SCIENCE CHINA
Life Sciences

• RESEARCH PAPER •

May 2015 Vol.58 No.5: 472–479
doi: 10.1007/s11427-014-4722-2

How does tree age influence damage and recovery in forests impacted by freezing rain and snow?

ZHU LiRong[†], ZHOU Ting[†], CHEN BaoMing & PENG ShaoLin[*]

State Key Laboratory of Biocontrol, Key Laboratory of Biodiversity Dynamics and Conservation of Guangdong Higher Education Institutes, School of Life Sciences, Sun Yat-sen University, Guangzhou 510006, China

Received June 7, 2013; accepted March 20, 2014; published online October 13, 2014

The response and recovery mechanisms of forests to damage from freezing rain and snow events are a key topic in forest research and management. However, the relationship between the degree of damage and tree age, i.e., whether seedlings, young trees, or adult trees are most vulnerable, remains unclear and is rarely reported. We investigated the effect of tree age on the degrees of vegetation damage and subsequent recovery in three subtropical forest types-coniferous, mixed, and broad-leaved—in the Tianjing Mountains, South China, after a series of rare icy rain and freezing snow events in 2008. The results showed that damage and recovery rates were both dependent on tree age, with the proportion of damaged vegetation increasing with age (estimated by diameter at breast height, DBH) in all three forest types and gradually plateauing. Significant variation occurred among forest types. Young trees in the coniferous forest were more vulnerable than those in the broad-leaved forest. The type of damage also varied with tree age in different ways in the three forest types. The proportion of young seedlings that were uprooted (the most severe type of damage) was highest in the coniferous forest. In the mixed forest, young trees were significantly more likely to be uprooted than seedlings and adult trees, while in the broad-leaved forest, the proportion of uprooted adult trees was significantly higher than that of seedlings and young trees. There were also differences among forest types in how tree age affected damage recovery. In the coniferous forest, the recovery rate of trees with broken trunks or crowns (DBH > 2.5 cm) increased with tree age. However, in the mixed and broad-leaved forests, no obvious correlation between the recovery rate of trees with broken trunks or crowns and tree age was observed. Trees with severe root damage did not recover; they were uprooted and died. In these forests, vegetation damage and recovery showed tree age dependencies, which varied with tree shape, forest type, and damage type. Understanding this dependency will guide restoration after freezing rain and snow disturbances.

freezing rain and snow, tree age, damage, restoration, subtropical forest

Citation: Zhu LR, Zhou T, Chen BM, Peng SL. How does tree age influence damage and recovery in forests impacted by freezing rain and snow?. Sci China Life Sci, 2015, 58: 472–479, doi: 10.1007/s11427-014-4722-2

A fundamental question in vegetation science is how different trees, especially those of different ages, respond to damage from extreme events such as ice storms, blizzards, hurricanes, and other natural disasters [1]. Ice storms destroy vegetation because the freezing rain covers plants with heavy ice, then the branches, upper trunk, or even the whole tree break from the weight. Because they usually develop from cold weather systems and rarely affect subtropical areas, previous studies mainly focused on temperate and cold zones, such as Northern Europe, Central Europe, and Northern and Southeastern America [2–4]. However, information on ice damage in subtropical forests is still sparse [5]. A major ice storm in January and February, 2008, in South China provided an opportunity to study the effects of a rare, intense disturbance on the structure of a subtropical

†Contributed equally to this work
*Corresponding author (email: lsspsl@mail.sysu.edu.cn)

© The Author(s) 2014. This article is published with open access at link.springer.com

forest [6].

Many studies have examined the relationship between tree age and damage incurred from ice storms, but no uniform conclusions have been drawn. Some studies showed that old trees suffered greater damage than younger ones, because the taller canopy trees intercepted more freezing rain on their larger crowns, accumulating more weight [7, 8]. The resistance of *Pinus taiwanensis* to ice and snow damage depended on tree size. Trees with greater diameter at breast height (DBH) were susceptible to limb and crown breakage [9]. Stunted trees tended to show mild damage [13]. Nevertheless, other studies have indicated that larger and older trees could have more structural rigidity and hence stronger resistance to ice damage [10]. For instance, *Cunninghamia lanceolata* trees with smaller DBH were more likely to suffer uprooting and freezing death, while those with greater DBH were more likely to experience crown and trunk breakage [11,12]. Some models predict severe trunk breakage in smaller diameter trees and increasing probability of crown damage as size increases in *Tsuga canadensis* forests and northern hardwoods [14]. After an ice storm, smaller pines had a much higher death rate than larger ones in Virginia, USA [14]. The proportion of damaged trees decreased with DBH in Wuzhishan, Hainan Province, in the Nanling Mountains of South China after an ice storm [15]. In a final example, middle age trees (10–20 cm DBH) had higher probabilities of bent boles or branches, main stem breakage, or uprooting [14,16]. Thus, no general conclusions can be drawn about ice storm damage as a function of forest age.

Forest type is also closely related to the degree of injury. Mixed forests were more susceptible to ice storms than single-species forests [17]. The ability to resist natural disasters of pure forest is weak relatively, such as a pure Masson's pine, including *Larix olgensis*, *Cunninghamia lanceolata*, *Cryptomeria fortunei*, Dahurian larch and so on[18]. Additionally, artificial forests were more susceptible to ice storms than natural forests [19,20], because natural forests have a relatively stabilized structure that allows them to survive natural disasters better [20–23]. Because of their large crowns, broad-leaved species generally suffer more damage than do conifers, and deciduous trees are more resistant to storms than coniferous ones [23]. These observations imply that forest resistance to ice storms varies with species composition and stand structure [11,24].

Most research efforts undertaken after ice storms aimed to evaluate storm severity and management practices [25], mainly with respect to vegetation restoration, community diversity, and plant modification [26,27]. Post-disaster studies have mainly focused on the improvement of soil fertility or ways to manage litter [15]. Some articles have discussed management strategies for recovery [5]. Despite the importance of tree regeneration and forest dynamics in forest management, only a few studies have characterized the growth of damaged trees after ice storms [28, 29]. In general, most injured trees recovered naturally, and recovery rate correlated with location and degree of damage. Tree species is one of the most significant factors influencing recovery [16,30,31]. Recovery also depends on the type of damage, with trees suffering crown breaks being more apt to resprout and survive [30]. Another study showed that the higher the damage ratio, the better the recovery rate [15]. Although many studies have analyzed how ice storm damage affects forests [11,12], little research has examined recovery in light of tree age.

The mechanisms by which trees respond to ice storm damage and then recover is a key topic in forest research and management. However, there are no general conclusions about the relationship between damage and forest age, and little research has addressed recovery in the context of forest age. Subtropical forests in southern China are the most typical such forests in the world [32], but only a few studies have examined ice storms there. The objective of this research was to compare the effects of an ice storm on different forests and discuss how damage and recovery were affected by tree age. The findings will improve the management of forest structure and function to enhance forest resistance to extreme climate events.

1 Study area and methods

1.1 Study area and sampling site

The survey was carried out in Mount Tianjing Forest Park (approximately 24°45′N, 112°55′E) (Figure 1) in Shaoguan, Guangdong Province, southern China. Mount Tianjing orients from northwest to southeast. Its total area is 27300 hm^2, and its highest and lowest elevations are 1700 and 200 m, respectively. The soils are mountain red earth and mountain yellow earth. The climate is a subtropical monsoon, with mean temperatures of 8°C in January and 22°C in July. Mean annual precipitation is 2600 mm (range: 2100–3500 mm), 70% of which occurs between March and June. The frost season is about 45 d. No unusual natural events have been recorded in Tianjing Mountain Forest Park during the last 50 years, with the exception of the well-publicized ice storms in January and February, 2008. As a result of convection, most of the storm damage occurred at 600–800 m elevation; other parts of Tianjing Mountain were undamaged in this storm.

To estimate the impact of the 2008 ice storm comprehensively, we investigated three types of representative forest for Mount Tianjing, i.e., coniferous, mixed, and evergreen broad-leaved forests. In each forest type, we established twelve 10 × 10 m plots. The coniferous forests are dominated by *Cunninghamia lanceolata*; the mixed forests by *C. lanceolata, Machilus chinensis, Elaeocarpus japonicus*, and *Castanopsis fabri*; and the broad-leaved evergreen forests by *M. chinensis, C. fabri, Diospyros morrisiana, Helicia reticulata, and E. japonicus* (Table 1).

Table 1 The importance value of species in different forest types

Species	Coniferous forest	Broad-leaved forest	Mixed forest
	Importance value	Importance value	Importance value
Castanopsis fabri		33.80	10.17
Cinnamomum porrectum		14.64	
Cunninghamia lanceolata	217.66		111.65
Diospyros morrisiana		16.05	17.68
Elaeocarpus japonicus		12.50	13.67
Helicia reticulata		15.18	
Machilus chinensis		40.60	46.64
Total coniferous species	217.66		111.65
Total broad-leaved species		132.77	88.16

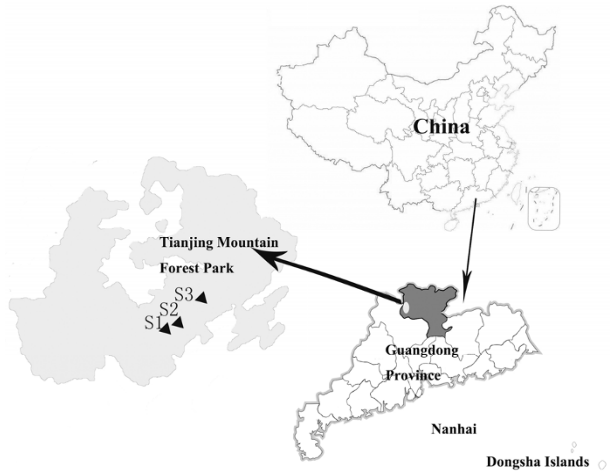

Figure 1 Location of the study area and sampling sites (Tianjing Mountain Forest Park, Shaoguan City, Guangdong Province, China).

1.2 Damage rates

Sampling took place in April, 2009. All trees with heights ⩾1.3 m and ground cover plants inside the plots was measured, including those trees killed or damaged by the ice storm. Because the stands were young, we grouped the trees into three categories: seedlings (<2.5 cm DBH), small trees (2.5–7.5 cm DBH), and big trees (>7.5 cm DBH) [33]. Five damage types were identified: uprooting (including death), crown breakage, trunk breakage, trunk bending, and undamaged [2,14]. The damage rate was defined as the number of damaged stems to the total number of stems within the same diameter class and plot.

1.3 Recovery rates

All trees were recorded and numbered in April, 2009. Measurements taken for each tree included DBH, total height, crown class, and viability.

Forest recovery was assessed by assigning one of four visually-assessed damage classes to each tree: 0 = no recovery (no sprouting, or lodging with death or near death); 1 = very slow recovery (a few sprouts); 2 = slow recovery (several sprouzts but no DBH growth); 3 = moderate recovery (many sprouts, and good crown and trunk growth) [15]. The recovery rate (%) was calculated as (number of recovered stems)/ (number of damaged stems).

One-way analysis of variance (ANOVA) was used to compare the damage and recovery rates (arcsine square-root transformed) of different forest types and age classes using SPSS v.17 for Windows (IBM, Chicago, IL, USA).

2 Results

2.1 Forest type and tree age dependency

The proportions of damaged vegetation in the three forest types all increased with tree age and gradually stabilized after reaching a threshold DBH. A common characteristic is that the damage rate was 100% (DBH > 10 cm) in all three forest types. Tree damage from the ice storm differed among age classes and forest types (Figure 2). In the coniferous forest, the damage rate did not differ significantly among age classes, however, seedlings in the mixed and broad-leaved forests had significantly lower damage rates than did small and big trees. Big trees suffered the highest damage rates in all three forest types, and the difference was significant except in the coniferous forest (Figure 2). This observation indicates that big trees are more susceptible to damage from ice storms in subtropical forests.

2.2 Damage type and tree age dependency

In the coniferous forest, most of the damage was crown breakage, followed by trunk bending. In the mixed and broad-leaved forests, trunk breakage accounted for the largest percentage of damage, followed by crown breakage. The damage rates of the five damage categories were compared among the three forest types; only crown damage differed significantly between the coniferous forest and the other two types of forest (Figure 3).

With respect to damage type, the effect of tree age varied with forest type. The proportion of young seedlings in co-

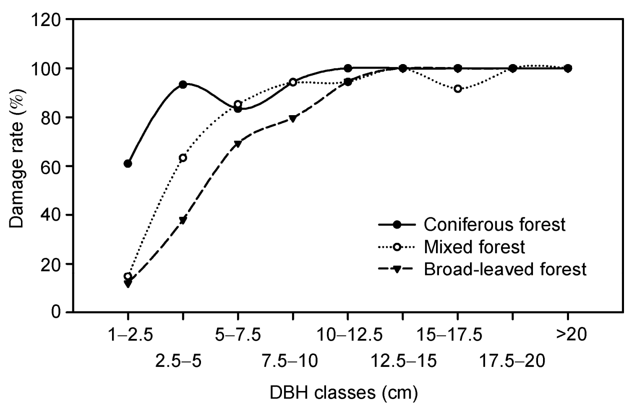

Figure 2 The relationship between damage rate and DBH class.

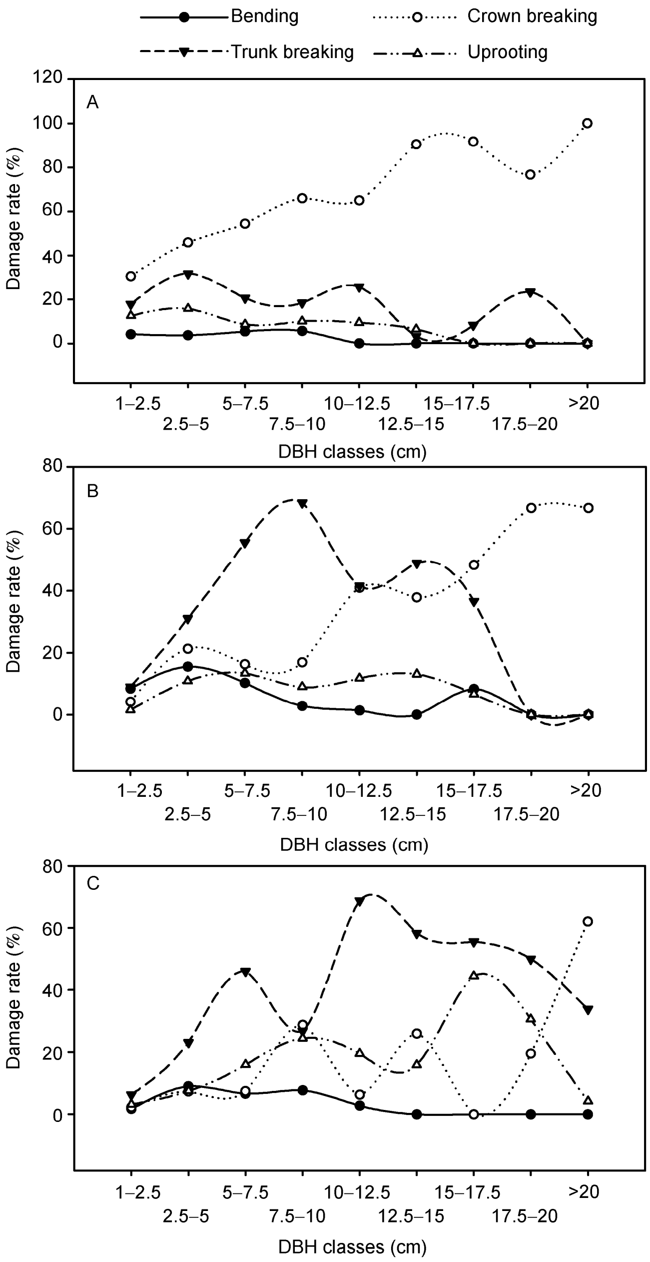

Figure 3 Damage rate of different damage types as a function of DBH in (A) coniferous forest, (B) mixed forest, (C) broad-leaved forest

niferous forest that were damaged by uprooting (the most severe type of damage) was highest. In the mixed forest, a significantly higher proportion of young trees were uprooted than seedlings and adult trees. However, in the broad-leaved forest, the proportion of uprooted adult trees was significantly higher than those of seedlings and young trees. There were significant differences in the stem breakage rate among age classes in the mixed and broad-leaved forests. Trees suffered a higher rate of stem breakage as age class increased. However, there were no significant differences in mortality among three forest types. In the mixed forest, small trees had a significantly higher rate of being uprooted than seedlings and big trees. In the broad-leaved forest, small trees showed a significantly higher rate of bole bending than seedlings and big trees, while crown damage and uprooting both increased in damage rate with higher age class. Mortality was not significantly different among the three age classes in any of the forest types (Figure 4).

2.3 Recovery and tree age dependency

There was difference in the tree age dependency of damage recovery among forest types (Figure 5). The recovery rate of trees in coniferous forest with trunk or crown breakage (DBH > 2.5 cm) increased tree age. However, in mixed and broad-leaved forests, the recovery rate of such trees fluctuated with tree age. The recovery rate small trees (DBH < 5 cm) in the mixed and broad-leaved forests were significantly higher than for the same DBH trees in the coniferous forest.

The tree age dependency of recovery also varied with forest type. In coniferous forest, the recovery rate of trees with trunk or crown breakage increased with tree age (Figure 6A). Neither an obvious increase nor a decrease was

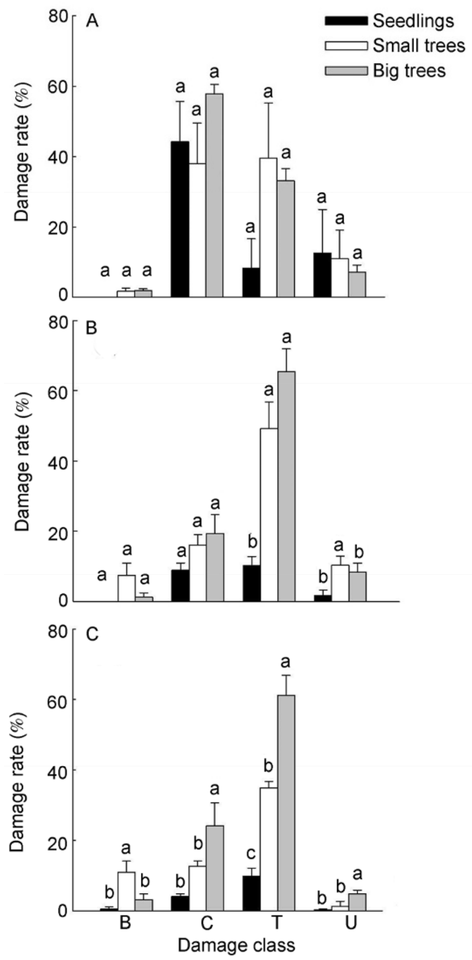

Figure 4 Damage rate of different age classes in three types of forest. B = trunk bending, but not breakage; C = crown breakage (≥ 10% of the crown removed); S = trunk breakage; R = uprooting. Different letters (a, b, c) indicated significant differences at the 0.05 level. (A) Coniferous forest, (B) mixed forest, (C) broad-leaved forest

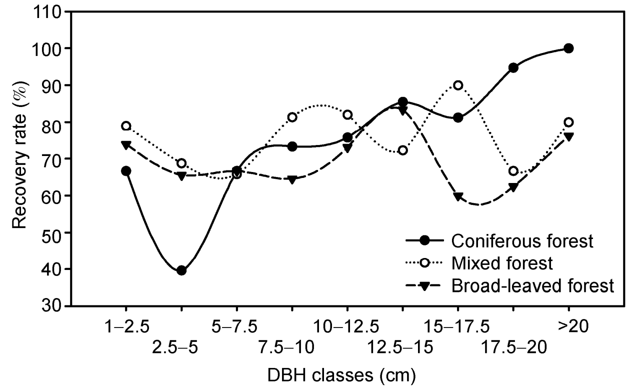

Figure 5 Recovery rate of damaged trees as a function of DBH in three forest types.

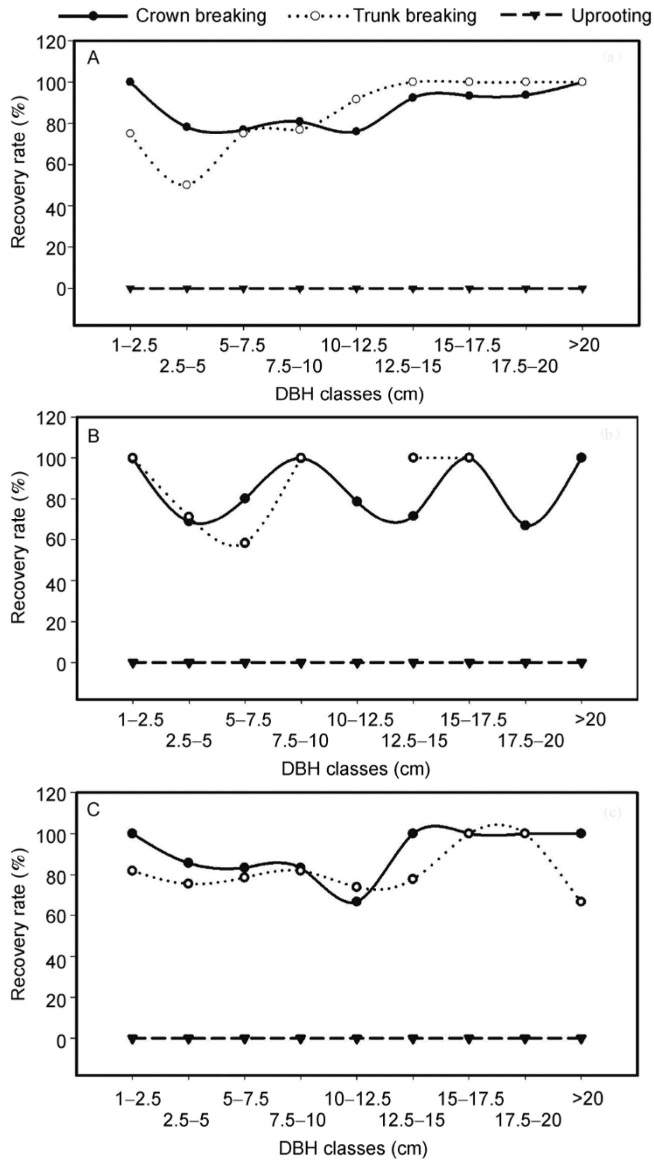

Figure 6 Recovery rate of different damage classes by DBH in (A) coniferous forest, (B) mixed forest, and (C) broad-leaved forest.

observed in mixed and broad-leaved forests (Figure 6B,C). Trees with severe root damage had zero recovery rates; they were uprooted and died. Trees with trunk bending had a 100% recovery rate. Overall, there were correlations between vegetation damage or recovery and tree age that were determined by several factors, including forest type, tree shape, and damage type.

3 Discussion

3.1 Influence of forest type and tree shape

Older trees had wider crowns as DBH increased. Therefore, the crown experienced heavier ice and snow loads, and the tree was more likely to suffer crown damage [13,34,35]. Other studies have indicated otherwise: older trees have thicker trunks and thus more resistance and better growth [3]. Our results showed that the proportion of damaged trees in the three forest types clearly depended on tree age. With an increase in DBH, a larger proportion of trees were damaged. In fact, there were few mature trees (diameter > 22.5 cm) in the study area; the big trees were middle-aged. Compared with some mature forests, plantation trees with larger DBHs are only intermediate in age (in a broad sense). Earlier studies suggested that intermediate-aged trees were more vulnerable [36–38]. An ice event in Canada and the northeastern United States in 1998 directly caused a large number of broken trunks and considerable uprooting of intermediate-aged loblolly pine, while only a few adult trees suffered broken crowns [5]. Adult trees with larger crowns, especially broad-leaved trees, accumulated more snow and ice and consequently broke more easily in the crowns [3,40]. However, young trees were only slightly damaged, because they were protected by the taller adult trees [39]. Our results indicated that the degree of damage depended on tree age, similar to observations in Alaska. Large trees were vulnerable to damage, with more crown and trunk damage as DBH increased, and young trees were more resistant to damage because they were sheltered by large trees. If the adult trees were not dense enough to provide protection, the young trees would be vulnerable to damage.

Tree shape also affected the degree of tree damage. Cone-shaped trees suffered the most severe damage from freezing rain and snow in this study, as shown by the results in the coniferous forest. Compared with trees with smaller DBH, larger Chinese firs were less cone-shaped. When the taper ratio was smaller than 1:90, the trees were more likely to suffer damage. In our study, when the taper ratio of Chinese fir was 1:100 [36,41], the trunk tended to gather more snow than did crowns that were more cone-shaped and the tree suffered more damage. Another risk factor was excessive tree height [42–44]. The results clearly indicate that the effect of tree age on the degree of damage varied with forest type and tree shape, which likely explains much of the diverse conclusions reported in different studies on the same topic.

3.2 Type of damage and tree age dependency

Damage generally was classified as broken crowns and broken trunks. For all three forest types, crown breakage was dependent on tree age, with a larger proportion of trees being damaged at larger DBH. This finding might be explained by the rarity of freezing rain and snow events in South China. In North America and Europe, these events are associated with high wind speeds [45,46], which increase the event-related loss and risk [10,47,48], resulting in uprooted trees and broken trunks and crowns. In China, the wind speed during freezing rain and snow events is usually low and humidity is high [49]. Clearing the cover of snow and ice on the top of the crowns is more difficult [46,50,51]. As a consequence, the tree trunks and crowns often break, especially when DBH is larger and more snow and ice accumulate on the tree.

The occurrence of uprooting differed among the forest types. The seedlings in the coniferous forest comprised the largest proportion of uprooted trees in our study. Within the mixed forest, young trees were most likely to be uprooted, while in the broad-leaved forest, adult trees constituted the largest proportion of uprooted trees. In the coniferous forest, the young trees uprooted easily because they lack protection by large trees. The mixed forest was more species rich, and the upper layer of vegetation protected the seedlings below, so few seedlings were uprooted. The trees with large DBH were mostly Chinese fir. These trees experienced a high degree of damage to crowns and trunks, and young trees were uprooted because they had weak roots. Broad-leaved forests have a varied community structure. The large trees uprooted easily, but the young trees in the lower layer were protected by the dense crowns above. Our analysis indicated that the dependency of damage level on age was also associated with the type of damage. Large trees were more susceptible to certain types of damage, while young trees were more vulnerable to other types.

3.3 Age dependency and tree recovery

After freezing rain and snow events, natural regrowth is the main method of forest restoration. Post-event forest restoration is closely associated with forest type, tree species, and vegetation size [52–56]. Our study showed that the recovery rate of damaged trees in the coniferous forest gradually increased with DBH; large trees had a significantly higher recovery rate than small trees. The recovery of damaged trees in the coniferous forest also showed an obvious age dependency, while that in the mixed and broad-leaved forests exhibited no apparent age dependency. The recovery rate of young trees (DBH < 2.5 cm) was the highest across all three forest types in the early restoration stage, because damaged canopy of taller trees may allow more understory light to promote the rapid growth of the young trees. Although young trees generally have a high recovery rate, the large amount of understory litter created by severe weather events may affect their regeneration [30]. Over the long term, crown damage can lead to changes in understory light, moisture, temperature, and soil fertility, facilitating the invasion of heliophilic, pioneer plants that can replace the existing shade-tolerant tree species. As a consequence, community structure is greatly altered. Thus, natural regeneration should be supplemented with artificial methods to promote forest health.

The restoration of forests following freezing rain and snow events is related to the type and degree of damage [45,57]. Generally speaking, bent trees recover most easily, while trees with damaged roots are most likely to die [58]. Our study showed that bent trees accounted for the smallest proportion of damage, and their recovery rate was as high as 100%, while that of the uprooted trees was zero. We found that the recovery rate of the crown in the broad-leaved forest was the highest, and the coniferous and mixed forests did not differ significantly in this aspect. Disturbance of the crown is believed to be important for maintaining species richness and diversity in the forest [14,29,44].

Studying the age dependency of natural tree regeneration is crucial, as it provides both a better understanding of the natural regenerative process of damaged trees as well as the scientific basis for artificial restoration measures. The recovery rate of damaged trees in the coniferous forest gradually increased with DBH, with a significant difference between the large and small trees and an obvious age dependency. The recovery rates of damaged trees in the mixed and broad-leaved forests showed no obvious age dependency. Because the recovery rate of the small trees was low in the coniferous forest, biodiversity in this type of forest cannot be restored in the short term; management with an appropriate mix of artificially-planted small and natural large trees should be considered to compensate for the low recovery rate of small trees. The damaged crowns in the broad-leaved forest had a high recovery rate, with no obvious age dependency. Both the small and large trees in the broad-leaved forest could recover naturally. Therefore, measures to restore biodiversity and promote community resistance should be implemented.

In addition to the regenerative ability of damaged trees, habitat is also an important consideration in forest restoration. Changes in the existing habitat caused by disturbance will affect the regrowth of damaged trees. For example, alterations to understory light after freezing rain and snow events will affect forest restoration [59]. In addition, the forest produces a large amount of litter after major weather events that interferes with soil nutrient cycling and the physical properties of the soil surface (e.g., a barrier effect owing to dead trees and broken branches on the soil surface) [60,61]. Litter further affects the regrowth of damaged trees. In the future, studies of the effects of uncharacteristic amounts and types of litter associated with forest damaged should be implemented as well as investigations into the restoration of forest biodiversity. Such studies will provide the scientific basis for evaluating the degree of damage to the forest and for understanding natural restoration in a damaged forest.

This research was financially supported by the National Natural Science Foundation of China (31300401, 31030015, 31100402), the Forestry Science and Technology Innovative Foundation of Guangdong Province (2008KJCX012, 2009KJCX015), the Guangdong Natural Science Foundation (S2012040007896), and the Fundamental Research Funds for the Central Universities. We thank the colleagues of Tianjing Mountain Forest Park for providing valuable help during this study, and we are also grateful to Lin Zhenguang, Chen Leiyi, Liang Liyin, and Wu Keke for their assistance in the investigation.

1 Nishimura TB. Tree characteristics related to stem breakage of *Picea glehnii* and *Abies sachalinensis*. Forest Ecol Manag, 2005, 215: 295–306

2 Nykänenet M, Peltola H, Quine C, Kellomäki S, Broadgate M. Factors affecting snow damage of trees with particular reference to European conditions. Silva Fenn, 1997, 2: 193–213

3 Pisaric MF, King DJ, Macintosh AJ, Bemrose R. Impact of The 1998 Ice Storm on The Health and Growth of Sugar Maple (Acer saccharum Marsh.) Dominated Forests in Gatineau Park, Quebec 1. The J Torrey Bot Soc, 2008, 135: 530–539

4 Warrillow M, Mou P. Ice storm damage to forest tree species in the ridge and valley region of southwestern Virginia. J Torrey Bot Soc, 1999, 126: 147–158

5 Bragg DC, Shelton MG, Zeide B. Impacts and management implications of ice storms on forests in the southern United States. Forest Ecol Manag, 2003, 186: 99–123

6 Zhou BZ , Yu MK, Cao YH, Wang XM, Sun HG, Ai C, Gu LH. Impact of the 2008 Ice Storm on China's Forests. Shanxi, China, 2011, 4:2652–2656

7 Rhoads AG, Hamburg SP, Fahey TJ, Siccama TG, Hane EN, Battles J, Cogbill C, Randall J, Wilson G. Effects of an intense ice storm on the structure of a northern hardwood forest. CAN J Forest Res, 2002, 32: 1763–1775

8 Smith K. Environmental Hazards: Assessing Risk and Reducing Disaster. Routledge. London/USA/Canada, 1996,1-324

9 Zhang ZX, Liu P, Qiu Z J, Liu CS, Chen WX, Li CH, Liao JP, Li HJ. Factors influencing ice and snow damage to *Pinus taiwanensis* in Jiulongshan Nature Reserve, China. Chinese J Plant Ecol (in Chinese), 2010, 34: 223–232

10 Amateis RL, Burkhart HE. Impact of heavy glaze in a loblolly pine spacing trial. South J of Appl For, 1996, 20: 151–155

11 Chen YH, Xue L, Li JY, Chen SQ, Qin XS, Chen CG, Jiang J. Comparison between characteristics of ice damage to three stands. J South China Agricultural University (in Chinese), 2010, 31: 78–81

12 Li HJ, Liu P, Zhang ZX, Chen WX, Qiu ZJ, Liu CS, Liu JL, Liao JP. Ice and Snow Damage and Subsequent Sprouting of Cunninghamia lanceolata (Taxodiaceae) Plantation and their related-factors analysis. Acta Botanica Yunnanica (in Chinese), 2010, 32: 158–166

13 He Q, Li JY, Chen XY, Chen HY, Peng HG, Fan SJ. Types and extent of damage to Cunninghamia lanceolata plantations due to unusually heavy snow and ice in southern China. Chinese J Plant Eco, 2010, 34: 195–203

14 Lafon CW. Ice-storm disturbance and long-term forest dynamics in the Adirondack Mountains. J Veg Sci, 2004, 15: 267–276

15 Huang CT, Zhuang XY, Li XR, Liu ZX, Jiang B, Zhai CH. Damaged status and early tree species in Wuzhishan of Nanling Mountain, South China after the ice storm in 2008. Chinese Journal of Ecology (in Chinese), 2012, 6: 1390–1396

16 Liu G, Ou YD, Li ZK, Li MZ, Ma DX, Su ZY. Floristic and Co enological analyses of the montane evergreen broadleaved forest in Chebaling National Nature Reserve impacted by a huge ice storm. J South China Agricultural University (in Chinese), 2010, 31: 82–87

17 Shao QQ, Huang L, Liu JY, Kuang WH, Li J. Analysis of forest damages caused by the snow and ice Chaos in Transect of Southern China in 2008 Spring. J Geographical Sci (in Chinese), 2009, 27: 177–187

18 Xu QJ, Liu BJ. Disaster effects of snow and freezing on different forest types in Chongqing city. Journal of Central South University of Forestry & Technology (in Chinese), 2011, 31: 74–78

19 Liu LF, Tan QS, Liu PL, Chen T. Study on formation mechanism of snow-frozen and the disaster relieve counter measure on forestry in Hunan Province. J Hengyang Normal University (in Chinese), 2008, 29: 101–104

20 Yang YZ, Zhang LW, Chen AL, Xu YL. A preliminary report on the loss of forest resources caused by consecutive snow and freezing weather in Shaanxi. Shaanxi Forest Science and Technology (in Chinese), 2008, 42–45

21 Cao KF, Chang J. The ecological effects of an unusual climatic disaster: the destruction to forest ecosystems by the extremely heavy glaze and snow storms occurred in early 2008 in southern China. Chinese J Plant Eco (in Chinese), 2010, 34: 123–124

22 Cao XH, Guo BJ. The reason of the lost in rain and snow freeze disaster TaiXian. Anhui Forestry Science and Technology (in Chinese), 2009, 135: 9–11

23 Xu DM, Han M. Study on the reasons and counter measures of snow and freezing-rain disaster. Serves of Agricultural Technology (in Chinese), 2010, 27: 111–113

24 Li XF, Zhu JJ, Wang QL, Liu ZG, Mao ZH. Relationships between snow wind damage and tree species as well as forest types in secondary forest. J Beijing Forestry University (in Chinese). 2006, 24: 28–33

25 Xu YW, Wu KK, Zhu LR, Lin ZG，Peng SL. A review of freezing rain and snow impacts on forests in southern China. Ecology and Environmental Sciences (in Chinese). 2010, 6: 1485–1494

26 Wu LJ, Liu XJ, Yan WB. Study on recovery strategy of damaged forest vegetation by ice disaster in Suxianling Scenery Zone. Modern Agricultural Sciences (in Chinese), 2008, 15: 14–16

27 Roberts EG, Clapp RT. Effect of pruning on the recovery of ice bent slash pines. J Forest. 1956, 54: 596–597

28 Carissa L, Wonkka, WC, Joslin AJ. A CSR classification of tree life history strategies and implications for ice storm damage. Oikos. 2013,122: 209–222

29 De Steven D, Kline J, Matthiae PE. J Veg. Sci. 1991, 2: 201-208

30 Duguay SM, Arii K, Hooper M, Lechowicz MJ. Ice storm damage and early recovery in an old-growth forest. Environ. Monit. Assess. 2001, 67: 97–108

31 Wang X, Huang SN, Zhou GY, Li JX, Qiu ZJ, Zhao X, Zou B. Effects of the frozen rain and snow disaster on the dominant species of Castanopsis forests in Yangdongshan Shierdushui Provincial Nature Reserve of Guangdong. Scientia Silvae Sinicae (in Chinese), 2009, 45: 41–47

32 Song YC, Chen X. Studies on evergreen broadleaved forests of China: a retrospect and prospect. Journal of East China Normal University (Natural Science) (in Chinese), 2005, 1: 1–8

33 Wang BS, Yu SX, Peng SL. Phytocoenology laboratory manual. Guangdong: Guangdong Higher Education Press (in Chinese), 1996, 23–105

34 Zhao X, Shen XQ, Huang SN, Luo XH, Luo TS, Zeng FZ, Zhang N, Yu WS, Xiao YH, Wang X. Mechanical damages to woody plants from a snow disaster in Yangdongshan Shierdushui Provincial nature reserve. Scientia Silvae Sinicae (in Chinese), 2008, 44: 164–167

35 Zhao JF, Dong WY, Mao WJ, Wang L. An investigation on snow Damage on four kinds of bamboo forests in Daguan County. China West Scientia Silvae Sinicae (in Chinese), 2009, 38: 96–100

36 Petty JA, Worrell R. Stability of coniferous tree stems in relation to damage by snow. Forestry. 1981, 54: 115–128

37 Cremer KW, Borough CJ, McKinnell FH, Carter PR. Effects of stocking and thinning on wind damage in pine plantations. New Zeal. J For Sci, 1982: 12: 244–268

38 Peterson CJ. Within-stand variation in windthrow in southern boreal forests of Minnesota: Is it predictable? CAN J Forest Res, 2004, 34: 365–375

39 Everham EM, Brokaw N. Forest damage and recovery from catastrophic wind. Bot Rev, 1996, 62: 113–185

40 Zhu JJ, Li XF, Liu ZG, Cao W, Gonda Y, Matsuzaki T. Factors Affecting the Snow and wind Induced damage of a montane Secondary Forest in Northeastern China. Silva. Fenn, 2006, 40: 37–51

41 Peltola H, Nykänen M, Kellomäki S. Model computations on the critical combination of snow loading and wind speed for snow damage of Scots pine, Norway spruce and birch sp. at stand edge. Forest Ecol Manag, 1995, 229–241

42 Webb S. Windstorm damage and micro site colonization in two Minnesota forests. CAN J Forest Res, 1988, 112: 18: 1186–1195

43 Matlack GR, Gleeson S, Good R. Tree fall in a mixed oak-pine coastal plain forest: immediate and historical causation. Ecology, 1993, 74: 1559–1566

44 Peterson CJ. Catastrophic wind damage to North American forests and the potential impact of climate change. Sci Total Environ, 2000, 262: 287–311

45 Dyke OV. A literature review of ice storm impact on forests in Eastern North America. SCSS Technical Report #112. Landmark Consulting, 1999

46 Beach RH, Sills EO, Liu T, Pattanayak S. The influence of forest management on vulnerability of forests to severe weather. In: PyeJ M, Rauscher H M, Sands Y, Lee D C, Beatty J S, eds. Advances in threat assessment and their application to forest and rangeland management General Technical Report PNW-GTR-802, 2010, 185–206

47 Bruederle LP, Stearns FW. Ice storm damage to a southern Wisconsin mesic forest. J Torrey Bot Club, 1985,95: 167–175

48 Hough AF. What a glaze storm brings. Pennsylvania Forest. 1965, 33: 4–5

49 Wang Y, Wang YS. Biomass-dependent susceptibility to drought in experimental grassland communities. Ecol Lett, 2007, 10: 401–410

50 Lemon PC. Forest ecology of ice storms. J Torrey Bot Club, 1961,88: 21–29

51 Gill D. Snow damage to boreal mixed wood stands in northern Alberta. Forest Chron, 1974, 50: 70–73

52 Bond WJ, Midgley JJ. Ecology of sprouting in woody plants: the persistence niche. Trends in Ecol Evol, 2001, 16: 45–51

53 Espelta JM, Retana J, Habrouk A. Resprouting patterns after fire and response to stool cleaning of two coexisting Mediterranean oaks with contrasting leaf habits on two different sites. Forest Ecol Manag, 2003, 179: 401–414

54 Hodgkinson KC. Sprouting success of shrubs after fire: height-dependent relationships for different strategies. Oecologia. 1998,115: 64–72

55 Bellingham PJ, Sparrow AD. Resprouting as a life history strategy in woody plant communities. Oikos. 2000, 89: 409–416

56 Luoga EJ, Witkowski E, Balkwill K. Differential utilization and ethnobotany of trees in Kitulanghalo forest reserve and surrounding communal lands, eastern Tanzania. Econ Bot, 2000, 54: 328–343

57 Allen DC. Ice Storm 1998 and the forests of the northeast. J Forest, 1998, 9: 32–40

58 Hyman. After the iceman cometh. Ala. Treas, 1985, 4: 10–11

59 Canham CD. Suppression and release during canopy recruitment in *Fagus grandifolia*. B Torrey Bot Club, 1990, 117: 1–7

60 Guo SH, Xue L. Effects of ice- snow damage one forest. Acta Eco Sin (in Chinese), 2012, 16: 5242–5253

61 Wu ZM, Li YD, Zhou GY, Chen BF. Abnormal litter fall and its ecological significance. Scientia Silvae Sinicae (in Chinese), 2008, 11: 28–31

Open Access This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.