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Forest Resilience, Tipping Points and Global Change Processes

Christopher P.O. Reyer[1]*, Anja Rammig[1], Niels Brouwers[2], Fanny Langerwisch[1]

[1]Potsdam Institute for Climate Impact Research, Telegrafenberg, PO Box 601203,
Potsdam, 14412, Germany
*Corresponding author: tel. + 49 331 28820725, fax + 49 331 288 2695, e-mail:
reyer@pik-potsdam.de
[2]State Centre of Excellence for Climate Change, Woodland and Forest Health, School of
Veterinary and Life Sciences, Murdoch University, Murdoch, 6150, Western Australia
[3]Environment Institute and School of Earth and Environmental Sciences, The University
of Adelaide, SA 5005, Australia

Summary:

1. Forests around the world are changing as a result of human activity. These changes have substantial impacts on the resilience of forests, possibly pushing them towards tipping points.
2. The objective of this Special Feature is to present research that fosters the understanding of forest resilience and potential tipping points under global change. This editorial summarizes the key findings of the seven papers in this Special Feature and puts them in the wider context of resilience thinking.
3. *Synthesis:* The contributions to this Special Feature show that resilience is a useful concept to understand ecosystem change but that we have to learn more about the mechanisms and feedback loops involved in forest resilience and potential tipping points. Finally, this Special Feature presents evidence how resilience thinking is used to better understand and manage degraded forests.

Keywords: climate change, forest management, mechanism, mortality, paleo-ecology, plant–climate interactions, regime shifts, seedling recruitment, spatio-temporal scales

Introduction

Around the globe, forest ecosystems are increasingly undergoing changes in function, structure and species composition due to alterations in climate, nitrogen deposition, anthropogenic pressures, and their interactions (e.g. Amazon: Phillips *et al.* 2009; Asia: Poulter *et al.* 2013; Australia: Boulter 2012; Europe: Lindner *et al.* 2010; USA: Dietze & Moorcroft 2011). Climate-induced forest dieback in the future cannot be ruled out for forest ecosystems of global importance such as the Amazon (e.g. Cox *et al.* 2013, Brando *et al.* 2014) or the boreal forests (e.g. Michaelian *et al.* 2011; Lenton *et al.* 2008).

Here, we define forest resilience according to Scheffer (2009) as "*the ability of a forest to absorb disturbances and re-organize under change to maintain similar functioning and structure*". A tipping point is defined as a threshold at which a relatively small change in conditions leads to a strong change in the state of a system (cf. Brook *et al.* 2013). For further discussion of these concepts, see Reyer *et al.* (2015).

As recently summarized by the Fifth Assessment Report of the IPCC (IPCC 2013), global climatic changes such as increasing temperatures, heat extremes, droughts, heavy precipitation events and altered precipitation patterns are likely to become more prevalent in the coming decades. These climatic changes will have substantial impact on the resilience of forests, possibly pushing forest ecosystems towards tipping points and into alternate states of vegetation cover (IPCC 2014). Consequently, there will be knock-on effects on the ecosystem services and functions forests provide, for instance by altering species composition, timber supply and carbon sequestration.

Forest ecosystems around the world respond in many different ways to changing conditions. It is, however, notoriously difficult to know how specific forest ecosystems will react to global change processes, because of their inherent complexity, possible feedbacks and nonlinearities. Therefore, the objective of this Special Feature is to present research that fosters the understanding of forest resilience and potential tipping points under global change. It is based on a series of contributions to a symposium entitled: “Forest Resilience, Tipping Points and Global Change Processes” held at the INTECOL 2013 conference on the 22-23 of August 2013, London, UK. This editorial summarizes the key findings of the seven papers in this Special Feature and puts them in the wider context of resilience thinking.

This Special Feature focuses on studies addressing resilience and potential tipping points in forest ecosystems. These studies are of crucial importance for assessing the impacts of global change processes on the ecosystem services forests provide to society and for a deeper ecological understanding of how (eco)systems organise. The focus of this Special Feature is deliberately broad to reflect the diversity of forest research on the topic that is undertaken globally. Such broad focus also calls for a variety of methods and spatio-temporal scales to be covered and hence the papers presented here stretch from plot-level observational (e.g. Camarero *et al.* 2015; Jakovac *et al.* 2015; Standish *et al.* 2015) or paleo-ecological (e.g. Cole *et al.* 2015) studies through experimental work (Holmgren *et al.* 2015) to global modelling (Steinkamp & Hickler 2015).

Spatio-temporal scales of forest resilience and tipping points under global change

In the first contribution to this Special Feature, Reyer *et al.* (2015) synthesize evidence of changing forests over a wide range of spatio-temporal scales. They stress that it is often not clear if these changes reduce resilience and/or whether they lead to a tipping point.

Moreover, the authors conclude that studies bringing together experiments, observations and models as well as covering interactions across a range of spatio-temporal scales are needed to further our understanding of forest resilience and tipping points.

The study by Cole *et al.* (2015) highlights the importance of long temporal scales for assessing forest resilience. Their paleo-ecological study of tropical peat swamp forests from Malaysian Borneo shows that for at least 2000 years, these ecosystems have been highly resilient even under various disturbances such as fire or changing climate variability due to the El Niño Southern Oscillation. Based on peat swamp pollen records, however, recent anthropogenic disturbances seem to have resulted in a lower forest pollen production, indicating a reduced resilience of this ecosystem. Altogether, these two papers show that resilience and scaling issues are intimately linked, which serves as a backdrop for interpreting the remaining papers of this Special Feature as well as existing and future studies on forest resilience.

Drought stress impairing resilience and triggering mortality – from local to global scales

Drought-induced forest mortality has been observed to affect forests worldwide (Allen *et al.* 2010) possibly indicating reduced forest resilience. However, the mechanisms of drought-induced tree mortality are uncertain and therefore intensively debated (McDowell *et al.* 2008; Sala *et al.* 2010). Steinkamp & Hickler (2015) use a dynamic global vegetation model to estimate the threat of increased forest mortality caused by drought and heat stress at the global scale. They examine the locations specified by Allen *et al.* (2010) that experienced drought-induced mortality events and simulate the contribution of drought to tree mortality using the model as a diagnostic tool. Based on observation and simulation results, they conclude that there is no strongly increasing trend in drought-induced forest mortality globally and consequently the observed mortality events reported by Allen *et al.* (2010) might not have solely been induced by droughts. However, Steinkamp & Hickler (2015) also highlight that vegetation models are known to underrepresent drought-induced mortality. Further model development is needed to better represent drought and other interacting disturbances in ecological models.

Taking up drought mortality at the very local level, Camarero *et al.* (2015) evaluate whether critical transitions of tipping points and tree mortality can be detected in a combination of measurements on tree growth and tree vigour. They investigate three sites in Spain that suffered a severe drought in 2012. They relate early warning signals to additional data of tree vigour such as defoliation, nitrogen content of needles, and the amount of non-structural carbohydrates in heavily defoliated/dying and non-defoliated trees. Even though they found diverging signals among tree species, the understanding this study generated may help to derive more general patterns of potential forest die-back, e.g. for modelling purposes. They indicate that the interaction between growth, defoliation and sapwood function is potentially an important proxy for the occurrence of tree death. These two papers highlight that processes related to drought stress and tree mortality in forests are highly complex and warrant further attention in future research.

Tree recruitment as an important mechanisms of forest resilience

Facilitation and positive feedbacks on tree recruitment represent a much overlooked mechanism contributing to resilience is that could lead to vegetation shifts under climate warming. Holmgren *et al.* (2015) conduct a multi-year field experiment in boreal ecosystems in southern-central Finland to unravel the mechanisms of peatbog transition to forests – an issue of tremendous importance for the global carbon cycle given the huge amount of carbon stored in these systems. They describe positive interactions between shrub cover and tree recruitment: Shrub cover favors tree seedlings and, in turn, higher tree basal area fosters shrub biomass. Such positive feedback loops could potentially trigger ecosystem shifts from peatbog to forest. This feedback seemed to be stronger in warmer years, which could induce larger changes in peatbogs under climate change than commonly considered. This experiment hence helps to increase our understanding of the mechanisms leading to alternative stable states in boreal ecosystems (Scheffer *et al.* 2012). Within the framework of this Special Feature, this paper shows that, for understanding forest resilience and tipping points, it is also crucial to understand the alternative states in which a forest may transition after resilience is exceeded and a tipping point has been passed.

Resilience as a concept to understand the functioning of disturbed forests and improve their management

While climate change is a prominent issue for global sustainability, other global changes such as land-use changes and invasive species have fundamental impacts on forest ecosystems as well. With such ongoing and interacting changes, the area of disturbed ecosystems is increasing and so does the need to restore them. Enhanced understanding of resilience processes and mechanisms can help to manage degraded ecosystems. Jacovac *et al.* (2015) investigate the consequences of land-use on the resilience of secondary forests in the Amazon basin. The importance of these secondary forests for maintaining and recovering nutrient-, water-, and carbon-cycles is often underestimated. Forest structure was found to recover more slowly with high management intensity, while species diversity in secondary forests decreased with decreasing area of surrounding old-growth rainforests. These findings suggest an interaction of land-use intensification, loss of remaining old-growth forests, and increasing dominance of resprouting plants and lianas leading to an arrested successional state. This arrested state would provide less ecosystem services such as protection from soil erosion, maintenance of water supply and protection from weeds and pests and could involve higher socioeconomic costs, for example, to prevent the spread of weeds. Jacovac *et al.* (2015) thus stress the role of assisted regeneration as well as a focus on faster growing species to maintain the resilience of the secondary forest.

Standish *et al.* (2015), on the other hand, provide one of the few studies to consider the impacts of changes in climate and restoration practice on seedling establishment of forest species in south-western Australia. The ability of a forest to regenerate is an important indicator of forest resilience. Standish *et al.* (2015) looked at the success of seedling establishment over a period of 19 years at bauxite strip-mine rehabilitation sites, in relation to climate variability and the restoration practice that was adopted. Restoration practice was found to be more important than climate variability in terms of the success of seedling establishment on these sites. Nonetheless, extant climatic changes were found to have a small but significant negative effect on the number of species that established. This research shows that adaptation of restoration practices, such as appropriate timing of seeding, can potentially alleviate the negative effects of changes in climate. Focusing restoration practice on improving seedling establishment might therefore be more effective compared to improving the health of declining mature trees in areas with persistent drying and warming conditions (e.g., Brouwers *et al.* 2012) and potentially elsewhere. These two contributions highlight that the concept of resilience is not just a theoretical framework, but can equally produce management related recommendations.

Conclusion

As climate, land-use and other global changes advance rapidly, so does resilience science, increasing our understanding of the mechanism leading to recovery of forests and/or their transition into alternative states. The contributions to this Special Feature allow for a few interim conclusions. Firstly, resilience is a useful concept to understand ecosystem change. Given the multiple direct, indirect and interacting changes that occur as a result of human activities worldwide, it is crucial to know when changes exceed the baseline variability and actually threaten to ‘tip’ a forest into an alternative state. Secondly, this Special Feature has shown that we still need to better understand the mechanisms and feedback loops involved in forest resilience and tipping points to increase confidence in model projections. For example, seedling recruitment and drought-induced mortality, which are treated in more detail in several of the papers of this Special Feature, are only two examples of important mechanisms contributing to forest resilience. Thirdly, we conclude that robust indicators of forest resilience are needed and that tipping points seem to be much harder to detect in forest ecosystems than in aquatic ecosystems where they are much better studied. Actually, every single study in this Special Feature still struggles to unravel potential tipping point behaviour and we call for further discussions and tests if the tipping point concept is suitable for forests. Related to this, we stress that there is a lack of studies considering effects of extremes compared to mean climate change (Smith 2011; Reyer *et al.* 2013), which is a key uncertainty in our understanding of how climate change may impair resilience. Finally, it is encouraging to see that this Special Feature presents evidence how resilience thinking is used to better understand and enhance the sustainable management of degraded forests in this time of rapid environmental change.

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