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Mapping and assessment of impacts of cold and frost on secondary forest in the marginally tropical landscape of Hong Kong

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ABSTRACT

Impacts of extreme climate events on terrestrial ecosystems are more severe than those due to normal climate variability, and IPCC expects extreme weather events to become more frequent, triggering a gradual or unexpected change in forest ecosystems. Secondary forest in Hong Kong is recovering through natural succession since 1945, after complete destruction during the Second World War (WW2). Over 70 of years of natural vegetation succession, forests have suffered three major extreme cold events, in 1974, 1991 and 2016. An intense cold event across Hong Kong and southern China from 23 to 25th January 2016 with temperatures of −6 °C and wind chill of −13 °C recorded at 950 m on Hong Kong's highest mountain, was preceded by unseasonably warm weather in early January. The intensity of cold had not been experienced in over 100 years of climate records. This study was conducted to map and assess the impacts of the frost event on Hong Kong's vegetation at landscape level using remotely sensed vegetation indices and GIS, and at species level from field observations. Results indicate that the vegetation below 400 m was largely unaffected, but then vegetation damage gradually increased along the elevation gradient from 400 m to the maximum elevation of 957 m. Furthermore, the cooler north and east-facing aspects appeared less affected by the event, showing less than half of the reduction in the remotely sensed Normalized Difference Vegetation Index (NDVI) compared to normal years, than warmer south and west facing slopes. This presumably indicates that more cold-tolerant woody seedlings are more able to compete and germinate on northerly aspects, as well as the more closed forest canopy on northerly aspects being resistant to wind chill. Plants on the warmer south and west facing slopes covered with earlier successional stages (grasses, shrubs, and very young forest pioneers) were more damaged. Field observations also confirmed the high degree of frost damage observed above 600 m, where a higher return frequency of frost explains the absence of tropical taxa and the presence of more temperate floristic elements. A higher frequency of frosts would favor deciduous species, which are more resilient to frost and, in the long-run, would cause the disappearance of evergreen forests above 600 m in Hong Kong. The predicted greater frequency of frost damage due to climatic warming could bring about such changes in coming decades. Given the predicted greater incidence of climate extremes to forests in climatic transition zones under climate change predictions, monitoring using satellite-derived vegetation indices is a low cost and effective means of identifying longer-term changes as opposed to natural inter-annual variability in forest growth.

1. Introduction

Frost is a meteorological phenomenon during which plants experience freezing injury due to occurrence of air temperature less than 0 °C (FAO, 2005). Frost can affect tree growth, species composition, and cause a sudden shift in biological processes such as plant phenology, evapotranspiration, moisture requirements, carbon fixation and decomposition (Aber and Melillo, 1991). Depending on the vegetation structure, landscape position or soil properties, frost may damage plant tissues by scorching and browning of young leaves, buds, fruit and flowers thus affecting productivity (Blennow and Lindkvist, 2000). Tolerance to frost operates as a species filter (Easterling, 2000).

Hong Kong at 22–23°N, is on the climatic edge of the tropics, and except for some non-tropical plants at higher elevations, its flora and fauna are mainly tropical and frost-sensitive. An intense cold event occurred across Hong Kong and southern China from 23 to 25th January 2016, with temperatures of −6 °C recorded at

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950 m on Hong Kong's highest mountain, Tai Mo Shan. The steep altitudinal temperature gradient is illustrated by the lowest temperature of 2.3 °C being recorded only 4 km away near sea level at Tsuen Wan Shing Mun Valley weather station. The coldest temperature previously recorded at Tai Mo Shan was −3.5 °C in 1974 (Peterson, 1981). The recent cold surge was remarkable in three respects: (i) temperatures well below freezing lasted for 72 h, far exceeding the duration of previous cold events, (ii) the cold surge was accompanied by strong winds of 56 km per hour and freezing rain, thus increasing the wind chill factor (chill factor was −13°) and horizontally-formed icicles were observed on tree branches, and (iii) the cold surge followed unseasonably warm weather in the previous three weeks, with a mean of 14.6 °C compared to a 20-year average for January, of 10.3 °C (Hong Kong Observatory, 2016). The unseasonably warm early January may be related to the ENSO conditions prevailing at the time, which normally reduces the strength of the Asian monsoon, bringing warm dry weather. Chang-Yang et al. (2016) observed that the number of species flowering and fruiting in Taiwan's sub-tropical forests tended to increase during El-Nino periods, thus it may be assumed that the risk of damage during spring frost events would increase. Indeed, Augspurger, (2013) noted that the spring damage risk to woody species due to frost in Illinois, USA, was increasing despite climate warming because the combination of warming trends and temperature variability associated with climate change made frost damage more common.

Corlett, (1992) documented the impacts of a cold spell in December 1991 on Hong Kong's mountain flora, when temperatures at Tai Mo Shan fell to −4.7 °C for a period of 26 h. He observed extensive frost damage in species whose main distribution was in tropical lowlands south of Hong Kong, although these were actually native species. There are no climatic records of cold events in Hong Kong exceeding the severity of the January 2016 event, but a written account (Skerchly, 1893) describes a great frost in 1893, which lasted four days at high altitudes, and killed several shrub species including *Melastoma candidum, Rhodomyrtus tomentosa,* and *Blechnum orientale* outright. Since the January 2016 frost event was more severe than that of 1991 and available evidence suggests a similarity to that of 1893, the return period of the recent frost may be considered to be 50 to 100 years. This may be a determinant of Hong Kong' native plant species composition, and would confirm Corlett's (1992) hypothesis that the absence of *Malayan*-style tropical rain forest from Hong Kong, while present at a similar latitude in southwest Yunnan, is due to such cold events. It is thought that extreme weather events are ecologically more important than natural climate variability (Easterling, 2000; Katz and Brown, 1992; Parmesan et al., 2000), and climate change predictions suggest that the frequency of ENSO and spring frost damage may increase (Augspurger, 2013; Collins et al., 2010; Gu et al., 2008).

Large parts of the tropics and subtropics have suffered greatly from deforestation over recent decades resulting in depauperate vegetation types often without sufficient seed sources available for natural recovery into diversity rich ecosystems (MacDicken et al., 2015). The long-term effects of such extreme cold events on biodiversity in general, has rarely been recorded in marginally tropical or subtropical habitats but Chang-Yang et al. (2016) observed a trophic cascade effect following a frost event in March 2005 in Taiwan's sub-tropical forests where temperatures fell to −1.3 °C. The Formosan rock macaques (*Macaca cyclopis*), which rely heavily on a fruit diet suffered high mortality and low birth rates in the following year. They also observed that the number of species flowering and fruiting in the following summer was greatly reduced and these remained at lower levels for a longer period of 5–6 years. Since Hong Kong's transitional tropical to sub-tropical montane forests are similar in structure and species composition to those of Taiwan, the greater severity of the frost event in Hong Kong, with −6.0 °C and wind chill factor of −13.0 °C recorded at mountain tops, suggests that even greater impacts on flora and fauna may be expected. Since the recent cold spell of January 2016 was more intense and of much longer duration than any cold event recorded over the last 100 years, the current study documents its impacts on Hong Kong's vegetation at landscape level using remote sensing and GIS as well as at species level from field observations.

2. Study area

Hong Kong's territory is mountainous, and approximately 40% is designated for protection in country parks, most of this being steeply sloping land at higher elevations. The study area comprises Tai Mo Shan and Shing Mun country parks in New Territories of Hong Kong (Fig. 1), an area of ∼2800 ha. Topography is rugged, with slopes rising to Hong Kong's tallest peak, Tai Mo Shan, at 957 m. The native vegetation of tropical and sub-tropical evergreen broadleaf forest was first cleared around 400–600 years ago (Meachem, 1994), and then almost complete destruction of the forest took place during the blockade years of World War II. Hong Kong's present day flora represents recovery since 1945 due to natural regeneration from tiny remnants in inaccessible sites. Due to frequent burning in the past, upper valleys support fire-maintained grasses, and lower elevations support early successional shrub, secondary forest, and plantations. Early successional pioneers generally give way to light-sensitive forest trees after 50–70 years. The climate is seasonal, with hot humid summers and cool dry winters, with frosts occurring several times per decade above 500 m. This leads to a transition in vegetation composition from tropical lowland to subtropical upland species confirmed by a reduction of tropical plant families such as *Clusiaceae, Euphorbiaceae, Myrtaceae, Moraceae* and *Apocynaceae* at higher altitudes.

3. Materials and methods

Accurate and rapid mapping of the impacts of extreme climate events on terrestrial ecosystems is a key aspect of restoration ecology. In this regard, satellite remote sensing and GIS based assessments have potential for mapping the distribution and intensity of frost damage. Therefore, to evaluate the spatial impacts of the 23–25th January 2016 frost event on the vegetation at different elevations and aspects, satellite images of Landsats 5 and 8 satellites with a spatial resolution of 30 m, were obtained from Earth Explorer (http://earthexplorer.usgs.gov/). These included dates shortly before the event (6th January 2016) and after the event (7th February 2016), as well as control images for January and February of another year [2009] as a comparison. Cloud-covered and burnt areas were masked out, and the images were atmospherically corrected using the 6S model (Nazeer et al., 2014).

The commonly used Normalised Difference Vegetation Index (NDVI) (Eq. (1)), which represents vegetation health or condition was derived from the Red and NIR wavebands. The NDVI shows a high correlation with green biomass and vegetation productivity (Pettorelli et al., 2005). The effectiveness of NDVI is based on the fact that chlorophyll in healthy green leaves strongly absorbs Red, and the spongy mesophyll layer in healthy leaves strongly reflects NIR radiation. Since the collapse of the mesophyll layer occurs earlier than a decline in chlorophyll, and before any visible changes, the NDVI is an early indicator of plant stress. NDVI values range from −1 to +1, with values above 0 generally representing vegetation (Tucker and Sellers, 1986).

$$NDVI = (NIR_{reflectance} - Red_{reflectance})/(NIR_{reflectance} + Red_{reflectance}) \quad (1)$$