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Impact of the 2008 ice storm on moso bamboo plantations in southeast China

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[1] A massive ice and snow storm occurred in early 2008 in south China and caused extensive damage to forests. Thirty-six plots of moso bamboo (*Phyllostachys pubescens*) plantation were established following the ice storm in the central growth area of moso bamboo, Fenyi, Jiangxi province, China. The topographical condition and stand attributes, and the ice storm impact on moso bamboo plantations were investigated. We found that an average of 54.48% (±17.58%) bamboo culms was damaged. The damage patterns included bending, snapping and uprooting, which accounted for 17.01% (±7.28%), 22.37% (±11.58%) and 15.11% (±11.54%) of the total, respectively. An average of 16.42 (±7.09) tons per hectare dead dry biomass was produced, accounting for 37.73% (±14.41%) of total aboveground biomass. A mean value of 8.21 (±3.55) Mg C per hectare was shifted from living biomass to dead. Stand level analysis showed a significant increase in damage level and dead biomass production at north oriented slopes, and with high stand density (between 3000 and 4500 culm/ha). High altitude caused a higher proportion of snapped culms but a lower proportion of uprooted. Analysis at individual culm level suggested that the susceptibility for a culm to break or uproot due to ice storm would rise as its diameter increased, while the susceptibility to bend would decline. The young (1 year old) culm was more susceptible to snapping or bending, while overmature (>5 years old) culm was more susceptible to uprooting, implying it is a good managing practice to harvest mature culm timely.

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1. Introduction

[2] An ice and snow storm occurred in early 2008 in China with a record-setting lasting duration, severity and area affected. This unprecedented storm caused a large-scale ecological disturbance to the natural and managed ecosystems [*Gao et al.*, 2008; *Wang et al.*, 2008; *Zhou et al.*, 2010]. According to the Ministry of Civil Affairs, 19 provinces were hit with a population of over 100 million affected and 129 lives claimed in this storm. About 485,000 homes were destroyed and another 1.6 million damaged, displacing nearly 1.7 million people. The ice storm slashed large areas of forests across China, with 20.86 million hectares forest and plantation damaged, accounting for one-tenth of China's forests and plantations, according to China's State Forestry Administration [*Stone*, 2008].

[3] With an area of 4.84 million hectares, bamboo plantations are one of the most important forest types in China and account for about a quarter of the global total, according to the sixth inventory of forest resources of China [*Li et al.*, 2005]. China, which has long been known as "Kingdom of Bamboo" [*Yi*, 1997], is rich in bamboo resources, with moso bamboo (*Phyllostachys pubescens*) being the most important commercial species due to its big size, rapid growth and versatile use. There is 3.37 million ha moso bamboo plantation in China, accounting for over 90 percent of the total in the world. In the context of the increasing rate of tropical deforestation and sharp shrinkage of forest timber production, the bamboo, one of the fastest growing plants in the world and one of the most important nonwood forest products, is an excellent alternative for the wood timber [*Zhou et al.*, 2005]. This situation greatly stimulates the development of bamboo resources, especially in developing countries. During the period between 1981 and 2003, bamboo plantation area has increased by 51.4% in China [*Li et al.*, 2005]. Bamboo industry has been the backbone in some rural area in developing countries, with a production of 1.3 billion culms and production value of ca. $8.2 billion in 2005 in China. 35 million farmers are fully or partly employed in bamboo industry [*Cheng and Wang*, 2007].

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Figure 1. Damage patterns of moso bamboo (*Phyllostachys pubescens*) culms. (a) bending, (b) snapping, and (c) uprooting. (Photo by the authors.)

[4] Ice storms are a major wintertime extreme weather event that occurs commonly in East Asia [*Ding et al.*, 2008]. However, the frequency of occurrence in south China is not as great as in north China [*Su and Han*, 2008] and therefore south China is in general unaware of and unprepared for large ice storms. Partly because of this, ice storms and their associated risks are rarely considered as a concern when bamboo afforestation and cultivation are implemented. There are few references in the literature reporting the effect of ice storm on bamboo plantation. Little is known about what types of damage bamboo culm could suffer due to ice and snow load, and what factors influence the degree of damage to bamboo stands. It is poorly understood how much litterfall or dead biomass can be produced due to great climatic disturbance and what the implication is to the carbon stock of bamboo plantation.

[5] The primary objective of the study is to quantify the intensity of damage and carbon shift from living to dead biomass caused by the 2008 ice storm. A second objective is to determine the correlation between damage severity and topographical variables as well as stand attributes. This study also aims to examine the difference of response to ice storm of individual bamboo culm with different age and size. With this study, we hope to establish standard procedures in analyzing impacts of ice storms on bamboo forests and call for increased awareness of the power of extreme events as a potential driving force in terrestrial carbon cycling.

2. Methods

2.1. Study Site

[6] The study was carried out at Mount Dagangshan, experimental area within Subtropical Forest Experimental Center, Chinese Academy of Forestry, located in Fengyi county, Jiangxi province. Mount Dagangshan, between 27°30′–27°50′N, and 114°30′–114°45′E, belongs to the north offset of Luoxiaoshan Mountain Range. The climate is subtropical monsoonal humid, with a mean annual temperature ranging from 15.8°C to 17.7°C. The mean maximum temperature in July is 28.8°C, with daily maximum of 39.9°C. The minimum mean temperature in January is −5.3°C, with daily minimum of −8.3°C. The annual sunshine hours vary between 1378 h and 2047 h, with an average of 1657 h. The annual precipitation ranges from 1069.8 mm to 2227.6 mm, with an average of 1590.9 mm, mostly occurring in the period between March and August. The frost-free period is about 265 days per year. The soil belongs to yellowish brown lateritic soil type [*Xi*, 1993], with a depth of around 1.0 m. The slope varies from 20 to 30 degrees.

[7] Moso bamboo was initially planted probably around 100 years ago, and invaded into the natural forest through the extension of the rhizome. By removing the overstory trees continuously from the invaded forest, people helped to establish pure bamboo plantations. Our experimental stand is part of these plantations. Weeds and shrubs are cleared once every 2 years in the stand. A number was written on the new culms' wall indicating the year when the culms were produced. The stand is thinned every year by harvesting the culms more than 7 or 8 years old and the culms with small size in autumn and winter season.

2.2. Measurements of Bamboo Damages

[8] Preliminary reconnaissance was carried out prior to the design for field survey. Two topographical variables (altitude and aspect) and a stand attribute (stand density) were selected to determine their effect on bamboo damage severity at stand level. Considering 2 groups for each factor

and 4–5 replications for each combination of these factors, we need to have 32–40 plots. For survey on single-species plantations, a plot size of 400 m^2 is found to be the balance between sampling accuracy and survey efficiency [*Huang et al.*, 1992; *Fan et al.*, 2003]. Therefore, we randomly established thirty-six 400 m^2 (20 × 20 m) plots in April 2008, following the great ice storm, across the study site. The slope, aspect and altitude were registered. The diameter at breast height (DBH) of each bamboo culm, either damaged or undamaged, was measured within each plot. The culm age was recorded by checking the number which had been written on the culms' wall in the year when the culms were produced.

[9] Culm status was categorized as undamaged, bending, snapping and uprooting, according to culm appearance after the ice storm (Figure 1). (1) Bending: the culm bended through the majority (>80%) of the whole length, or the culm leaned more than 30 degree to vertical with its root and rhizome held tightly in earth (Figure 1a). (2) Snapping: the culm broke or splitting at the clear bole (Figure 1b). (3) Uprooting: the root system and basal part of the culm were unearthed partly or completely, with the culm leaning or overturned (Figure 1c). The degree of bending, snapping and uprooting was expressed separately as percentage of bended, snapped and uprooted culms to the total culms in each plot. Bending, snapping and uprooting were combined into overall damage degree expressed as percentage of damaged culms to the total in each plot.

2.3. Calculation of Ice Storm–Induced Carbon Transfer Among Different Pools

[10] To calculate the ice-induced carbon transfer among different pools, the total biomass and dead biomass caused by the ice storm was estimated first. The total biomass for each plot was expressed as the sum of the biomass of each individual bamboo (damaged or undamaged) in this plot (equation (1)), and the dead biomass for each plot was expressed as the sum of the biomass of snapped and uprooted individual in this plot because the bamboo with these two patterns was going to die off within a few months following the ice storm (equation (2)). Individual bamboo biomass (equation (3)) was expressed as the sum of its culm biomass, which was highly related to the culm DBH in accordance with power model (equation (4)), and its foliage biomass, which was highly related to the culm DBH and the stand density in accordance with power model (equation (5)). These two empirical models were established by *Nie* [1994] in this study area.

$$B_a = \sum_{i=1}^{n} Wi \tag{1}$$

$$B_d = \sum_{j=1}^{m} Sj + \sum_{k=1}^{p} Uk \tag{2}$$

$$W = Wc + Wf \tag{3}$$

$$Wc = 0.0925D^{2.081} \qquad R^2 = 0.998 \tag{4}$$

$$Wf = 1.134\,N^{-0.3054}D^{0.933} \qquad R^2 = 0.885 \tag{5}$$

where B_a and B_d are the total biomass (kg) and dead biomass production (kg) in a plot, respectively; Wi the biomass of ith bamboo of the plot; Sj the snapped bamboo biomass of jth bamboo; Uk the uprooted bamboo biomass of kth bamboo; n, m and p are the total number of bamboos, the snapped bamboos and uprooted bamboos within a plot, respectively; W, Wc and Wf are the individual bamboo biomass, the culm biomass and the foliage biomass (branch and leaf) respectively; D the DBH (cm) of the bamboo; N the stand density (culm/ha). The carbon was estimated by multiplying biomass by carbon fraction where 0.5 was used for moso bamboo [*Zhou and Jiang*, 2004; *Chen et al.*, 2009].

2.4. Statistic Methods

[11] At stand level, the altitude, aspect and stand density were grouped each into two categories based on the plot data set. High altitude (HA) referred to altitude between 600 m and 700 m above sea level, while low altitude (LA) between 300 m and 400 m above sea level. High density (HD) referred to stand density between 3000 and 4500 culms per hectare, while low density (LD) between 1500 and 3000 culms per hectare. The density of almost all the moso plantations in this area fell into this range. North oriented slope (NS) referred to slope facing north, northwest or northeast, while south oriented slope (SS) to south, southwest and southeast. For the individual culm, DBH was classified into 10 categories: 5.0–5.9 cm, 6.0–6.9 cm, and etc. The largest DBH class was DBH > 14 cm. Bamboo produces new shoots at a 2 year interval, with the new shoot production year known as on-year and the following year as off-year. The majority (more than 90%) of new shoots are produced in the on-year. At the study site, the odd-numbered years (for example, 2005, 2007) are on-year, resulting in age series of odd numbers (1 year old, 3 year old, etc.) for almost all the culms when they were surveyed in 2008. Because of this, only the culm ages of 1, 3, 5 and 7 years old were selected for data analysis at individual level and the even-numbered ages were not included.

[12] The damage severity caused by ice and snow varied with site conditions and stand attributes [*Valinger et al.*, 1993; *Van Dyke*, 1999; *Bragga et al.*, 2003]. To examine the correlation between stand damage and the topographical variables as well as the stand density, a univariate analysis of variances (UNIANOVA) was applied using altitude, aspect and stand density as fixed factors. The analysis was performed separately using as dependent variables the overall damage degree, bending degree, snapping degree and uprooting degree. The main effects for each factor were tested. The statistics of F value and significance (p) were given for hypothesis testing. To quantify the relationship between ungrouped stand density and the overall damage degree, a linear regression analysis was applied with determination coefficients (R^2) and significant level (p) of the model calculated and the fit line drawn. The relationship between individual culm DBH and the culm status (i.e., bending, snapping, uprooting or damaged overall) was separately examined in a two-way cross tabulation table, with associated Pearson chi-square (χ^2) and asymptotic significance (p) calculated. To quantify the relationship between DBH class and the proportion of each damage pattern, a linear regression analysis was applied with determination coefficients (R^2) and significant (p) of the

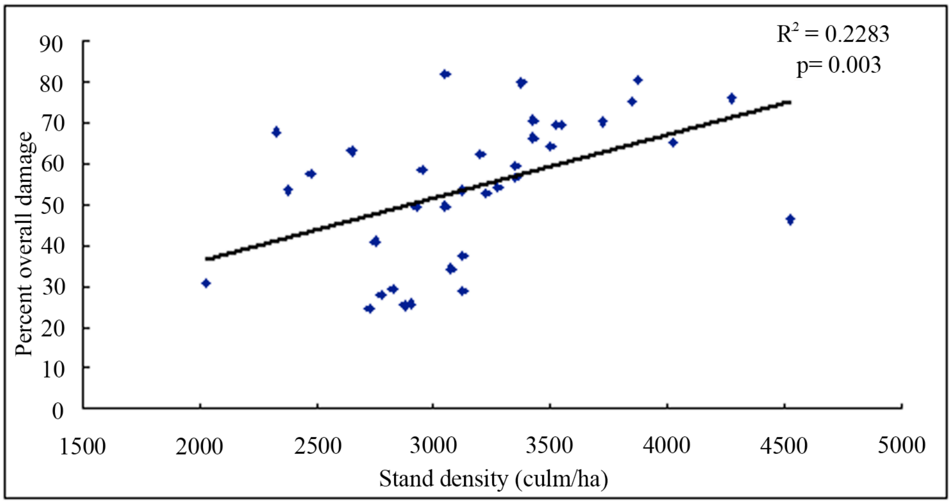

Figure 2. Linear regression between stand density and percent overall damage, with fit line and determination coefficient R^2 and significance p.

models calculated. Similarly, cross tabulation analysis was also applied to test the correlation between culm age and damage status.

[13] To assess the effects of topographical variables and stand density on dead biomass production, an UNIANOVA analysis was applied with the grouped altitude, aspect and density as fixed factors and the aboveground dead biomass production (B_d, expressed in ton per hectare) and percent B_d (ratio of B_d to B_a) as dependent variables separately. The main effects for each factor were tested and no interaction was included. The statistics of F value and significance (p) were given for hypothesis testing. Results were considered significant at $p < 0.05$. Data were analyzed with SPSS program V.16.

3. Results

3.1. Stand Level Damage

[14] In the study area, the damage severity of moso bamboo stands varied widely, with a percentage of damaged culms ranging from 24.77% to 81.97% (averagely 54.48% ± 17.58%). Among them, 17.01% (±7.28%) culms bended over (ranging from 4.48% to 34.51%), 22.37% (±11.58%) snapped or broke (ranging from 9.3% to 52.55%), and 15.11% (±11.54%) uprooted (ranging from 0 to 46.67%).

[15] The UNIANOVA analysis indicated that the overall damage levels of bamboo stand were affected significantly by the site altitude, slope aspect and stand density in accordance with a general linear model ($R^2 = 0.521$, $F = 11.62$, $p < 0.001$). However, the significance of impact on damage level for each factor was different. Averaged damage rate (±SE) for bamboo stand with a HD and a LD was 63.19% (±2.84%) and 51.22% (±4.86%), respectively, presenting a statistically significant difference ($F = 5.742$, $p = 0.023$). A linear regression between ungrouped stand density and overall damage degree (Figure 2) revealed that the overall damage intensity of bamboo stand went up with increased stand density ($R^2 = 0.228$, $F = 10.059$, $p = 0.003$). A more densely populated bamboo stand suffered from ice damage more severely than a less densely populated stand. A mean percent damage degree of 68.06 (±5.02) occurred at sites with NS, whereas 46.35 (±2.86) with SS. The difference between NS and SS was also significant ($F = 16.669$, $p < 0.001$), i.e., stands at NS experienced much more damage than at SS. A higher altitude tended to aggravated ice damage (a mean percent damage degree of 62.34 ± 5.72 at HA compared to 52.06 ± 2.47 at LA) but the difference was not statistically significant ($F = 2.702$, $p = 0.11$) (Table 1).

[16] Generally, high altitude, high stand density and north oriented slope caused more severe damage to bamboo stands. However, different patterns of damage did not show a same tendency proportionally as the overall damage. No significant difference was found in bending degree between levels either of elevations ($F = 0.326$, $p = 0.572$), aspects

Table 1. Topographical Variables and Stand Density Effects on Overall Ice Damage and Each Damage Pattern[a]

Variables		Overall				Bending				Snapping				Uprooting			
		Mean	SE	F	p	Mean	SE	F	p	Mean	SE	F	P	Mean	SE	F	p
Altitude	high	62.34	5.72	2.701	0.11	15.37	3.00	0.326	0.572	37.01	3.52	26.499	<0.001	9.95	3.27	4.594	0.04
	low	52.06	2.47			17.25	1.30			17.18	1.52			17.63	1.41		
Aspect	north	68.06	5.02	16.669	<0.001	18.52	2.63	2.522	0.122	25.31	1.76	1.197	0.282	20.64	2.87	20.257	<0.001
	south	46.35	2.86			14.1	1.50			28.89	3.09			6.94	1.64		
Density	high	63.19	2.84	5.742	0.023	18.46	1.49	2.684	0.111	28.00	1.75	1.526	0.226	15.73	1.63	1.842	0.184
	low	51.22	4.86			14.16	2.55			25.20	2.99			11.85	2.78		

[a] Based on a UNIANOVA analysis, showing mean percentages of damage with different pattern and their standard errors (SE), as well as statistics calculated with hypothesis testing.

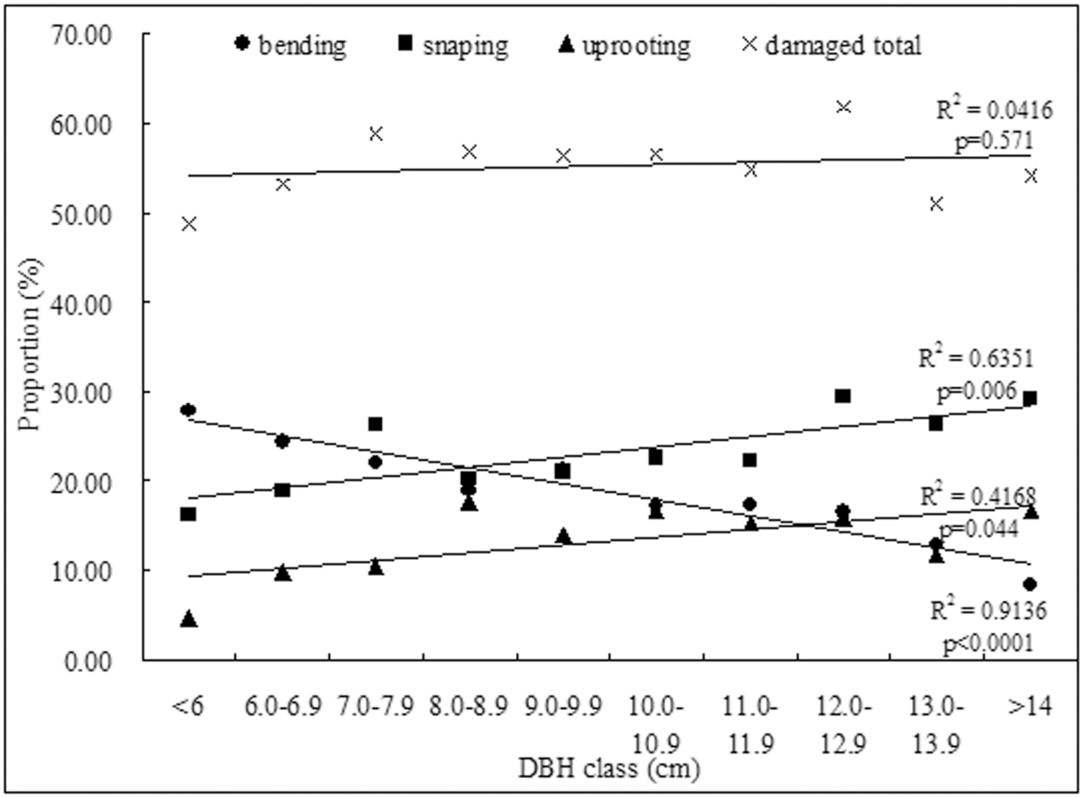

Figure 3. Proportion of culms bended, snapped, uprooted, and overall damaged in association with culms' DBH class, with fit lines, and statistics of R^2 and p.

(F = 2.522, p = 0.122) or stand densities (F = 2.684, p = 0.111). Snapping degree at HA (37.01% ± 3.52%) remarkably higher than at LA (17.18% ± 1.52%), and the difference was statistically significant (F = 26.499, p < 0.001), although altitude effect on overall damage degree did not show a statistically significant difference as showed above. Snapping degree did not show significant difference between levels for aspect (F = 1.197, p = 0.282) and density (F = 1.526, p = 0.226). The uprooting degree was unexpectedly lower at HA (9.95% ± 3.27%) than at LA (17.63% ± 1.41%) with a significant difference (F = 4.594, p = 0.04), a contrary tendency to overall damage and snapping. Uprooting occurred much more heavily in NS (20.64% ± 2.87%) than SS (6.94% ± 1.64%); and the difference was significant (F = 20.257, p < 0.001) (Table 1).

3.2. Individual Culm Damage

[17] The Chi square analysis indicated that vulnerability of a bamboo culm to ice damage had no significant correlation with its DBH class (χ^2 = 12.984, p = 0.163). However, separate tabulation analysis for the association between DBH class and each damage pattern exhibited a difference from overall damage. There was a significant association between culm DBH and the proportion of culms suffered from bending (χ^2 = 43.652, p = 0.001), snapping (χ^2 = 45.086, p < 0.001), and uprooting (χ^2 = 17.99, p = 0.035). A linear regression between the midpoint of DBH class and percentage of each damage pattern as well as overall damage (damaged total) corroborated above findings (Figure 3). As Figure 3 showed, the linear regression models were significant for each damage patterns (for bending: R^2 = 0.9136, p < 0.0001; for snapping: R^2 = 0.6351, p = 0.006; for uprooting: R^2 = 0.4168, p = 0.044) but not for overall damage (R^2 = 0.0416, p = 0.571). A small-sized culm was more likely to suffer from bending damage while a large-sized was more susceptible to snapping and uprooting damage resulted from ice and snow.

[18] Cross tabulation analysis suggested there existed a significant association between culm age and the proportion of bamboo culms with an overall damage (χ^2 = 153.3, p < 0.001), bending (χ^2 = 61.16, p < 0.001), snapping (χ^2 = 75.73, p < 0.001) as well as uprooting (χ^2 = 54.57, p < 0.001). Figure 4 shows the proportion of bamboo culms with each damage pattern associated with culm age. Generally, a younger culm was more likely to suffer from ice damage, especially from bending and snapping, while uprooting was more likely to occur in old culms.

3.3. Dead Biomass Production and Carbon Transfer Among Different Pools

[19] The 2008 ice storm brought down considerable loss of standing biomass in moso bamboo stands, producing large amount of dead dry biomass ranging from 4.39 t/ha to 28.2 t/ha (averagely 16.42 t/ha ± 7.09 t/ha), accounting for 15.26% to 59.94% of the total aboveground biomass (averagely 37.73% ± 14.41%). Accordingly, 8.21 (±3.55) Mg C per hectare (ranging from 2.20 Mg C to 14.1 Mg C per hectare) in living biomass was transferred into dead biomass.

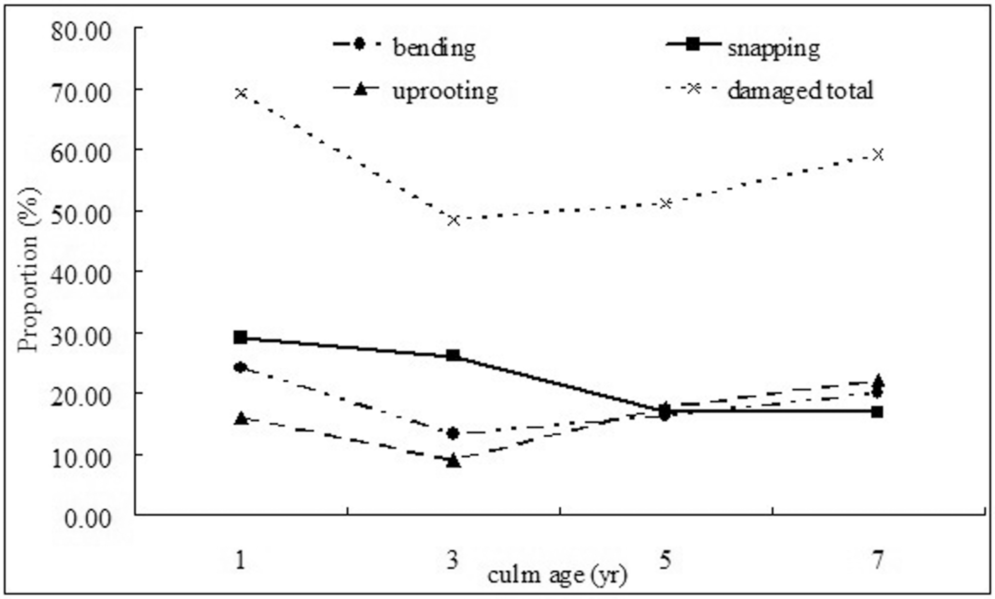

Figure 4. Proportion of bamboo culms with bending, snapping, uprooting damage, and total damage in association with culms' age.

[20] Similar to damage level, the UNIANOVA analysis prompted a significant correlation between aboveground dead dry biomass production and the topographical variables as well as stand density in accordance with a general linear model ($R^2 = 0.527$, $F = 11.86$, $p < 0.001$). A significant correlation was also found between the proportion of dead dry biomass to total biomass and above mentioned variables ($R^2 = 0.476$, $F = 9.68$, $p < 0.001$). At HA, the ice storm produced an average of aboveground dead biomass of 19.07 (±2.29) t/ha (or 9.55 ± 1.15 Mg C per hectare was transferred into dead biomass from living biomass), accounting for 47.71% (±4.91%) of the total aboveground biomass, considerably higher than that at LA (14.9 ± 0.99 t/ha), accounting for 34.58% (±2.12%), although the difference for the former was not significant ($F = 2.767$, $p = 0.106$). NS and HD had similar effects on dead biomass production with a mean value of 20.03 (±2.01) t/ha and 20.53 (±1.14) t/ha respectively, accounting for 49.29% (±4.3%) and 45.56% (±2.44%) of the total biomass, significantly higher than their opposites (13.93 ± 1.15 t/ha for SS; 13.43 ± 1.95 t/ha for LD). The high altitude, high stand density and north oriented slope, with a higher damage level as found earlier, produced higher dead biomass and more carbon was transferred into dead biomass from living biomass (Table 2).

4. Discussion

[21] Damage from ice storm is affected by numerous climatic factors and geographic variables, including ice thickness, elevation, slope aspect, wind velocity, crown form, stand density and tree size [*Bruederle and Stearns*, 1985; *Seischab et al.*, 1993; *Sissini et al.*, 1995; *Rhoads et al.*, 2002; *Millward and Kraft*, 2004; *Olthof et al.*, 2004]. Previous observations have revealed that forests at higher elevation could encounter higher risk of damage from snow and ice [*Megahan and Steele*, 1987; *Valinger and Lundqvist*, 1992; *Rhoads et al.*, 2002]. In our study, the bamboo stand at the site between 600 and 700 m above sea level received higher degree of damage and more dead biomass production than that at site between 300 and 400 m above sea level. Moso bamboo is a typical subtropical plant which is suitable for growing hilly area with an elevation not higher than 800 m. Bamboo stands at higher altitude experienced a longer duration of snow and ice load following an ice storm due to lower temperature and was exposed to heavier wind, resulting in a more severe damage to the stand, and consequently, a higher dead biomass production. Heavier snowfall at HA might be another reason for the more damage to the bamboo. *Zhu et al.* [2006] noted that the snow and wind-induced damage increased with the elevation in a montane secondary forest in northeastern China. *Rhoads et al.* [2002] reported that ice damages in mature forests increased with elevation following 1998 ice storm, with damage only occurring above about 600 m. However, there was inconsistent report concerning elevation's effects on ice storm damage. *Millward and Kraft* [2004] observed a strong influence of elevation on forest damage caused by 1998 great ice storm, with impacts concentrated between 200 and

Table 2. Topographical Variables and Stand Density Effects on Aboveground Dead Biomass Production and Its Proportion to Total Biomass[a]

Variables		Aboveground Dead Dry Biomass Production (t/ha)				Proportion of Dead Dry Biomass (%)			
		Mean	SE	F	p	Mean	SE	F	P
Altitude	high	19.07	2.29	2.767	0.106	47.71	4.91	5.986	0.020
	low	14.9	0.99			34.58	2.12		
Aspect	north	20.03	2.01	8.179	0.007	49.29	4.30	12.754	0.001
	south	13.93	1.15			33.01	2.45		
Density	high	20.53	1.14	12.553	0.001	45.56	2.44	4.245	0.048
	low	13.43	1.95			36.74	4.17		

[a] Based on a UNIANOVA analysis, showing mean values of aboveground dead biomass and its percentages and their standard errors (SE), as well as statistics calculated with hypothesis testing.

600 m, and the damage at the altitude beyond 600 m was slighter. The differential effect of elevation on forest damage could be attributed to the meteorological conditions unique to a particular storm, for example, the vertical stratification of the varying temperature of air masses [*Millward and Kraft*, 2004].

[22] The damage severity of bamboo stand and dead biomass production presented a significant difference between SS and NS, with percent overall damage decreasing by around half at SS compared with NS. In southeast part of China, the south faced slope receives more sunlight and heat in winter season than north faced slope, leading to a warmer microclimate, and consequently reducing the lasting duration of ice accumulation and snow load, lessening the damage of bamboo stand eventually. Several studies for other forests recognized the effect of slope aspect on forest damage, but the effect varied greatly. *Millward and Kraft* [2004] reported a strong influence of aspect on ice storm damage in the Adirondack Park forest in northern New York State, which was concentrated at locations with a landscape orientation facing eastward and ranging between northwest and southeast, however. *Zhu et al.* [2006] noted that percent snapped trees seemed to increase from southern slope to northwestern slope. *Seischab et al.* [1993] found that glaze storm damage was usually worse in north and eastern slope exposure. *Foster and Boose* [1992] observed that the most important site factor was the degree of wind exposure, which controlled tree damage caused by hurricanes, the natural disturbance perhaps most similar to ice storms [*Turner and Dale*, 1998; *Dale et al.*, 2001]. It was the consistent wind direction from the east-northeast throughout the duration of 1998 North America ice storm [*DeGaetano*, 2000] caused greater damage to forests with an east-northeast exposure than other exposures [*Millward and Kraft*, 2004]. In our study area, which is under the monsoonal climate, the northwestern or northeastern wind prevails almost throughout winter seasons, giving another reason that the north faced slope exhibited greater damage on bamboo stand than south faced slope.

[23] We found in our study that there was a positive relationship between bamboo stand density and overall damage degree, as well as the dead biomass production, a conclusion similar to that in several other studies. *Ryall and Smith* [2005] reported a strong positive relationship between crow damage and stand density for red pine (*Pinus resinosa*) plantations in eastern Ontario damaged by the 1998 ice storm. *Burton* [1981] and *Cremer et al.* [1982] observed that overstocked or dense plantations suffered more severe damage than more widely spaced plantations with trees with sturdier boles and well developed canopies. However, there were some observations reported in literature differing from ours. *Amateis and Burkhart* [1996] found no relationship between stand density and severity of damage. Other studies on plantations or secondary montane forest have shown that thinned, or less dense, stands were more resistant to ice storm damage than unthinned stands [*Stroempl*, 1971; *Van Dyke*, 1999; *Zhu et al.*, 2006]. The effect of stand density is, in a way, the representative of the DBH effect on ice damage level, and it is difficult to separate them from each other [*Ryall and Smith*, 2005; *Zhu et al.*, 2006] because there is a natural inverse relationship between stand DBH and stand density in regular tree plantations. For the bamboo stand we surveyed, however, no relationship could be found between mean DBH and stand density with linear regression analysis (F = 3.474, p = 0.071). Unlike woody trees, bamboo, under grass family, has no cambium within the culm and there is no secondary growth for culm diameter. Therefore, the culm size retained constant through its life. *Sterck and Bongers* [1998] noted that, to reach high light levels above the canopy, a plant can invest more resources to height growth. In a denser bamboo stand with worse light condition, the newly produced culms tend to grow higher and be more spindly, resulting in a lower taperingness (ratio of diameter to height) for bamboo culm which was proven to be more susceptible to ice and snow damage [*Petty and Worrell*, 1981; *Paatalo et al.*, 1999]. Another reason for higher damage percentage in denser bamboo stand was that, with the bamboo crowns supporting each other, the ice and snow matted the overstory canopy together, resulting in bending over of the culms and collapsing of the entire sections of the stand eventually. *Harrington and DeBell* [1996] described similar findings in young, dense hybrid poplar plantations.

[24] With respect to each damage pattern, the bamboo stand at HA appeared to be more vulnerable to snapping damage and less to uprooting damage compared with LA. Besides the total maximum turning moment (the ice and snow load exerted on bamboo canopy, for example), it depended on the support provided by the root-soil plate anchorage whether a bamboo culm uprooted or not [*Peltola et al.*, 1999]. It is reported that anchorage of grasses and herbaceous species usually depends on a combination of root number, size, length, depth, and branching characteristics [*Bailey et al.*, 2002; *Dupuy et al.*, 2005]. *Stokes et al.* [2007] found that the best predictors of uprooting resistance for big node bamboo (*Phyllostachys nidularia*), a species under the same genus as moso, were total lateral root volume and a combination of the number of lateral roots and their volume. We observed that the soil at HA sites was obviously gravelly and infertile. The significantly decreased mean stand DBH at HA compared with LA (t = 2.696, p = 0.011) gave another indirect evidence of worse soil condition at HA, which induced an increased ratio of root to shoot [*Vitousek and Sanford*, 1986; *Gower*, 1987; *Cavelier*, 1992; *Gerhardt and Fredriksson*, 1995], i.e., more biomass was allocated to the root system and rhizome, consequently, strengthening the root anchorage support for the bamboo stand at HA. Because of this, the culms were prone to break or snap before uprooting occurred as the ice and snow load persisted.

[25] At individual level, tree DBH was important in determining its susceptibility to ice and snow damage [*Whitney and Johnson*, 1984; *Rebertus et al.*, 1997; *Boerner et al.*, 1988; *Rhoads et al.*, 2002; *Hopkin et al.*, 2003]. In our study, the proportion of overall damaged culms looked like independent on its DBH, but the separated proportion of bended, snapped and uprooted culms was significantly correlated to its DBH. The declining pattern for bending proportion and the rising pattern for proportion of snapping and uprooting with increased DBH counteracted each other, leading to a statistically nonsignificant relationship between proportion of overall damage and culm DBH (Figure 3). Previous studies reported more damage to larger trees [*Webb*, 1989; *Van Dyke*, 1999; *Platt et al.*, 2000; *Manion et al.*, 2001; *Proulx and Greene*, 2001; *Nielsen et al.*, 2003;

Rhoads et al., 2004]. However, there were some contrasting reports. *Rubin and Manion* [2001] suggested the relationship between damage and diameter might depend on the tree species. *Belanger et al.* [1996] found no difference in damage to loblolly pines (*Pinus taeda* L.) of different size classes (DBH) following an ice storm. *Ryall and Smith* [2005] observed that large diameter trees were less damaged by ice accumulation than small diameter trees. In our study, a larger bamboo culm was more likely to break or uproot, while a small-sized culm was more likely to bend over, consistent with *Yorks and Adams* [2005] who stated that the proportion of trees leaning or arched was generally highest in small size classes, while uprooting was restricted to intermediate and large size classes. Larger culms tended to have larger crown and, therefore, more surface area available for snow loading and ice accumulation [*Bruederle and Stearns*, 1985; *Seischab et al.*, 1993]. Tree health condition may partly explain the differential susceptibility between large and small trees [*Rhoads et al.*, 2002]. Larger trees, usually mature or overmature, are more likely to be partially decayed or attacked by insect pests or pathogen, deteriorating the mechanical properties and increasing the susceptibility to damage from ice and wind [*Bruederle and Stearns*, 1985]. For bamboo, however, that was not a reason. Unlike other woody trees, whose size is usually a function of age, the bamboo culms inherently remain constant in their size. That is, a large-sized culm is not necessarily a mature or old one, and it is generally in good health. The small-sized culm, with a relatively small crown, and under the protection offered by upper canopy of culm, was more likely to suffer from bending damage and less to snapping and uprooting.

[26] Culm age was another influencing factor to ice damage at individual culm level, even though bamboo's life span was narrow compared with other trees, leading to a shorter age interval between which the difference in damage level was examined. As mentioned earlier, the age, for regular woody trees, is closely correlated with their size, heath status and mechanical properties. In contrast, bamboo completes its radial and apical growth within its first growing season, reaching its full diameter and height in a matter of two to three months [*Zhou et al.*, 2005]. As a result, the bamboo culm remains constant in size through its lifetime, and quality growth for culm will occur in following years, with increased basic density (ratio of absolute dry weight/green volume) and structural strength resulted from declined moisture content in culm [*Jiang*, 2007]. The difference in damage level between culm age can be attributed mostly, if not exclusively, to culm's mechanical strength, even if there has been no direct correlation found between mechanical wood strength and susceptibility to ice damage for many other trees [*Deuber*, 1941; *Carvell et al.*, 1957; *Lemon*, 1961; *Bruederle and Stearns*, 1985; *Hauer et al.*, 1993]. The highest proportion of damaged culm was found in 1 year old culms. With the culm age increasing, the proportion of damaged culm went down but it rose a little at the age of seven and older. This trend complies highly with the developing process of culm's mechanical strength as the age increases. The basic density of juvenile culm is ca. 40% of that mature culm. As the culm is getting older, the cell inclusion lignifies continuously and its density increases. At the age of ca. seven or eight, the density of moso bamboo tends to decrease and its mechanical strength goes down correspondingly due to the declination of cell vitality and diversion of substances [*Zhou*, 1998; *Jiang*, 2007]. As the culm ages, the proportion of snapped culms goes down while that of uprooted goes up except the 1 year old culm which is a little higher than 3 year old. Since the younger culm is less lignified than older one, it is more susceptible to snapping damage. On the other hand, the more lignified culm is more susceptible to uprooting damage other than bending or snapping due to the less flexibility for the culm. For the bending damage, the youngest culm exhibits the highest percentage because of its lower lignification and higher flexibility.

[27] The deadly damage of the 2008 ice storm to moso bamboo stands enabled an abrupt conversion of biomass from living to dead. A mean value of aboveground dead biomass of 16.92 tons per hectare substantially exceeded the annual accumulated aboveground litterfall in undisturbed bamboo plantation and other subtropical forests. *Wu et al.* [1992] reported pure moso bamboo stand accumulated 5.8 t/ha of litterfall, while moso mixed with broadleaf and with *Cunninghamia lanceolata* produced literfall of 7.2 t/ha and 9.4 t/ha per year, respectively. *Pandey et al.* [2007] observed the total annual litterfall in a subtropical natural oak forest in northeastern India was 5.48 t/ha and 4.2 t/ha in managed plantation. A single climatic event could produce dead biomass approximately 2–4 times more than the normal annual production of litterfall under similar climate.

[28] In terms of the dead biomass production, the 2008 ice storm falls into the most powerful climatic events causing the greatest damage to forest. The 16.92 t/ha oven-dried dead biomass produced by the 2008 ice storm in moso bamboo stand was equivalent to 19.9 t/ha of air-dried, woody litter brought down by the 1998 North America ice storm at Mont St. Hilaire of Canada [*Hooper et al.*, 2001], and to 18.1 t/ha of woody biomass and foliage produced by Hurricane Hugo in a tropical, broad-leaved forest in the Luquillo Mountains of Puerto Rico [*Frangi and Lugo*, 1991]. This figure was also comparable with the figure of 16 t/ha of coarse woody debris (>10 cm diameter) felled by Hurricane Gilbert in the dry, tropical forests of Yucatan Peninsula of Mexico [*Whigham et al.*, 1991]. Considering the proportion of the dead biomass production to the total standing biomass stock, the 2008 China ice storm was probably the most intensive climatic disturbance on record. An average of 37.96% of the total aboveground biomass was shifted into dead litter in moso bamboo stand, much higher than the figures of the reduced standing biomass by Hurricane Hugo (10%) [*Frangi and Lugo*, 1991] or by 1998 ice storm (7–10%) [*Hooper et al.*, 2001]. Beyond the biomass losses already occurred, the actual biological impact of the ice storm would be greater. Due to the remarkable decrease of mother culms in stand, the recruitment of new culms would be greatly reduced in the coming years. The reduced biomass growth was another form of biomass losses.

[29] The 2008 ice storm made a large amount of carbon shift from living biomass to dead biomass. An average of 8.21 Mg C per hectare in living bamboo culms was transferred into litter following the ice storm. Considering the living biomass loss within the belowground system as a result of the death of bamboo's root and rhizome caused by the eradication of the culms and canopy, more carbon was

involved in this shift. Although carbon in dead biomass is not immediately respired to the atmosphere, this litter pulse largely represents committed future CO_2 emissions [*Chambers et al.*, 2004]. Furthermore, the shrunken stand canopy and decreased new recruitment will consequentially reduce carbon sequestration in near future following the ice storm.

5. Conclusion

[30] The massive ice and snow storm in 2008 caused an extensive damage and brought down a large amount of dead biomass production to moso bamboo plantation in southeast China. An average of 16.42 (±7.09) tons per hectare dead dry biomass was produced, accounting for 37.73% (±14.41%) of total aboveground biomass. A mean value of 8.21 (±3.55) Mg C per hectare was shifted from living biomass to dead biomass. In terms of the proportion of dead biomass production to total aboveground biomass in bamboo stand, the 2008 China ice storm was probably the most powerful climatic disturbance. A stand level survey showed that over half of the culms were damaged by bending, snapping or uprooting. An elevation of 600 m above sea level could lead to a heavier damage and produce more dead biomass to moso bamboo stand than that between 300 and 400 m above sea level, with a higher percent snapped culms and lower percent uprooted culms at the higher altitude. Moso bamboo stand at north oriented slope (north faced, northeast faced and northwest faced) received more damage and produced higher dead biomass than its opposite. Ice damage and dead biomass production to moso bamboo seemed to rise with increased stand density.

[31] At individual culm level, large-sized culm was more likely to suffer from snapping and uprooting damage, and the larger the culm, the higher the susceptibility for the culm to snap or uproot. A small-sized culm was more likely to suffer from bending damage, and its susceptibility declined as its DBH decreasd. Juvenile and overmature culm was more susceptible to ice damage, with juvenile more vulnerable to bending and snapping while older one more vulnerable to uprooting. To harvest the mature culms timely will not only facilitate increasing production for bamboo timber, but also lessening the potential damage caused by ice storm or other extreme events. We also suggest to carry out partial artificial decapitation to the newly produced culms, as the farmers do in some bamboo production areas, which can greatly reduce the crown size and decrease the snow load and ice accumulation, alleviating possible damage caused by snow or ice storm.

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