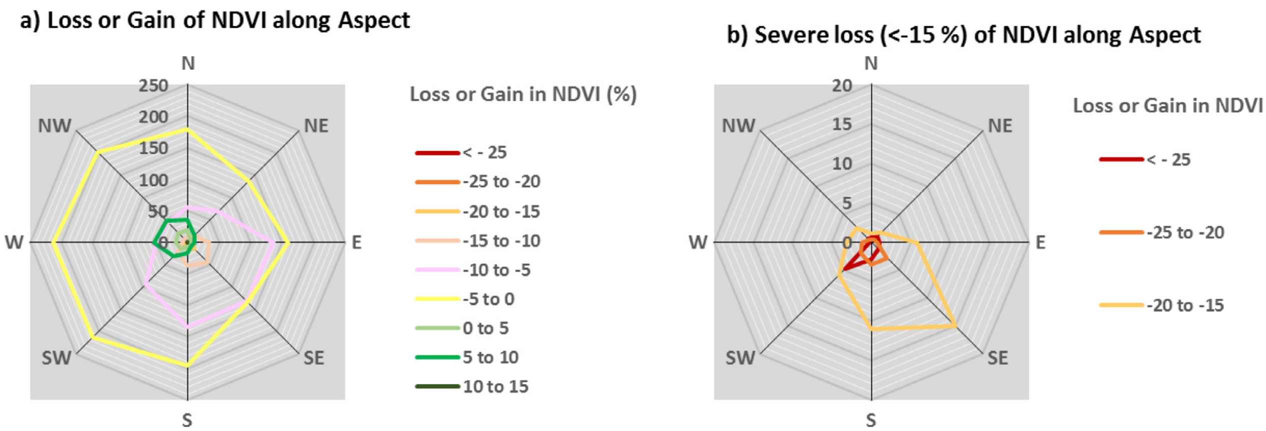

Fig. 7. Damage of the typhoon along aspect in the landscape.

unpublished). Indeed hill fires initiated in nearby grasslands are common in the dry season, and have been recognized as the main impediment to structural succession from grassland to shrubland and forest (Dudgeon and Corlett, 2011; Lee et al., 2005). The ease of fire ignition decreases after a few years of succession and in normal conditions, it is very rare for woodlands and shrubland to catch fire (Chau, 1994). Most of the hill fires in Hong Kong last less than 90 min, and a few last up to 3 h (Chau, 1994). But, considering the excessive fuel from storm debris, future dry seasons may bring more intense and longer fires which could cause reversion to grassland, thus reversing the structural succession.

A number of studies suggest that multi-stemmed structures are both a response to disturbance and an adaptation to future disturbance (Crausbay and Martin, 2016), as multi-stemmed trees have been seen to experience lower mortality after cyclones in montane forests in Jamaica (Tanner and Bellingham, 2006) and the Dominican Republic (Gannon and Martin, 2014). However, those studies were conducted in windy montane forests with steep slopes and exposed ridgetop locations, where tree height is limited by wind and harsh environmental conditions. In such locations multi-trunked trees can reach the canopy and therefore are able to survive. Our study observations suggest that in flat land, lower and middle slopes, the multi-trunked habit is negative because single trunked canopy trees grow taller and will out-shade multi-trunked individuals. Once suppressed by overtopping trees, multi-trunked trees are weaker and become vulnerable to pathogens and wind stress. Fig. 5d shows an example of a *Machilus chekiangensis*, which suffered from bark inclusion caused by multi-trunking. The bark inclusion makes a weak point where the trunk is not solid, and one of the co-dominant trunks snapped in the typhoon. Such injuries are fatal and won't heal. Trees which eventually succeed are those which can both tolerate shade to grow beneath an intact canopy, but can also initiate rapid height growth when a canopy disturbance occurs (Ashton et al., 2001), and this would exclude multi-trunk trees whose height growth is limited due to division of resources between several stems. The negatives of multi-trunking are known in arboriculture, which aims to remove co-dominant trunks (Edward, 2015), and this may also be beneficial in regenerating lowland tropical forests.

5. Conclusion

Almost 90% of the landscape, across all elevations, showed abnormal change following the typhoon, with all successional stages affected, but greatest damage was seen in the youngest growth forest, and in exotic monocultural plantations. The greater loss of biomass observed in exotic plantation patches than in the natural forest, indicated an evolved adaptability of local species to periodic wind disturbance, as super-typhoons have occurred at least once a decade over the last 100 years. The foregoing analysis along with previous findings by the research team on frost damage, suggest that exotic plantations are less resilient to extreme climatic events possibly, in part, due to the lack of tree and shrub recruitment below the main canopy. Among the forest successional classes, young forest dominated by dense stands of fast-growing softwood species of *Mallotus* and *Machilus* showed most damage. High competition for resources weakens individual trees in these young forests and those affected by pathogens or structural deficiency, (for example with poor root systems multiple trunks or co-dominant crowns) were most damaged. Therefore to aid the natural thinning of these early stage secondary forests, which usually takes a very long time, weak and damaged trees may be removed. Along with intervention to introduce some mid- and late-successional species, this may help to speed up the 'arrested succession' currently seen in Hong Kong's young secondary forests. Large amounts of debris resulting from storm

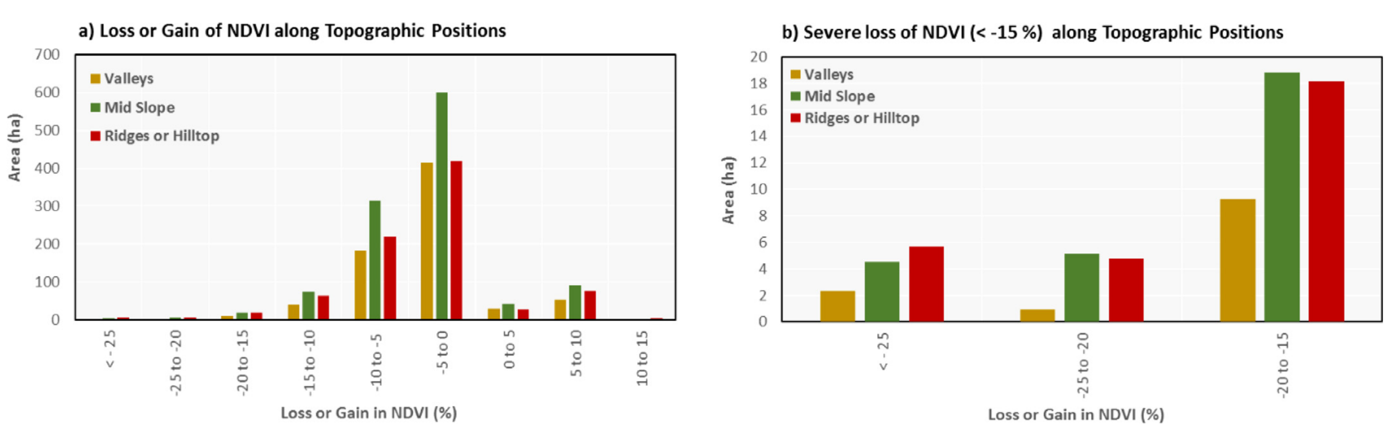

Fig. 8. Distribution of different magnitude of typhoon damage across topographic landforms.

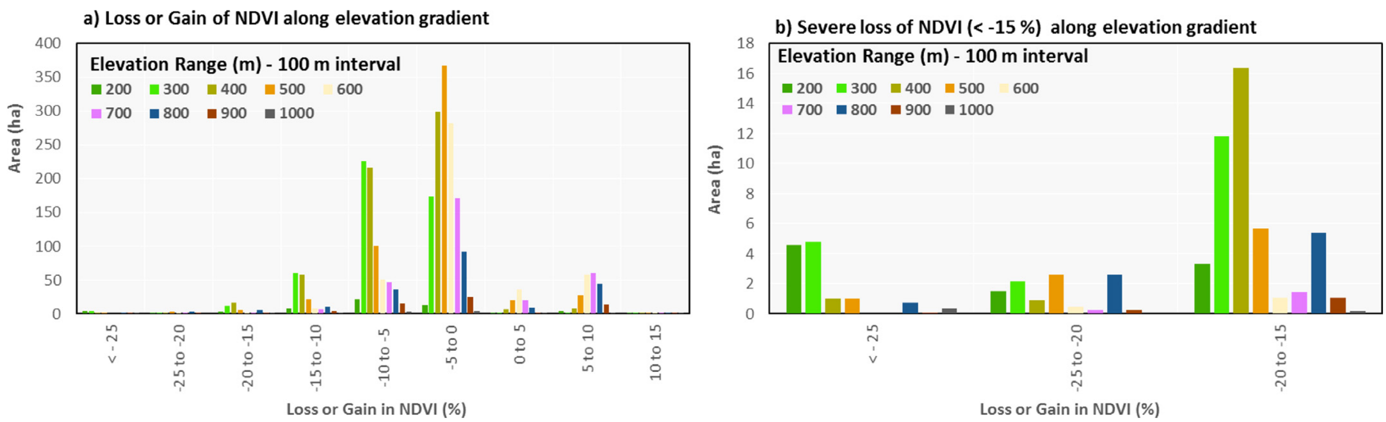

Fig. 9. Distribution of different magnitudes of typhoon damage across the altitudinal gradient.

damage constitute a fire risk during the following dry season, and this could also be reduced by establishing a high diversity mix of native species, to enhance resilience to extreme climatic events.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2019.107784.

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