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Analysis of forest damage caused by the snow and ice chaos along a transect across southern China in spring 2008

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Abstract: An abrupt ice and snow storm disaster which occurred in the spring of 2008 severely destroyed forests over a surprisingly large portion of southern China. A transect crossing Jinggang Mountain-Jitai Basin-Yushan Mountain-Wuyi Mountain was selected as the study area. The authors integrated field data collected in two field surveys to analyze the impacts of the disturbance on forests. The following results were obtained. (1) The extent of damage to plantations along the transect decreased in the order of slash pine > masson pine > mixed plantation > Chinese fir. Slash pine is an introduced species from southern America which is characterized by fast growth, low wood quality and rich oleoresin, and showed a damage rate of 61.3% of samples, of which 70.4% cannot recover naturally. Masson pine is the native pioneer species of forests with harder wood, and 52.5% were damaged due to turpentine, of which 60.9% cannot recovery naturally. Chinese fir is a local tree species and samples showed a rate of 46% and a relative rate of 32.5%, lower than the mixed plantation. (2) From west to east along the transect, we can see that evergreen broad-leaved forest of the western transect on Jinggang Mountain showed the lightest damage extent, and a Cryptomeria plantation at an altitude of 700 m was severely destroyed while Chinese fir showed light damage below 700 m and relatively severe damage above 900 m. Masson pine and slash pine in the central transect in Jitai Basin were damaged severely due to turpentine activities, and closed natural secondary deciduous broad-leaved forest was damaged severely due to high ice and snow accumulation on intertwined shrubs. Masson pine aerial-seeding plantations below 400 m along the eastern transect in Xingguo and Ningdu counties were nearly undamaged for small tree sizes, and Chinese fir at 500–900 m altitude showed a lighter damage extent. However, masson pine which was distributed above 400 m and planted in the 1960s, was severely damaged due to turpentine.

Keywords: ice-snow disaster; wood damage; forest transect; damage rate

1 Introduction

The greatest extreme ice-snow disaster once in half-a-century or even a-century swept across

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most areas of southern China between January 11 and February 5, 2008 (Figure 1), and the Yangtze River Basin suffered its most severe freezing weather of the last one hundred years. Sudden onset, excessive precipitation and long duration characterized this severe weather disaster. The snow, ice and sleet caused severe forest losses and destroyed 1.98×10^7 ha of forests, or nearly 13% of China's forests, in the 19 provinces of Jiangxi, Hunan, Hubei, Guangdong, Guizhou, Anhui, Guangxi, Henan, Yunnan, Sichuan, Qinghai, Shanxi, Gansu, Xingjiang, Zhejiang, Jiangsu, Fujian and Hainan (Dong, 2008), and especially in the former five provinces. The total included 6.83×10^6 ha of bamboo, 1.16×10^7 ha of woodland and 1.35×10^5 ha (9.9 billion in number) of saplings, according to the administration. The low-temperature, sleet and freezing weather that lasted more than 20 days caused the greatest disaster in one hundred years in Jiangxi and caused massive destruction of forests: 3.56×10^6 ha forests were damaged, which represented 40.8% of the Jiangxi forests, totaling 15.45 billion yuan of direct economic losses (State Forestry Bureau, 2008).

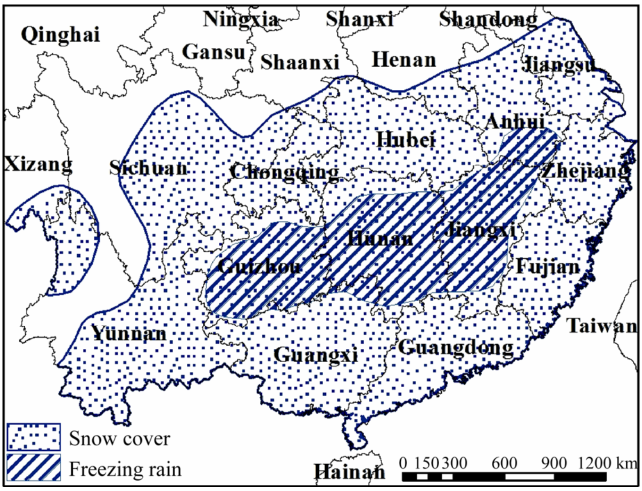

Figure 1 The distribution map of snow and ice for January 7– February 5, 2008 in southern China (Sources collected from National Climate Center: http://cmdp.ncc.cma.gov.cn)

Ice-snow disasters severely affect tree species composition, biodiversity, stand structure and tree growth (Rhoads *et al.*, 2002; Lafon and Speer, 2002; Lafon, 2004, 2006). Sustained snow pressure, freezing and frost heaving leave trees prone to physiological damage such as cold injury of tender branches and leaves, weak tree growth or dead wood, etc. (Gu *et al.*, 2008). Further, when ice adheres to the tree crown, the extra loading on the stem can exceed the strength of the tree and cause structural damage in the form of bending or breaking (of the crown or branches) or uprooting (Rhoads *et al.*, 2002). Here we ask what damage was caused by the spring ice-snow disaster in southern China, and whether the damage varied according to site and species. The Normalized Difference Vegetation Index (NDVI) value before and after the disaster was applied to evaluate the destruction, and determine whether the variation in NDVI can reflect the actual damage. Answers to these questions are important for the evaluation of forest loss, and for restoration and reconstruction planning after the disaster.

Areas of mountains and hills cover 36% and 42% (respectively) of the Poyang Lake basin in Jiangxi Province. The main vegetation types are coniferous forest, mixed wood, evergreen broad-leaved forest, evergreen deciduous broad-leaved mixed forest, bamboo, elfin forest and shrub, etc. Forest coverage had decreased to 36% before the 1980s due to overcutting and blind cultivation, but has since increased to 60.05% following implementation of the mountain-river-lake project 20 years ago (Wang *et al*., 2006; Wei *et al*., 2006). A transect crossing Jinggang Mountain-Jitai Basin-Yushan Mountain-Wuyi Mountain was selected as the study area (Figure 2).

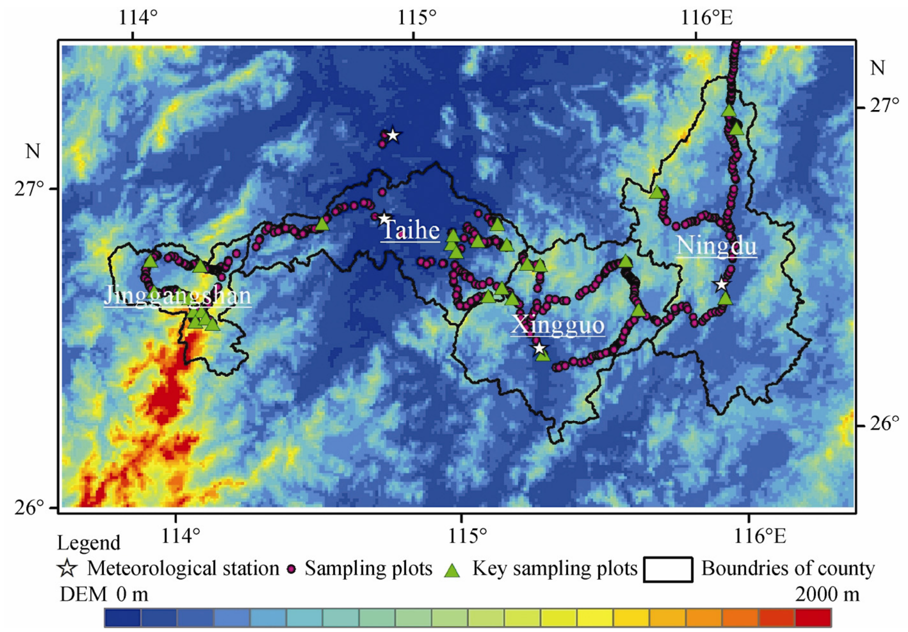

Figure 2 Locations of the transect and sampling points, and meteorological stations

The transect is located in central and southern Jiangxi Province, including Jinggangshan City, Taihe County, Xingguo County and Ningdu County, with Luoxiao Mountain in the west, Jitai Basin and Yushan Mountain in the middle and Wuyi Mountain in the east. The climate of the transect belongs to a moist middle subtropical monsoon type, and the landforms are characterized by red beds that are typical of the subtropical regions of China. Situated on the provincial boundary between Jiangxi and Hunan, the annual average temperature of Jinggangshan City is 14.2℃, the coldest month is January with a mean temperature of 3.2℃, the warmest month is July with a mean temperature of 23.9℃, and annual precipitation is 1856.3 mm (Zhu *et al*., 2007). The forest types are dominated by natural broad-leaved forest, Chinese fir and mao-bamboo, including 7000 ha of secondary virgin forests that represent an important fraction of the world's subtropical evergreen broad-leaved forest; these are appreciated by environmental protection organization of the United Nations. The forest coverage in the nature reserve is 86% (Ma *et al*., 2007). Taihe County is located in the hinterland of Jitai Basin. The annual average temperature is 18.6℃, ranging from a mean monthly temperature of 6.5℃ in January to 29.7℃ in July. Annual precipitation is 1318–1575 mm, and annual average evaporation is 1154.1 mm. The dominant forests are slash pine (*P. elliotii*), masson pine (*P. massoniana*) and Chinese fir (*Cunninghamia lanceolata*), and forest coverage is 51.6% (Taihe Information Port, 2008; Shao *et* *al*., 2009). The geomorphology of Xingguo County is primarily low mountains and hills. The annual average temperature is 18.9℃, with a mean temperature of 3.4℃ in January and 34.4℃ in July, and the annual precipitation is 1500 mm. Due to excessive use of the poor soil, soil and water loss is severe. Over-felling and a long history of conflict has destroyed the forest in Xingguo County, and only 1.08×10^5 ha remained in 1982 leaving a forest coverage of just 33.8%. Artificial forestation and aerial seeding forestation since the 1970s, dominated by masson pine, has increased the forest area and forest coverage which has now reached 72.2% (Li, 2001; Chen *et al*., 2004). Ningdu County is a typical hilly and mountainous area. The annual average temperature is 17.6℃, with a mean temperature of 6.3℃ in January and 26.8℃ in July, and the annual precipitation is 1650 mm (Chen and Lin., 2000). Primary forest types are masson pine and Chinese fir, and forest coverage is 71% (Ningdu County Government homepage, 2008).

2 Data and methods

Forest resource investigation data, meteorological data, forest resource distribution, topographic maps and remote sensing images were obtained for this study. Meteorological data included daily average temperature and precipitation in January and February at three China Central Meteorological Stations: Jinggangshan (1999–2004), Ji'an City (1953–2002) and Ganzhou City (1952–2004). Also, daily precipitation, daily average temperature, and minimum and maximum temperature between 1 January and 10 February, 2008 were recorded at four local meteorological stations at Jinggangshan, Taihe, Xingguo and Ningdu. Finally, images were obtained from MODIS NDVI beijing-1 micro satellite.

Field investigations were carried out from 28 February–9 March and 27 March–24 April, 2008 along a transect of typical forest damage from which 339 damage samples were collected. The survey recorded: (1) latitude, longitude and altitude; (2) identification of tree species and ages; (3) estimate of damage (percentage) and damage types (top-breaking, crown breakage, stem breakage, uprooting, stem bending); (4) estimate of slope angle and aspect, supported by DEM analysis; (5) supplementary information such as turpentine, soil thickness, stand structure, etc. The following survey methods were applied: (1) general methods such as position fixing, photography, video and visual inspection (2) special methods such as measurements within the stand; (3) sampling and observation of trees (mostly at the four plots); (4) interviews with farmers.

Location and damage data were plotted on a 1:50000 topographic map, and subsequent spatial overlay analysis with a DEM was carried out following digitization in ArcGIS. Elevation, aspect and slope angle for all samples including general plots, special plots and sampling plots were calculated and analyzed, and then statistically analyzed by MATLAB and EXCEL.

Tree damage was classified as dislodging (uprooting and overturn), stem breakage, crown and branch breakage (crown breakage, tip breakage and branch breakage), bending, mixed damage, and the physical damage was further divided into natural recovered damage (crown breakage, tip breakage and branch breakage), natural unrecovered damage (bending, stem breakage, uprooting and overturning) and mixed damage, Next the actual damage ratio and relative damage ratio were calculated.

The actual damage ratio of a certain damage degree for a certain tree species (A_{per}) was calculated as:

$$A_{per} = Z_{per} * K_{per} = \left(\sum_{i=1}^{n} Z_i \right) / N \times 100\% \quad (1)$$

where N is the total number of samples for a certain tree species, n is the total number of samples of a certain damage degree for a certain tree species; Z_{per} is the weighted average damage rate in a sample plot of a certain damage degree for a certain tree species, the damage rate is the ratio of the number of damaged trees to the total number of trees in a certain sample plot; and K_{per} is the ratio of the number of damaged samples of a certain damage degree for a certain tree species to the total number of damaged samples for the tree species.

The relative damage ratio of a certain damage degree for a certain tree species (R_{per}) is the ratio of the actual damage ratio of the certain damage degree for the tree species, to the actual damage ratio of all damage degrees for that tree species, and is calculated as follows:

$$R_{per} = A_{per}{}^{i} / \sum_{i=1}^{3} A_{per}{}^{i} * 100\% \quad (2)$$

The actual damage ratio reflects the true level of destruction in the damage samples.

3 Results

3.1 Local climate anomalies in spring 2008

Ice-snow disasters in forests depend on the type of precipitation. Sleet or snow following rain, accompanied by a rapid fall in temperature to 0℃, leads to rapid accumulation of verglas, snow and ice in the tree crown and consequent damage (Irland, 2000). Wind is a significant external force that can severely damage the trees, especially if strong winds coincide with high levels of ice accumulation (Zhu *et al*., 2006).

Jinggangshan meteorological station is situated at Ciping (gray five-point star in Figure 2) and is representative of a mountain climate. The mountain and hill region climate in Xingguo County and Ningdu County are best represented by Jianggangshan, because the meteorological stations at Ganzhou, Taihe, Xingguo and Ningdu are located in a basin, valley or lowland.

3.1.1 Anomalous warming and rapid temperature fall

We can see from Figure 3 that the annual average daily air temperature from 1 January to 10 February, 1999–2004 at Jinggangshan meteorological station shows a minimum of –0.8℃, maximum of 7.4℃, mean of 4.5℃ and variation of 6.6℃. The daily average air temperature has a mean of 0.8℃, and a range from –3.5 to 15.6℃ with a variation of 12.1℃, including a period of over 20 consecutive days with temperatures lower than 0℃. Comparison of the daily average air temperature between 1 January and 10 February, 2008 with the contemporary annual average daily air temperature shows maximum increasing amplitude of 9.8℃ and decreasing amplitude of 9℃.

The annual average daily air temperature between 1 January and 10 February, 1952–2004 at Ganzhou City meteorological station shows a minimum of 7.1℃, maximum of 10℃,

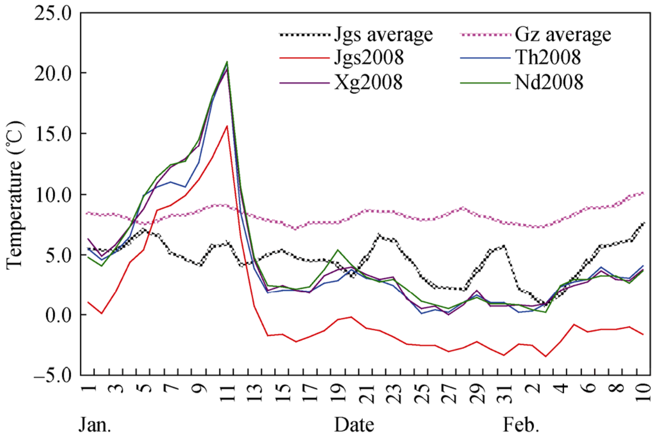

Figure 3 The mean daily air temperature between 1 January and 10 February, 2008, and annual average daily air temperature between 1 January and 10 February, along the transect. Jgs is Jinggangshan meteorological station, Gz is Ganzhou meteorological station, Xg is Xingguo meteorological station, Th is Taihe meteorological station, and Nd is Ningdu meteorological station

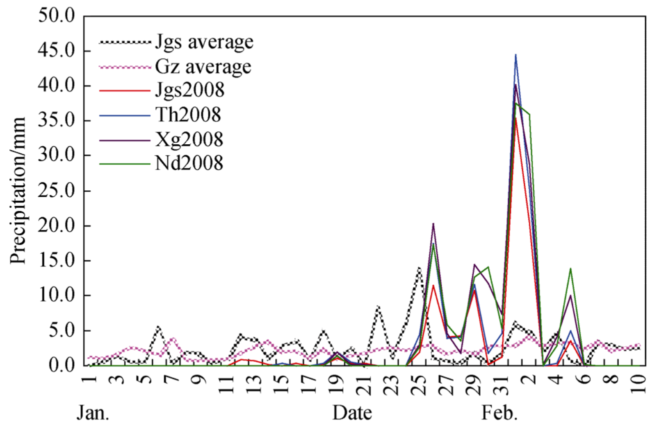

Figure 4 The mean daily precipitation between 1 January and 10 February, 2008 and annual average daily precipitation between 1 January and 10 February along the transect

mean of 8.2℃ and variation of 2.9℃. At Taihe County meteorological station the contemporary daily average air temperature has a mean of 4.4℃ and a range of 0.1–20.8℃ with a variation of 20.7℃. At Xingguo County meteorological station the contemporary daily average air temperature has a mean of 4.7℃, and a range of 0–20.3℃ with a variation of 20.3℃. Finally, in Ningdu County meteorological station the contemporary daily average air temperature has a mean of 4.8℃, and a range of 0.2–20.9℃ with a variation of 20.7℃. Comparing the daily average air temperature between 1 January and 10 February, 2008 in Taihe, Xingguo, and Ningdu County meteorological stations with contemporary annual average daily air temperature in Ganzhou City meteorological station, shows maximum increasing amplitudes of 11.8℃, 9.1℃, 11.9℃ and decreasing amplitude of 8.1℃, 8.8℃, 7.8℃, respectively.

The temperature rapidly and continuously increased by 11.6–14.3℃ from 4 to 11 January, and decreased abruptly by 17.1–20.8℃ between 12 and 14 January and from when there were over 20 days at low temperature.

3.1.2 Heavy precipitation events

We can see from Figure 4 that the annual average daily precipitation between 1 January and 10 February, 1999–2004 at Jinggangshan meteorological station shows a range of 0–13.7 mm, a mean of 2.5 mm and a variation of 13.7 mm. The contemporary mean daily precipitation has a mean of 2.4 mm, a range of 0–35.4 mm and a variation of 35.4 mm.

The annual average daily precipitation between 1 January and 10 February, 1952–2004 at Ganzhou City meteorological station shows a minimum of 0.7 mm, a maximum of 4.3 mm, a mean of 2.2 mm and a variation of 3.6 mm. At Taihe County meteorological station the contemporary daily average precipitation has a mean of 3.1 mm, a range of 0–44.4 mm and a variation of 44.4 mm. At Xingguo County meteorological station the contemporary daily average precipitation has a mean of 3.6 mm and a range of 0–40.3 mm with a variation of 40.3 mm. Finally, at Ningdu County meteorological station the contemporary daily average precipitation has a mean of 3.7 mm, and a range of 0–37.5 mm with a variation of 37.5 mm.

Four heavy precipitation events (sleet and snow) occurred between 25 January and 5 February, including a particularly severe precipitation event on the 1 and 2 February with precipitation reaching 73.5 mm, and precipitation in the two days reached 55.9 mm, 69.6 mm, 69.1 mm and 73.5 mm at the four meteorological stations respectively.

3.2 Extent of tree damage along the transect and its relation to site characteristics

3.2.1 Damage type

Tree damage by the ice-snow disaster was divided into physical damage and physiological damage. Further, the physical damage could be classified as bending, tip breakage, branch breakage, crown breakage, splitting, stem breakage, dislodging (uprooting and overturning), etc. Trees suffering light damage like bending, and tip and branch breakage, could still grow normally; however, severe damage like splitting, uprooting and stem breakage could cause weak growth or even death. Physiological damage including cold injury of tips (25%–50% leaves withered and fallen, but with healthy branches and stems), branches (50%–75% leaves withered and fallen, most branches injured but with healthy stems) and cold mortality (75% leaves withered and fallen, branches and stems both injured).

We found that Eucalyptus (almost killed by the ice-snow disaster) and Camellia (flowering and fruiting influenced by the cold) exhibited physiological damage along the transect; however, it was difficult to fully assess the scale of the problem because the effects are not obvious at such an early stage. Therefore, we focused on the physical damage and classified it into five types: dislodging (uprooting and overturning), stem breakage, branch and crown breakage (tip breakage, branch breakage and crown breakage), bending and mixed damage. The percentage of physical damage (plot damage rate) in sampling plots was classified into four degrees: 4%–20%, 21%–50%, 51%–80% and 81%–100%, according to the ratio of damaged trees to total number of trees in the stand.

A total of 339 damage samples were investigated, of which, 35.8% were branch and crown breakage, 31.7% were stem breakage, 15.6% and 15.9% were dislodging and mixed damage, respectively, and only 1.0% was bending. According to Figure 5, the plot damage rate for most stem breakages was ranked 81%–100%, and mainly occurred in the turpentined slash pine and masson pine plantation. Plot damage rates of 51%–80% and 81%–100% for branch and crown breakage were primarily due to damage in deciduous broad-leaved forest, and the low rates of damage (4%–20% and 21%–50%) were mainly found in coniferous forest.

In addition, steep slopes and a thin soil layer promoted uprooting and overturning (Figure 5).

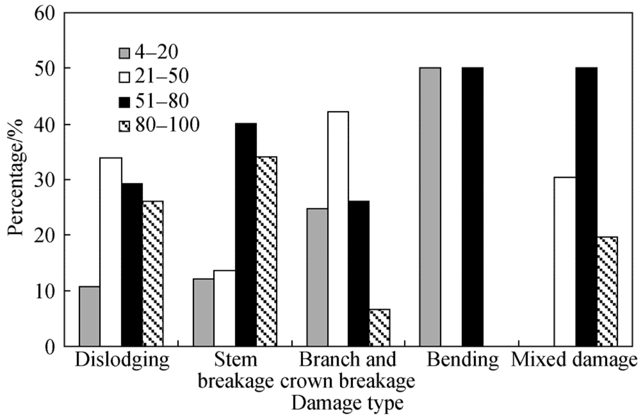

Figure 5 The range of damage ratios for each forest damage type in the transect

3.2.2 Tree species/stand types and physical damage

We divided the forest into 11 types: masson pine, Chinese fir, slash pine, Cryptomeria, bamboo, evergreen broad-leaved, deciduous broad-leaved, weed trees, mixed coniferous, mixed needle broad-leaved, and mixed forest and bamboo according to tree species and stand types. The mixed coniferous group is composed of masson pine, Chinese fir and slash pine, the mixed needle broad-leaved group is a combination of evergreen broad-leaved and masson pine, Chinese fir or slash pine, and the mixed forest and bamboo are combinations of bamboo and evergreen broad-leaved, Chinese fir or slash pine.

The ratios of damaged tree samples to total tree samples decrease in the order of Chinese fir > masson pine > slash pine, evergreen broad-leaved > deciduous broad-leaved, mixed coniferous > mixed needle broad-leaved > mixed forest and bamboo (Table 1). Plot damage rate decreases in the order of slash pine > masson pine > Chinese fir, natural secondary deciduous broad-leaved > bamboo > mixed forest and bamboo > mixed needle broad-leaved > evergreen broad-leaved > mixed coniferous.

Table 1 The percentage of damaged samples for tree species along the transect

Tree species	Masson pine	Chinese fir	Slash pine	Mixed coniferous	Evergreen broad-leaved
Percentage (%)	19.0	26.9	15.9	16.7	6.0
Tree species	Deciduous broad-leaved	Mixed needle broad-leaved	Bamboo	Mixed forest and bamboo	
Percentage (%)	4.6	4.1	7.5	11.5	

Slash pine in low-altitude hilly regions in Taihe County shows 30.2%, 25.4% and 22.2% of crown breakage, lodging and stem breakage, respectively (Figure 6). These results are caused by the rapid growth in young and middle-aged forest, lower transverse intensity of wood fiber and stem tapering grade, and higher water content in the needles. Furthermore, some slash pine suffered serious damage due to turpentine, poor wood quality and local terrain, however, damage was relatively light for young non-turpentine trees. The plot damage rate ranked 81%–100% and 21%–50% for slash pine samples and accounted for 36.5% and 33.3% of the total damage, respectively (Figure 6).

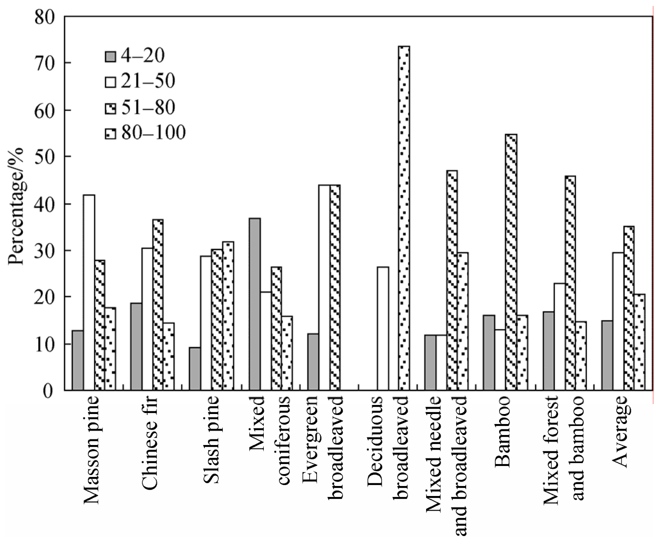

Figure 6 The range of percentage damage rates for different species/stands along the transect

Masson pine in Xingguo and Ningdu counties was severely damaged due to turpentine and local terrain. The primary damage type for high-altitude pine planted in the 1950s–1960s or even earlier was dislodging and branch breakage, and crown breakage, accounting for 30% and 22.9% of the damaged masson pine samples, and 17.1% and 12.9% of stem breakage and tip breakage, respectively. However, masson pine plantations at low-altitudes (<300 m), which were aerially-seeded in the 1980s–1990s, are young and slow-growing and escaped with almost no damage. The plot damage rates ranked 21%–50% and 81%–100% for masson pine samples and accounted for 43.4% and 27.6% of the total damage, respectively (Figure 6).

After felling, the Chinese fir plantations and secondary forests, which have a wood quality between slash pine and masson pine, were mostly crown damaged (about 47.4%), but also suffered from 26.3% and 13.2% tip breakage and stem breakage, respectively. The plot damage rates ranked 21%–50%, 51%–80% and 81%–100% for Chinese fir samples and accounted for 30.4%, 27% and 24.4% of the total damage, respectively (Figure 6).

Cryptomeria plantations distributed at an altitude of 700 m on Jinggang Mountain suffered locally severe damage, of which 38.5% and 15.4% were lodging and stem splitting, respectively, with relatively long extents, and 30.8% was mixed damage (Figure 6). Cryptomeria distributed at altitudes exceeding 1200 m was almost undamaged, because of its adaptation to low temperature and harsh climates, and slow growth and relatively hard wood quality.

About 84% of evergreen broad-leaved forests were subject to branch and crown breakage; plot damage rates ranked 21%–50% and 51%–80% and accounted for more than 80% of the total damage (Figure 7). The primary damage type for natural closed secondary deciduous broad-leaved forests was stem breakage, with plot damage rate ranking 81%–100% and accounting for 73.7% of the total damage. The plot damage rate of mixed needle and broad-leaved trees ranked 51%–80% and 81%–100% and accounted for 50% and 27.8% of the total damage respectively; the main damage types were stem breakage and mixed damage. The plot damage rate of mixed coniferous forests ranked 4%–20% and 21%–50%, accounting for 33.3% and 29.6% of the total damage respectively, with the main type of damage being crown breakage.

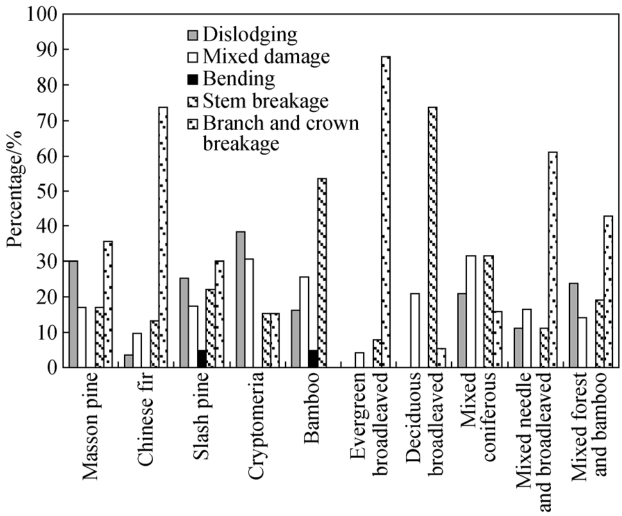

Figure 7 The percentage of damage type for each tree species along the transect

The primary damage types of mixed forest and bamboo were crown breakage and dislodging, with plot damage rates of 4%–20% and 21%–50% accounting for 37.5% and 31.3% of the total damage respectively. The bamboo was broken by stem cracking, with a plot damage rate of 51%–80% accounting for 41.9% of the total damage.

3.2.3 Stand origin and physical damage

We classified the forest as natural forest, artificial plantation, aerial-seeding plantation, natural secondary forests after cutting and natural closed secondary forest, according to stand origin. The damage rate for different stand origins decreased as: artificial plantation> natural forest> natural closed secondary forests> aerial-seeding plantation > secondary forests after cutting (Table 2), and overall more than 70% of samples were damaged.

Table 2 The percentages of sample stand origin types

Stand origin	Natural forest	Artificial plantation	Aerial-seeding plantation	Natural secondary forests after cutting	Natural closed secondary forest
Percentage (%)	15.3	73.2	3.2	1.8	6.4

Plantations were severely destroyed in low-altitude hilly regions due to low density wood quality, dense stands and turpentine, especially when located between mountains where there is a strong influence of local climate. The plantation plot damage rate was 30% and reached 51%–80% (Figure 8). Aerial-seeding plantations mainly distributed in low-altitude hilly regions of Xingguo County and Ningdu County along the eastern transect were still mostly healthy because of the young forest age and sparse stands. Taihe County, mainly composed of secondary deciduous broad-leaved trees planted in the closed forest project, were almost all damaged due to high accumulations of ice and snow on intertwined shrubs, although the fallen leaves decreased the surface area of freezing. Secondary forests planted after cutting, primarily Chinese fir planted soon after logging of masson pine, are distributed in low-elevation areas and had lighter damage due to young stand age. Natural evergreen broad-leaved forests on Jinggang Mountain along the western transect suffered relatively light damage, mainly consisting of branch and crown breakage. Generally, the resistance of trees to ice-snow disasters is stronger in natural forest than in plantations, because of natural selection.

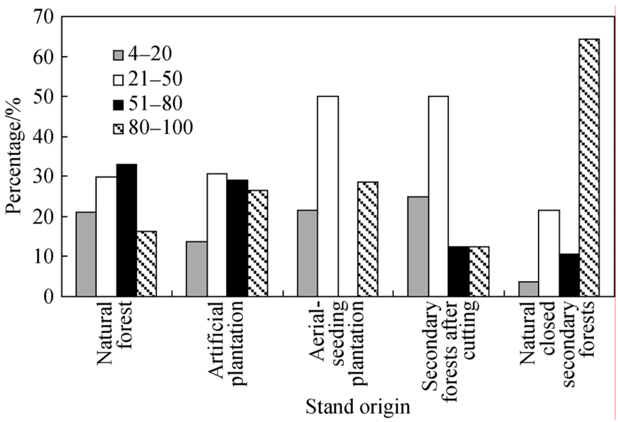

Figure 8 The percentage damage rate range for different forest stands

3.2.4 Forest site and physical damage

Topography is one of the most significant factors influencing the impact on forests by ice storms (Foster *et al*., 1998; Rhoads *et al*., 2002). On the basis of meteorological data, aerial photography and field observations from several sites, Lafon *et al*. (1999) concluded that slope aspect was important for the patterns of disturbance that resulted from the two ice storms in southwestern Virginia during 1994. Slopes facing south and east (windward slopes) sustained the heaviest forest damage. Millward and Kraft (2004) used satellite imagery to explore topographic patterns of forest damage caused by an ice storm that struck eastern Adirondack forests of northern New York, USA in 1998. They found that elevation and aspect were important controls on forest disturbance. The damage was concentrated within the 200–600 m elevation zone on east-facing (windward) slopes. Stueve *et al*. (2007) found that damage by ice storms periodically disturbing forests in eastern North America may vary spatially, especially in complex terrain. They used satellite imagery to investigate the spatial heterogeneity of forest damage caused by ice storms that affected the Appalachian Mountains, Virginia, during 1994, and the results display a region-scale (southwest-to-northeast) gradient in damage that apparently corresponds to a gradient in the depth of ice that accumulated during the storms. Damage also varied topographically, particularly by aspect, which was most extensive on east-, southeast- and south-facing slopes; at middle elevations; and on slopes of moderate steepness. A similar pattern was evident in Xingguo and Ningdu, where tree damage was very light below 300 m, relatively serious from 500 to 700 m and severe above 700 m (Table 3 and Figure 9). However, this pattern was not obvious in Taihe County. Most of the slash pine plantations at low-altitude were damaged due to turpentine, and closed natural secondary deciduous broad-leaved forest damage was severe due to a lot of ice and snow accumulating on intertwined shrubs. Natural forest on Jinggang Mountain sustained a high damage rate, mainly by branch and crown breakage. Cryptomeria plantations suffered mainly stem breakage, and Chinese fir plantations were mostly damaged by branch and crown breakage. Therefore, severe damage occurred in various elevation zones in different regions, indicating variable resistances to ice-snow disaster (Nykänen *et al*., 1997), and the effects of tree species, stand composition and stand origin.

Table 3 The percentage of different damaged types in each elevation ranges

Elevation (m)	Dislodging	Stem breakage	Branch and crown breakage	Bending	Mixed damage	Total
0–300	16.67	23.81	36.90	1.79	20.83	100
300–500	10.34	17.24	56.55	0.00	15.86	100
500–700	7.25	5.80	73.91	0.00	13.04	100
700–900	14.00	4.00	56.00	4.00	22.00	100
900–1100	9.52	9.52	71.43	4.76	4.76	100
1100–1300	38.46	30.77	23.08	0.00	7.69	100
>1300	10.00	13.33	70.00	0.00	6.67	100

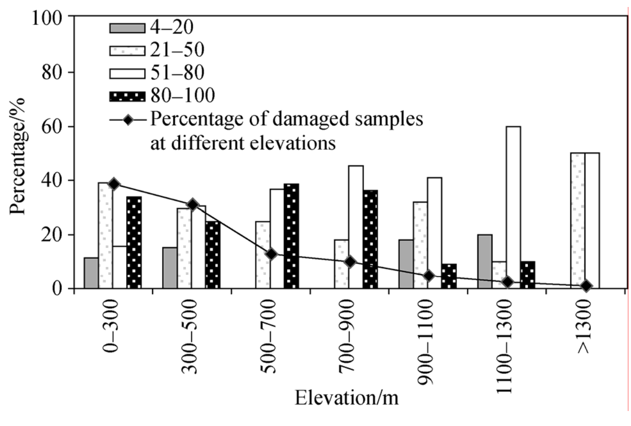

Figure 9 The relations between damage degree and altitudes

Damage also depended on slope angle and aspect. Some field studies have found that ice storm damage to forests increases with increasing slope inclination, and trees on steep slopes with asymmetric crowns sustained the heaviest damage (Rhoads *et al*., 2002; Lafon, 2004; 2006). We found that 75% of samples were located on slopes >15º, for which plot damage rate ranked 81%–100% in damaged samples facing north and accounted for more than 45% of the total damage.

Furthermore, forests on windward slopes and in topographic gaps between mountains tended to suffer severe damage due to crown inclination, because rapid freezing and stronger winds in air gaps are the most important external forces leading to damage.

3.2.5 Variations in damage extent for main plantations

The order of damage extent for different plantations along the transect decreased as slash pine > masson pine > mixed plantation > Chinese fir (Table 4 and Figure 10). The damage percentage for slash pine was 61.3% of all samples, of which 43.2% cannot recover naturally and the relative damage rate was 70.4%. This means that 43.2% of the slash pine forest should be cleared and reforested. On the one hand, slash pine is an introduced species from southern America with annual average temperatures of 18.9–22.2℃ and is characterized by fast growth and low wood quality. On the other hand, turpentine activities lead to its vulnerability: 71.4% of tree samples were turpentined and the damage rate was 92% with a naturally unrecoverable damage rate of 72.4%, however, the turpentine rate is 39.9% in healthy samples. Therefore, the turpentine rate should be controlled within a

Table 4 Extent of damage in slash pine, masson pine, Chinese fir and mixed forest

Damage extent	Slash pine			Masson pine		
	Sample number	Actual damage ratio	Relative damage ratio	Sample number	Actual damage ratio	Relative damage ratio
Naturally unrecoverable	40	43.2	70.4	41	31.8	60.9
Mixed damage	13	11.3	18.5	12	10.7	20.6
Naturally recoverable	10	6.8	11.1	23	9.7	18.6
Total	63	61.3	100.0	76	52.2	100.0

Damage extent	Chinese fir			Mixed forest		
	Sample number	Actual damage ratio	Relative damage ratio	Sample number	Actual damage ratio	Relative damage ratio
Naturally unrecoverable	27	14.9	32.5	11	29.6	60.2
Mixed damage	11	6.4	13.8	5	13.4	27.3
Naturally recoverable	54	24.7	53.6	10	6.2	12.5
Total	92	46.0	100.0	26	49.2	100.0

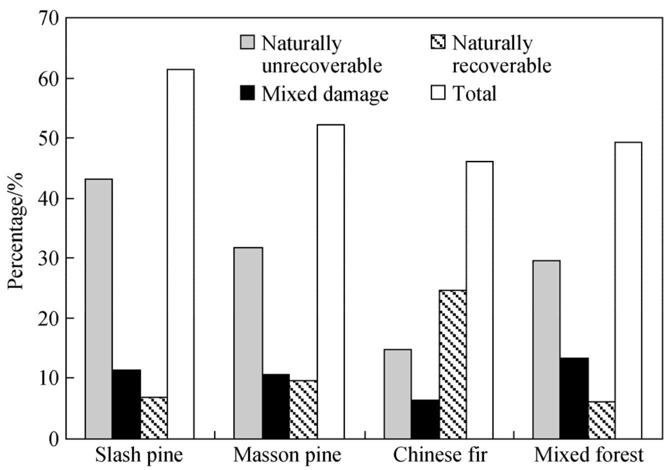

Figure 10 The actual percentage of main forest plantation in damaged samples along the transect

certain range to strengthen the slash pine.

Masson pine is the native pioneer species and is widely distributed along the transect. Its wood quality is harder than slash pine, and middle-aged and mature masson pine were almost all turpentined. Therefore, its actual damage percentage was 52.2% in locations immediately adjacent to slash pine, its natural unrecoverable damage rate was 31.8%, and its relative damage rate was 60.9%.

The actual damage percentage of mixed coniferous and needle broad-leaved plantations was 49.2%, although fewer samples were collected and the natural unrecovered damage rate was 29.6% with a relative damage rate of 60.2%.

Chinese fir is a local tree species that is common along the transect, and has been partly planted for forest regeneration after masson pine cutting. Chinese fir shows the lowest damage rate of 46%, and its natural unrecoverable damage rate was 14.9% with a relative damage rate just of 32.5%.

3.2.6 Influences of human activities on physical tree damage

Along the transect, human activities related to the physical damage by the ice-snow disaster were the addition of turpentine for slash pine with tree ages more than 15 years and mature masson pine. Sampling was carried out at the argo-purlieu ecotone in Guping village, Guanxi town, Taihe County, where slash pine is distributed on western and northern slopes and the crest of the mountain at an altitude of 100 m. Here, almost all damage was stem breakage. About 71.4% of slash pine in a 30 m×30 m sampling plot at the crest of the mountain was turpentined and 92.9% of pine was damaged physically, of which 70.4% was stem breakage and 72.5% was broken at 1.5–2 m stem height (Table 5). However, a patch of slash pine on south facing slope was damaged because of local terrain changes, its young age and lower turpentine levels. Three sampling plots on the south slope had sizes of 20 m×20 m, 20 m×10 m and 30 m×10 m, with a total of 193 trees, a turpentined rate of 39.9% and unturpentined rate of 60.1%.

Table 5 Results for slash pine forest

	Uprooting		Bending		Grow normally		Stem breakage		Total	
	Tree number	%	Tree number	%	Tree number	%	Tree number	%	Tree number	%
Unturpentined	1	50	16	80	1	14.3	10	14.5	28	28.5
Turpentined	1	50	4	20	6	85.7	59	85.5	70	71.4
Total	2	100	20	100	7	100	69	100	98	100
%	2.0	–	20.4	–	7.1	–	70.4	–	100	–

4 Discussion and conclusions

A climatic anomaly was the primary cause of the ice-snow disaster. The temperature rapidly increased by 11.6–14.3℃ during 4–11 January, and then decreased abruptly by 17.1–20.8℃ during 12–14 January, with a subsequent period of over 20 days at low temperature. There were four heavy precipitation events (sleet and snow) from 25 January to 5 February, including especially severe precipitation during 1 and 2 February with a total of 73.5 mm. Furthermore, the continued freezing, snow cover, fog, verglas, rain, snow and ice particles lasting more than one month aggravated the damage.

Damage extent in different plantations along the transect decreases in the order of slash pine > masson pine > mixed plantation > Chinese fir. The damage percentage in slash pine samples is 61.3%, of which 43.2% cannot recover naturally. On the one hand, slash pine is an introduced species from southern America with an annual average temperature of 18.9–22.2℃ and is characterized by fast growth, low wood quality and rich oleoresin content. On the other hand, turpentine activities lead to its vulnerability: 71.4% of the trees were turpentined in samples with a damage rate of 92% and naturally unrecoverable damage rate of 72.4%; however, the turpentine rate is 39.9% in healthy samples. Therefore, the turpentine rate should be controlled within a certain range to strengthen the slash pine. Masson pine is the native pioneer species in forests and has harder wood; 52.5% were damaged due to turpentine, in which 60.9% were naturally unrecoverable, when immediately adjacent to slash pine. Chinese fir is a local species and shows the lowest damage rate. The results indicate that we should abide the rule of matching tree species with site conditions as much as possible in forest ecosystem restoration and reconstruction, and restrict excessive turpentine activities to guarantee the resistance of forest ecosystems to disaster.

The extent of damage along the transect shows regional differences. From west to east, we can see that evergreen broad-leaved forests on Jinggang Mountain show light damage with branch and crown breakage; Cryptomeria plantations located at an altitude of 700 m were severely destroyed, mainly by stem splitting; Chinese fir shows light damage with crown breakage below 700 m and relatively severe stem breakage and mixed damage above 900 m. Masson pine and slash pine in the central transect at low altitude in Jitai Basin were severely destroyed due to turpentine activities and local microclimate, and the damage type was stem breakage and uprooting, while Chinese fir showed light damage; closed natural secondary deciduous broad-leaved forest damage was severe due to high ice and snow accumulation on intertwining shrubs. Therefore, we should tighten the management of natural secondary forest to prevent ice-snow disasters and satisfy the demands of IPCC LULUCF regarding increasing carbon sinks by forest management. Masson pine aerial-seeding plantations below 400 m altitude along the eastern transect in Xingguo and Ningdu counties remained almost undamaged for small tree sizes, and Chinese fir distributed between 500 and 900 m shows light branch and crown breakage. However, masson pine distributed above 400 m which was planted in the 1960s was severely damaged due to turpentine.

Based on the conclusions of the field investigation, we preliminarily analyzed the MODIS 16-days maximum value composite NDVI data from February to April in 2007 and 2008. Results demonstrated that the difference in NDVI for the same period in the two years is difficult to interpret in terms of physical damage to forest stands, which may be due to the luxuriant understorey. Further work will focus on remote sensing methods that can evaluate the loss by the ice-snow disaster, which will integrate the forest resource investigation data with time series from NDVI.

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