LETTER

Forest greenness after the massive 2008 Chinese ice storm: integrated effects of natural processes and human intervention

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Forest greenness after the massive 2008 Chinese ice storm: integrated effects of natural processes and human intervention

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Abstract
About 10% of China's forests were impacted by a destructive ice storm and subsequently subjected to poorly planned salvage logging in 2008. We used the remote-sensing products of Enhanced Vegetation Indexes (EVI) corroborated with information gathered from ground visits to examine the spatial patterns and temporal trajectories of greenness of these nearly 20 million hectares of forests. We found (1) the EVI of about 50% of the impacted forests returned to normal status (i.e., within the 95% confidence interval of the long-term mean) within five months, and about 80% within one year after the storm, (2) the higher the pre-storm EVI (relative to the long-term mean), the slower the rebound of post-storm EVI, and (3) the rebound of greenness was slowest in forests that were moderately impacted by the ice storm only (i.e. before the occurrences of logging), resulting in a nonlinear relationship between greenness rebound time (GRT) and ice storm impact severity (IS). Ground visits suggested a hypothesis that the region-wide rebound in greenness was a consequence of resprouting of physically damaged trees and growth of understory plants including shrub, herbaceous and epiphytic species. These processes were facilitated by the rapid increase in temperature and ample moisture after the ice storm. Gap-phase dynamics could be responsible for the counterintuitive relationship between IS and GRT that was obtained. However, a more parsimonious explanation appears to be biased salvage logging, which may have selectively targeted lightly to moderately impacted forests for economic and accessibility reasons and thus adversely affected the GRT of these forests. Although a purely natural disturbance may result in forest greenness patterns different than those reported here, we suggest that remote-sensing-based dynamic analyses of greenness can play a major role in evaluating disturbance theories and in developing testable hypotheses to guide ground-based studies of the integrated effects of large extreme events and human intervention on forest ecosystems.

Keywords: ice storm, large extreme events, forests, remote sensing, human intervention

S Online supplementary data available from stacks.iop.org/ERL/7/035702/mmedia

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1. Introduction

Forests currently offset a substantial portion of anthropogenic carbon emissions (Pan *et al* 2011). The sustainability of this carbon sink is strongly affected by the frequency and intensity of large extreme events (LEEs) (Frolking *et al* 2009, Turner and Dale 1998) and hinges upon how quickly impacted forests can regain their photosynthetic capacity (e.g., Amiro *et al* 2010). At present, our understanding of ecophysiological processes controlling the post-LEE regaining of forest photosynthetic capacity is very limited, which contributes to the large uncertainties in the estimated components and net exchanges of terrestrial carbon cycles at various scales (Liu *et al* 2011, Running 2008). Also, humans often take immediate actions to minimize economic loss after a sizable area of forests has been impacted by natural forces (e.g. salvage logging, Donato *et al* 2006, Foster *et al* 1997, Lindenmayer *et al* 2004). As a consequence, ecophysiological processes and intervening anthropogenic activities may jointly control the post-LEE regaining of forest photosynthetic capacity. Knowledge of these joint controls is needed to develop realistic representations of LEEs and associated societal responses in ecosystem and earth system models (Running 2008).

It is difficult to conduct controlled experiments on LEEs because of their unpredictability and broad spatial and temporal scales. Yet a common feature of LEEs is their spatially heterogeneous impact which could be caused by either initially heterogeneous landscapes or heterogeneous disturbance forces or both (Turner 2010). Spatial heterogeneity can also be caused by intervening human activities which may selectively target the impacted landscapes for various reasons including economics, accessibility and conservation. This spatial heterogeneity provides a natural laboratory for studying the post-LEE photosynthetic rebuilding process and its controlling factors in much the same way that ecologists use chronosequences to study plant community succession (e.g., Amiro *et al* 2010, Pickett 1989).

Remote sensing is an effective tool for assessing the spatial heterogeneity of the impact of LEEs on forests (Frolking *et al* 2009, Mildrexler *et al* 2009). Satellite greenness indices such as the Normalized Difference Vegetation Index (NDVI) (Goetz *et al* 2006) and the Enhanced Vegetation Index (EVI) (Huete *et al* 2006) have been used routinely to monitor photosynthetic activities at large scales. A challenge is how to use remote sensing to fill our current knowledge gaps about natural and anthropogenic factors controlling the post-LEE photosynthetic rebuilding process as remote sensing itself does not provide direct information about underlying ecological, biological and societal mechanisms. One approach is to employ satellite data to identify spatial and temporal patterns of post-LEE forest greenness and then use the identified patterns to evaluate existing disturbance theories or develop testable hypotheses to guide ground-based studies. A rare opportunity to assess this approach was provided by a massive ice storm that occurred in 2008 in China (Zhou *et al* 2011b).

Ice storms are common in East Asia (Zhou *et al* 2011b) and in North America (Changnon 2003). Individual ice storms can cause losses of over millions of dollars and their devastating impact often dominates news headlines in winters. Yet climatological and ecological studies pay relatively less attention to these winter storms compared to extreme events that occur in warm periods of a year. Like hurricanes and tornadoes (e.g., Chambers *et al* 2007, Lindroth *et al* 2009), ice storms exert their impact on forests mainly through physical forces.

The 2008 ice storm struck southern and central China from 10 January to 6 February 2008 (Zhou *et al* 2011b), a region of prominence for China's terrestrial carbon storage (Piao *et al* 2009). Record-breaking ice thickness, ranging from 60 to 160 mm, coated 12% of China's territory (supplementary figure 1 available at stacks.iop.org/ERL/7/035702/mmedia). Direct economic losses were estimated to exceed \$20 billion (Zhou *et al* 2011b). Forests suffered massive physical destruction and to a lesser degree, physiological damage. The area of impacted forests with at least 10% standing volume loss was estimated to be about 20 million hectares, equivalent to 10% of China's total forest cover. Also, the lost standing volume of the impacted area was 3% of the overall forest volume of the country (Zhou *et al* 2011b). Impacts on forests were diverse across the storm region (Shao *et al* 2011, Zhou *et al* 2011b, 2011a). Damage to individual trees included crown decapitation, stem breakage/splitting, branch snapping, bending and uprooting. Some species experienced physiological damage, typically showing cambium browning (Zhou *et al* 2011b). At stand levels, damage ranged from loss of foliage to whole-stand destruction. The initial storm impact also led to some secondary impacts such as increased soil erosion, landslides, fires and insect infestation (Zhou *et al* 2011b). Poorly planned salvage logging was observed during our visits to the region shortly after the storm ended. In this study, we take advantage of the spatial heterogeneity in the ice storm impact on China's forests to address the following questions: how do the degrees of ice storm impact, pre-storm vegetation growth status and salvage logging jointly affect the spatial and temporal patterns of satellite-derived forest greenness? Can current disturbance theories explain the satellite-derived patterns which represent the integrated effects of natural processes and human intervention?

2. Methods and datasets

We needed a measure to quantify the impact severity (IS) of the ice storm itself on forests (without the effect of subsequent disturbance caused by salvage logging). The IS of a LEE on forests can be defined in numerous ways with ground-based information, e.g. percentage of trees (basal area/volume) damaged, the amount of coarse woody debris produced, reduction in photosynthetic capacity, and changes in species composition and ecosystem biogeochemical processes (Foster *et al* 1997, Frolking *et al* 2009). These measures require carefully planned, intensive investigation with extensive ground-survey plots carried out shortly after the LEE is over but before regrowth or salvage logging takes place. This, however, was not possible for the 2008 Chinese ice storm. The impacted area was too large and the time window allowed to complete these massive tasks was too short for adequate ground-based investigation. The ground-based measures also require pre-storm vegetation information for reference, which was also not available. Therefore we defined IS in terms of immediate change in post-storm forest greenness because greenness is routinely measured with remotely sensed vegetation indices.

The use of satellite-derived forest greenness indices such as EVI and NDVI to define the IS of a LEE has shortcomings. These indices tend to saturate at high leaf area indices, an issue of particular concern for regions with dense vegetation such as tropical rainforests (e.g., Brantley *et al* 2011). Even though the southern and central China is mostly occupied by young and secondary growth forests (Zhou *et al* 2011b) and is not known to have very dense vegetation, we decided to use EVI because it is less likely to saturate with respect to leaf area index and more robust to different atmospheric conditions and different soil types (Huete *et al* 2002). This characteristic is important to studying the ice storm impact. We used the EVI products (MOD13A1) of the moderate resolution imaging spectroradiometer (MODIS) on board the TERRA satellite. The data covered the period from January 2001 to December 2010 and had a spatial resolution of 500 m and a temporal resolution of 16 days (16-day composites).

We quantified the IS of forest pixels by transforming EVI into a Standardized Detrended Vegetation Index (SDVI) (cf supplementary data available at stacks.iop.org/ERL/7/035702/mmedia), hence removing long-term trends and seasonal variations from the original 16-day composite data and allowing the resulting SDVI to be compared across time and across pixels for disturbance effects. The IS was objectively determined with SDVI, following the framework shown in figure 1. A 95% confidence interval (CI) for the long-term mean SDVI was computed and used as a benchmark of inter-annual variation against which impacted pixels were detected and pixel-specific IS was measured. A sigmoid function was fitted to the post-storm SDVI time series of each forest pixel. The reduction of SDVI from its long-term mean (zero) on 1 March 2008 was calculated with the optimized function and used as an IS index. The choice of 1 March for IS reflects our desire to measure the direct impact of the ice storm itself (i.e. avoiding the effects of regrowth and salvage logging; see supplementary data available at stacks.iop.org/ERL/7/035702/mmedia). A pixel was deemed impacted by the storm if its IS value was outside the 95% CI.

To provide a measure of how quickly the greenness of an impacted pixel rebounded, we calculated the time when the optimized sigmoid curve crossed the lower threshold of the 95% CI. The duration between the ending date of the storm and the crossing date was termed the greenness rebound time (GRT). GRT should reflect the integrated effects of natural processes as well as salvage logging if occurred, while IS should measure the direct impact of the ice storm physical forces only. Furthermore, we determined the mean SDVI for the previous main growing season (May to October 2007). The 2007 mean growing season SDVI could be considered as a measure for the pre-storm vegetation growth status relative to the long-term mean and thus be used to investigate how pre-storm vegetation growth status might interact with the storm to determine the impact.

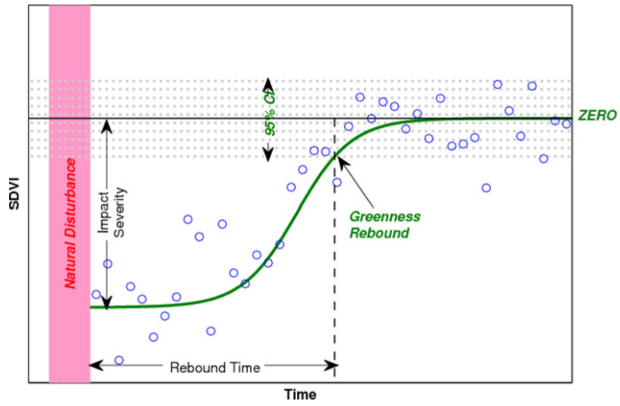

Figure 1. Objective determination of the impact severity (IS) and greenness rebound time (GRT). The long-term time series of Standardized Detrended Vegetation Index (SDVI) of pre- and post-disturbance is used to establish its inter-annual variability—the 95% confidence interval (CI), which serves as a benchmark for both detecting the impacted pixels and determining their IS and GRT. A sigmoid function is fit to the post-disturbance SDVI time series. The IS is measured by the reduction of SDVI from its long-term mean (zero), calculated with the optimized function at a time right after the disturbance. An impacted pixel has an IS value outside the 95% CI, and its greenness rebounds when the optimized curve crosses the CI lower threshold.

The post-storm spatial and temporal patterns of forest greenness were analyzed in terms of the quantifiable variables of IS, GRT and pre-storm growing season SDVI. The use of a 95% CI in the analysis was not a biological mandate but a statistical necessity. EVI varies both seasonally and annually even under normal conditions and these normal variations must be considered in order to tease out the true disturbance signal. Using a different threshold may affect the determination of the total area of forests impacted or the total biomass lost, neither of which is the focus of this study. For our objective, only relative measures of disturbance impact are of importance and the criterion of a 95% CI satisfies our needs. Nevertheless we understand any spatial and temporal patterns identified with this criterion will be of statistical nature in general and their ecological implications will have to be examined within this context.

We conducted Jarque–Bera tests and other cross-examinations to ensure that proper statistical models were applied and the obtained relationships were robust. To provide some ground truth, the remote-sensing-based analysis was corroborated with information gathered from spatially extensive ground visits to the impacted region. Detailed description about methods and datasets is available in the supplementary data (available at stacks.iop.org/ERL/7/035702/mmedia).

3. Results

The spatial distribution of forest pixels with IS below the 95% CI and thus identified as impacted by the ice storm

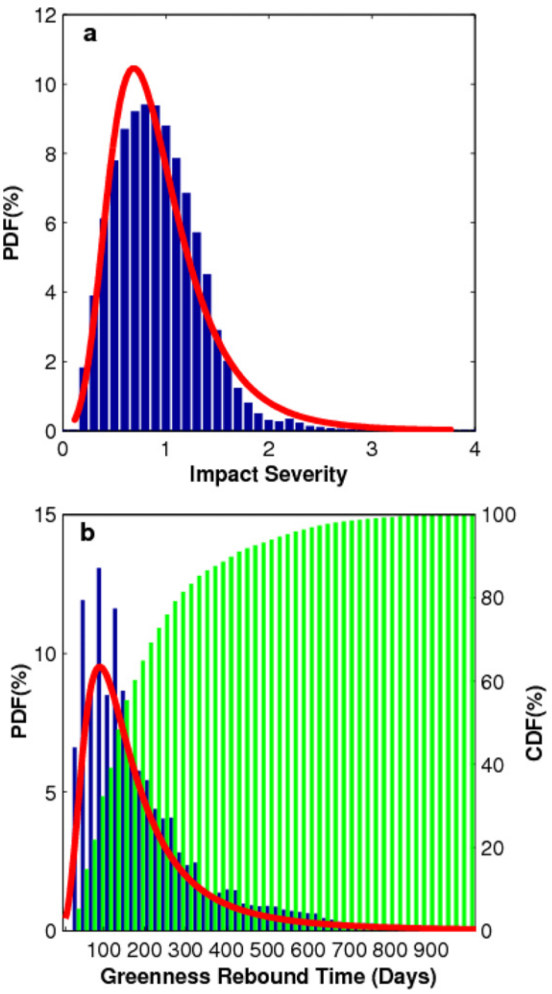

Figure 2. The probability density function (PDF) of (a) impact severity and (b) greenness rebound time. Blue bars denote the spatial fraction of each bin, and the red curves represent the fitted PDF using a distribution of generalized extreme value. The cumulative distribution function (CDF) of greenness rebound time (green bars) is also shown in (b).

is given in supplementary figure 2a (available at stacks.iop.org/ERL/7/035702/mmedia). The locations were mostly mountainous regions where ice storm damages to forests were reported in ground-based studies (Shao *et al* 2011, Zhou *et al* 2011b, 2011a) and also observed in our ground visits (supplementary data available at stacks.iop.org/ERL/7/035702/mmedia). These pixels tended to cluster and be more highly impacted in the mountains of Wuyishan, Jinggangshan, Lushan and Wugongshan. Nevertheless, IS varied widely across space, with different degrees of impact occurring in close proximity. The probability density function (PDF) for the spatial variation of IS was a skewed unimodal distribution with a long tail towards high IS (figure 2(a)), indicating factors determining the degree of the ice storm impact may not be completely random and the ice storm caused extreme reduction in the relative values of EVI of some pixels.

The GRT also showed large variations occurring on a small scale (supplementary figure 2b available at stacks.iop.org/ERL/7/035702/mmedia). Similar to that of IS, the PDF of GRT was also a skewed unimodal distribution with a long tail towards protracted restoration of greenness (figure 2(b)). It had a peak around mid-May 2008 (GRT $\sim$ 100 days). About 50% of the impacted pixels had the greenness restored to within the 95% CI of their long-term mean by early July 2008 (GRT $\sim$ 150 days), and about 80% within approximately one year after the storm (figure 2(b)).

The IS, pre-storm growing season SDVI and GRT formed a tight relationship in the 3D space (figure 3(a)). A local regression model (LOESS) fit the 3D scatter plot well (figure 3(b)). Both the 3D plot and its cut-through views (figures 3(c) and (d)) indicated that the three variables varied highly nonlinearly with each other. Higher pre-storm growing season SDVI tended to correspond to longer GRT for a given IS (figure 3(d)).

Given the close resemblance between the IS and GRT PDF distributions (figure 2), one might anticipate that GRT would be a monotonic function of IS, i.e., the more severely a pixel was impacted by the ice storm, the longer it would take for greenness to rebound. The observed relationship, however, showed that the maximum GRT occurred at an intermediate level of IS (figures 3(a) and (c)). For lightly to moderately impacted forests, GRT indeed increased with IS. This is in contrast with moderately to severely impacted forests for which GRT shortened with increasing IS (figures 3(a) and (c)).

4. Discussion: potential natural and anthropogenic causes of observed patterns

Overall, the post-storm greenness rebounded quickly even though the physical damage caused by the ice storm to the forests was massive. This fast rebound was likely a consequence of combination of abiotic and biotic factors. Shortly after the storm ended, temperatures in the region rose rapidly and precipitation was ample throughout the year (supplementary figure 3 available at stacks.iop.org/ERL/7/035702/mmedia). These favorable environmental conditions may have facilitated regional-wide regrowth of vegetation as seen in similar studies of other disturbances elsewhere (Law *et al* 2002). Also the newly available nutrients released from dead biomass after disturbance may have stimulated vegetation regrowth (e.g., Franklin *et al* 1987). Site visits between April and November 2008 by the authors revealed fairly thick growth of understory shrub/herbaceous/epiphytic plants taking advantage of an improved forest floor light environment under broken canopies (cf supplementary data available at stacks.iop.org/ERL/7/035702/mmedia). This response is a benefit of high species diversity in the storm region, one of the main biodiversity hotspots in China (Liu *et al* 2003). Furthermore, tree species in the impacted region appear to have exceptional resprouting capacities (Nanami *et al* 2004), an important life-history strategy for persistence and quick recovery in tropical and subtropical forests (Poorter *et al* 2010). Indeed, widespread resprouting of physically damaged trees was observed throughout the region (supplementary figure 4 available at stacks.iop.org/ERL/7/035702/mmedia). Although forest greenness rebounded rapidly, forest structure and some ecosystem functions, e.g., living biomass volume and carbon balance, may take

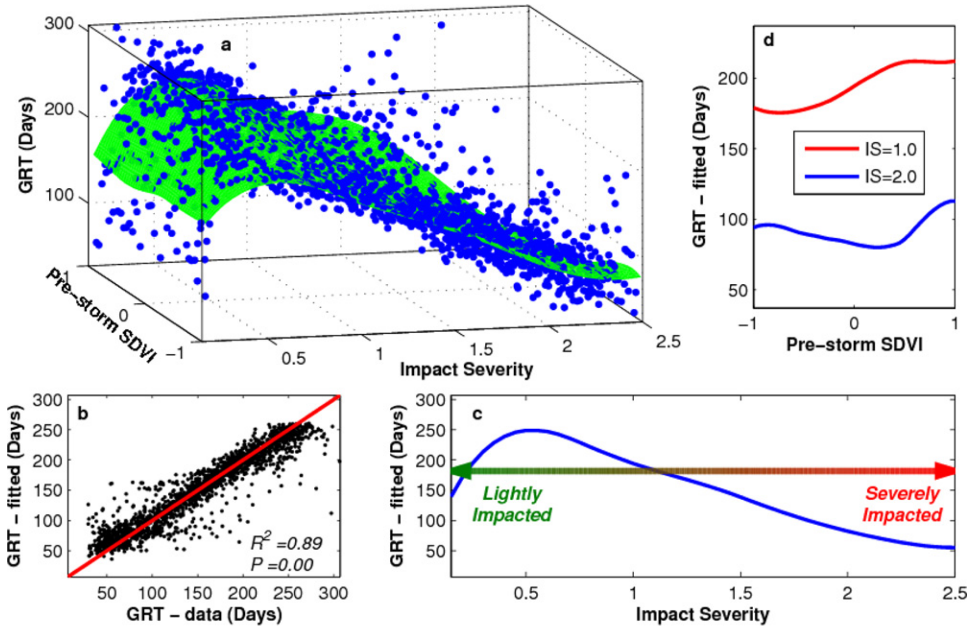

Figure 3. Greenness rebounded time (GRT) as a function of impact severity (IS) and the mean SDVI for the main growing season prior to the storm (pre-storm SDVI). (a) The 3D scatter plot, surface-fitted with a local regression model (LOESS, green surface) with values of IS and pre-storm SDVI each binned at 0.05 intervals for clarity. (b) The goodness of surface fitting. (c) A slice in the GRT–IS plane at pre-storm SDVI = 0, showing GRT as a nonlinear function of IS. (d) A slice in the GRT—pre-storm SDVI plane at IS = 1.0 (red) and another at IS = 2.0 (blue), showing GRT as a nonlinear function of pre-storm SDVI.

decades or even longer time to recover (e.g., Amiro *et al* 2010).

It is possible that anomalously high pre-storm growth relative to the long-term mean may have resulted in more post-storm necromass production, leading to increased fuels for fires (Zhou *et al* 2011b); or, thicker biomass debris at better growth sites in 2007 relative to the long-term mean may have covered the ground and adversely affected post-storm understory growth in response to rapidly rising temperatures (supplementary figure 3 available at stacks.iop.org/ERL/7/035702/mmedia).

The exact causes of the satellite-derived patterns in forest greenness are difficult to ascertain because there is limited ground information on vegetation before and after the storm. However, it is interesting to compare these observed patterns with predictions of existing ecological disturbance theories. The insurance hypothesis suggests that higher species diversity can reduce the realized impact of a disturbance (Hughes *et al* 2007, Tilman 1996). Ecologists also believe uncommon or rare species can play a pivotal role in the response of ecosystems to disturbances (Duffy 2009, Lyons *et al* 2005) and that higher functioning and more stable ecosystem services over time are maintained by more diverse plant communities (Allan *et al* 2011, Isbell *et al* 2011). The region impacted by the ice storm is known for its high species diversity and our post-storm ground visits observed thriving shrub/herbaceous/epiphytic species under damaged canopies. Thus it is reasonable to suggest that species that normally do not dominate forest structures may have played a major role in the satellite-derived rapid rebound of forest greenness after the 2008 Chinese ice storm. If so, then our study appears to support the insurance hypothesis and the uncommon species hypothesis, suggesting that these hypotheses, which have been developed primarily from studies at scales much smaller than the massive ice storm, may transcend scales. The existing disturbance theories can be broadened by explicitly considering diversity in the life-history strategy of species as our ground visits suggested that resprouting of physically damaged trees may be also important for the rapid rebound of forest greenness.

It is challenging to explain the occurrence of longest GRT at some intermediate IS (figure 3). According to the theory of gap-phase dynamics (Franklin *et al* 1987, Osborne 2000), greater canopy gaps may be created in more disturbed forests, allowing more light and nutrients available to r-selected species for opportunist growth. As a result, more severely impacted forests had faster restoration of greenness. However, this cannot explain why GRT initially increased from lightly to moderately impacted forests. It is possible that relatively mild impact may have prevented the gap effect from being realized, a phenomenon that has been reported in previous studies (Hubbell 1999). If so, the temporal patterns of greenness of lightly to moderately impacted forests may largely reflect the changes of overstory canopies. The secondary hazards that occurred after the initial storm impact (Zhou *et al* 2011b) could also contribute to the GRT–IS relationship if they took place more frequently in intermediately impacted forests. However we do not have information to confirm or refute this hypothesis.

An alternative and more parsimonious explanation is that salvage logging after the ice storm preferentially targeted lightly to moderately impacted forests. Previous studies have shown that salvage logging can be detrimental to post-disturbance vegetation regrowth (Donato *et al* 2006, Lindenmayer *et al* 2004). Substantial salvage logging occurred after the ice storm. In 2008, the State Forestry Administration of China received requests for increasing logging quota from provinces affected by the ice storm and approved an average increase of 65% in logging quota (supplementary figure 5 available at stacks.iop.org/ERL/7/035702/mmedia). Our field visits observed salvage logging activities that were apparently carried out hastily with limited planning as they took place shortly after the storm ended (cf supplementary data available at stacks.iop.org/ERL/7/035702/mmedia). Salvage logging might have occurred preferentially in lightly to moderately impacted forests because of their easy access or higher timber values compared with severely impacted ones. The concentrated occurrence of salvage logging in forests lightly to moderately impacted by the ice storm may have damaged ground vegetation and trees survived the ice storm, reduced resprouting, and disturbed soils and thus delayed the rebound in greenness of these forests compared with more severely impacted forests. Without the intervening effect of salvage logging, the obtained nonlinear GRT–IS relationship may be quite different. More discussion on salvage logging is provided in supplementary data (available at stacks.iop.org/ERL/7/035702/mmedia).

These findings and explanations need to be further validated through ground observations, e.g., eddy covariance measurements and chronosequences techniques (e.g., Amiro *et al* 2010). They may be also region-specific (i.e. they may not be applicable to pure natural disturbances, which are difficult to find in places such as southern China). The carbon balance pre- and post-storm may be a more important way to reflect forest recovery than greenness. For carbon balance, spatial scaling is an important issue (Liu *et al* 2011) and would require more work than conducted here. Some theoretical or empirical ecological models (Lindroth *et al* 2009, Chambers *et al* 2007) have been used to study storms; these models may be used to study the ice storm although they will need to explicitly consider human factors.

5. Conclusion

The rapid rebound of forest greenness after the massive 2008 ice storm in southern and central China will help the region's forests regain their carbon sink potential. The spatial and temporal patterns of forest greenness after the storm could be explained in the context of natural processes including species diversity, life-history strategy of trees, and gap-phase dynamics as well as human intervention, i.e., salvage logging, although further ground-based studies are needed to pinpoint the exact causes. Major findings from this study reflect the integrated effects of natural processes and human intervention and thus may not be applicable to pure natural disturbances. Nevertheless, the methodology developed may be equally effective to other destructive natural disturbances such as hurricanes, tornadoes and fires. Although remote sensing does not provide direct information about mechanisms controlling the impact dynamics of large extreme events, it can be used to construct the pre- and post-event spatial and temporal patterns of vegetation conditions, which can then be applied to test extant disturbance theories or develop new hypotheses to guide ground-based studies. To represent disturbance impact realistically, carbon cycle models may have to explicitly consider species that under normal conditions may not contribute much to forest primary production but are nevertheless important to the post-storm rebuilding of photosynthetic capacity. These models may also have to employ mechanisms (e.g. rapid mobilization of carbon reserves) to enable roles of life-history strategies of species (e.g. resprouting) in simulating post-disturbance vegetation dynamics. Potential human intervention must also be considered in these models. A close collaboration between the remote-sensing community, experimental and theoretical ecologists, social scientists and large-scale modelers is needed to advance the study of large extreme events and associated human intervention.

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