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Discussion
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Discussion

Extreme Events: Managing Forests When Expecting the Unexpected

Klaus J. Puettmann

Klaus J. Puettmann (Klaus.Puettmann@oregonstate.edu), Department of Ecosystems and Society, Oregon State University, 321 Richardson Hall, Corvallis, OR 97331, USA.

For centuries, forest management has provided great benefits for local and global populations, especially in terms of wood production (Wagner et al. 2004, Puettmann et al. 2009). However, recent events have begun to undermine the confidence that our management practices are adequate to ensure the continued provision of desired ecosystem services (Figure 1). For example, large-scale insect infestations in western Canada and western Europe and large, high-intensity fires in Australia and California have encouraged discussions, with many people suggesting that we will have to deal with such "extreme events" (defined as rare, but high-impact events that lead to irreversible, unacceptable outcomes, see Box 1) more frequently in the future (Dale et al. 2001, Sheehan et al. 2015, Seidl et al. 2018). A closer look at statistical and analytical concepts suggests that extreme events are an inherent part of forest ecosystems, and that we may be well advised to acknowledge this fact in research, education, and planning and implementing forest management in the face of a novel and highly uncertain future. One of the reasons that these events have not gotten sufficient attention is that because of their rarity, extreme events are hard to study, and thus often are easily and—understandably—ignored in silvicultural and management decisions. For example, we have paid limited attention to the role of fires in the moist, western forests in the Pacific Northwest with a fire return interval of 300 years or longer (Agee 1993), even though describing the disturbance regime by its fire return interval acknowledges that we understand the high impact that fires can have on the landscape. Furthermore, typically used statistical approaches and assumptions may not apply to extreme events (see Box 1). Thus, acknowledging extreme events suggest the need for a critical review of our silviculture practices and any assessment should use a solid scientific basis.

A tremendous amount of work in terms of risk analysis and management has been done, not only in the investment and insurance fields, but also in ecology (Yachi and Loreau 1999) and forestry (e.g., Goodnow et al. 2008). Figure 2 is a simplistic presentation of a typical risk model and provides some basic insights. The lower income under conditions of low uncertainty when managing risk averse (RAM) rather than business as usual (BAU) can be viewed as an insurance premium (Puettmann and Messier 2019). In turn, the relatively high gain (i.e., higher income when using risk averse management [RAM]) after perturbations is the insurance payout. Forest owners are, de facto, paying that insurance premium through economic losses when salvage logging after disturbances is less profitable. In these instances, harvesting income is often lower because the timing does not allow owners to harvest trees at their economically optimal size; or harvesting costs are higher because of stem breakage, safety concerns, and a high demand for loggers; or prices are lower in a market flooded by an oversupply of salvaged logs. The amount of salvage logging after massive disturbances can be multiple times the planned cutting level (e.g., during the mountain pine beetle [*Dendroctonus ponderosae*] infestations in British Columbia or on selected ownerships affected by the 2020 wildfires in Oregon). Knowing the regional and long-term probabilities of disturbances and their impact on costs and prices allows managers to decide which strategies (e.g., BAU or RAM) to pursue (Goodnow et al. 2008, Knoke et al. 2008). Such strategies (as displayed in Figure 2) or similar approaches

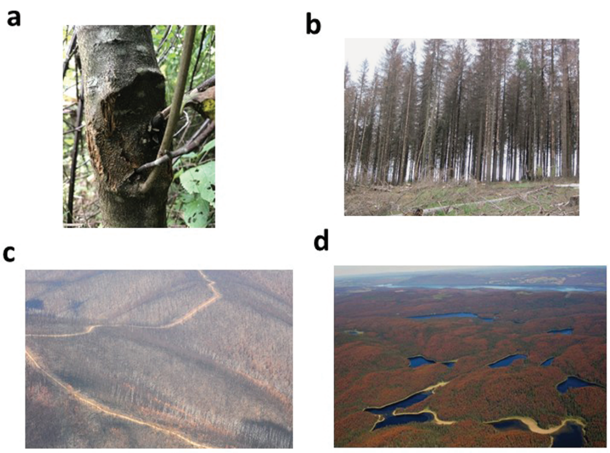

Figure 1. Photos of extreme events, including (a) American chestnut (*Castanea dentata*) infected with the chestnut blight (photo credit: USDA Forest Service); (b) large-scale Norway spruce (*Picea abies*) mortality in central Europe because of extended drought and bark beetle infestations (photo credit: B. Leder); (c) fire mortality 2019 in East Gippsland, Australia (photo credit: T.A. Fairman); and (d) mountain pine beetle mortality near Bonaparte Lake, BC (photo credit: L. MacLauchlan).

have been used extensively on many forest ownerships (Goodnow et al. 2008). These approaches typically base management decisions on average probabilities of perturbations that are derived from long term or regional data. This makes sense when damages are limited to conditions that allow managers to continue operations long term, even after the perturbation event. In contrast, an extreme event leads to halting and possible resetting of forest mangement operations, and knowing long-term average probabilities that were calculated for settings that do not include these possibilities are not applicable (Taleb 2020). This is why insurance companies will limit their liability for single events to levels that prevent them from going bankrupt (the so-called Cramer condition; Taleb 2020)—that is, insurance companies limit their business to conditions as presented in Figure 2, where they can rely on long-term average probabilities and will not provide policies that do not have a payout cap. In contrast to insurance companies, foresters cannot simply ignore extreme events, as events that have a convex relationship between disturbance intensity and severity can be very influential in forests (Figure 3).

Figure 4 shows conceptually that extreme events are happening when resistance (the inverse of sensitivity), resilience, and adaptive capacity are not sufficient and consequences of perturbations include irreversible failure or conditions that are legally or ethically unacceptable and typically lead to halting of forestry operations. In forestry, we may view unacceptable outcomes in three dimensions: (1) an ecological dimension, such as species extinctions or irreversible changes in habitat or plant and wildlife populations; (2) an economic dimension, such the suspension of forestry operation (e.g., because of loss of infrastructure [closure of mills or logging companies] or substantial change in laws or regulations that halt forestry operations); and (3) a social dimension, as such as loss of human lives or other life-changing events. Extreme events can also play out at smaller scales (e.g., events that lead to plantation failures that require foresters to start the reforestation process all over again).

Regardless of whether one views extreme events as “unavoidable natural disasters” or “partially man-made” (Lidskog and Löfmarck 2016), the brief discussion above highlights why we cannot afford to ignore the possibility of their occurrence, although the probability is very small and very difficult to predict. The discussion and Figure 4 also suggest the only silviculture or management option to avoid unacceptable outcomes when resilience and adaptation are not sufficient, is to reduce sensitivity (i.e., increase resistance; De Lange et al. 2010, Allen et al. 2017).

Management Implications

The first step to address the challenge of extreme events is to acknowledge the fact that we do not have a good understanding of the future, especially in times of global change. To ensure that we acknowledge the possibility of extreme events, foresters are starting to use a scenario planning approach (Kahane 2012). Examples of scenario planning in forestry at larger scales (Leslie 2009) and smaller operational settings (e.g., Kaslo & District Community Forest), as well as in educational efforts (Puettmann et al. 2016) suggest that it has great potential to broaden participants’ minds toward the notion of including the possibility of extreme events in decision processes.

Once we acknowledge that extreme events are part of our future, the next question is, what specifically enables an event to become extreme—that is, what allows perturbations to have extremely large impacts? Investigations into what specifically leads to extreme events with unacceptable outcomes in a variety of fields show a consistent pattern pointing to the connectivity (i.e., the extent to which a perturbation can spread in the system) as most influential (Norman et al. 2020), specifically the connectivity within and across scales. For example, concerns about the spread of infectious diseases have identified increased contacts among individuals

Box 1: Statistical Implications of Ignoring Extreme Events

Extreme events typically do not follow normal distributions, but instead some type of fat-tail distributions. These distributions are strongly influenced by events located in the tails. Thus, their statistical properties are less determined by events near the mean, as compared with Gaussian or normal distributions. The distinction is not just a measure of the frequency of events far away from the mean, typically quantified as kurtosis. Fat-tail distributions do not necessarily have more events in the tail; they may even have fewer, but at least one of these events has an extremely large impact. Thus, fat-tail distributions may be more appropriate and useful when such impacts lead to unacceptable outcomes (Figures 4 and 5; Taleb 2020).

Statistical implications when events follow a fat-tail distribution include the following:

1) Fat-tail distributions have a large sample error as, by definition, rare events are tough to study. Thus, standard measures used to describe distributions, such as variance or standard deviations are meaningless.
2) The central limit theorem, a basis for statistical sampling, does not apply. Thus, a much larger sample size is required to stabilize the sample mean. Instead of 30 observations in the Gaussian, "it takes 1,011 observations in the [fat-tailed] Pareto [distribution] to bring the sample error down by the same amount" (https://www.sr-sv.com/the-dangerous-disregard-of-fat-tails-in-quantitative-finance/; last accessed January 25, 2021).
3) Even with a larger number, the population mean cannot be properly estimated from the sample mean.
4) Many common statistical methods applied to data from a fat-tail distribution will lead to erroneous results—for example, when applying linear regression, principal component analysis, or method of moments (Taleb 2020).
5) One of the challenges we have to accept when acknowledging the presence of extreme events is that even when our sample suggests a normal distribution, we cannot necessarily rule out that the event is actually best represented by other distributions—with fat-tail distribution being of special interest in this context (Taleb 2020). This is a classic example of the aphorism that "the absence of evidence is not evidence of absence." Because extreme events are rare, they are most likely not detected in standard sampling procedures and thus not considered in management decisions (Figure 3).
6) In contrast, when we observe an event that is 25 standard deviations out, we likely can rule out a normal distribution. Clearly, our standard analytical approaches that rely heavily on information about the mean are not particularly well designed to deal with extreme events. Instead, in such situations, Taleb (2020) suggests using statistical approaches and distributions that are driven by events far away from the mean—for example, a type of power-law distribution such as the Pareto distribution (Figure 3). In addition, even if the frequency of events is symmetric, the impact of these events may not be. It is better to mistake a rock for a bear than a bear for a rock". https://www.businessinsider.com/cognitive-biases-2014-6?op=1#negativity-bias-30; last accessed March 03 2021.

(Brennan et al. 2013), populations (Eames 2008), and species (Parrish et al. 2008) and increased global connectivity (Brockmann 2017) as major concerns.

In the context of forest restoration and management, connectivity typically has been viewed as a desirable feature with the most attention paid to its role in allowing species to spread and migrate (Bennett 1999, Correa Ayram et al. 2016). However, connectivity implies much more than just a means to facilitate species movement. For example, in the context of extreme events, foresters need to focus on connectivity in regards to various types of perturbation events that can propagate from one tree, stand, or landscape to another. Thus, connectivity needs to be defined as scale specific and as event specific, as different type of events have different spreading mechanisms. Table 1 provides examples of several types of events and whether they connect at the tree, stand, and landscape scale. For example, neighboring elm (*Ulmus* spp.) and maples (*Acer* spp.) may be "connected" in regard to the spread and impact of the Asian longhorned beetle (*Anoplophora glabripennis*), but not in regard to the Dutch elm disease (*Ophiostoma novo-ulmi*). It may be simplest to consider connectivity within a single scale (e.g., within an individual tree, population [stand], and landscape; Table 1). However, it is also important to understand that connectivity acts across scales: small-scale events can be propagated and amplified across the landscape, such as when lightning strikes in a spot that starts a small fire, which then can spread because the landscape has a high fuel loads because of recent bark beetle outbreaks (Rykiel et al. 1988, Drever et al. 2006). At the same time, conditions at larger scales can set the stage for how events at smaller scales play out. Examples include landscape-level wood supply and associated marketing opportunities, regional or national environmental policies and regulations, or international certification standards that determine whether selected trees in a stand are harvested or which management practices can be applied (Olschewski et al. 2019). However, it is important to keep in mind that connectivity is not

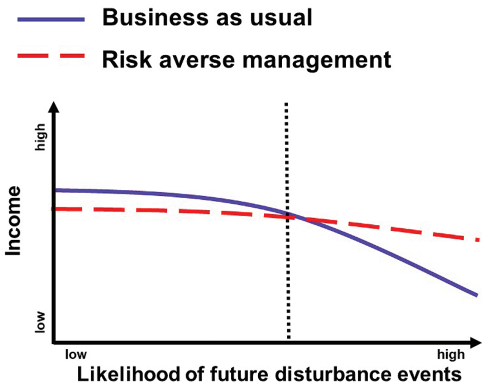

Figure 2. Example of a typical risk assessment approach describing the tradeoff between "paying an insurance premium" (lower yield when managing risk averse) and incurring damage (lower yield when managing business as usual [BAU], as a function of variability of future conditions). Note that optimizing management for current conditions (BAU) is most profitable to the left side of the dashed line, when future conditions are predictable. On the other hand, if the future does not follow predictions, including unexpected surprises, risk-averse management is more profitable (to the right side of the dashed line). As an example, Knoke et al. (2008) showed that in central Europe monocultures may be more profitable in the absence of perturbations (left side of the dashed vertical line). However, including the probability of perturbations in their calculation shifted their results. Under these conditions, mixed-species forests were more profitable (right side of the dashed vertical line).

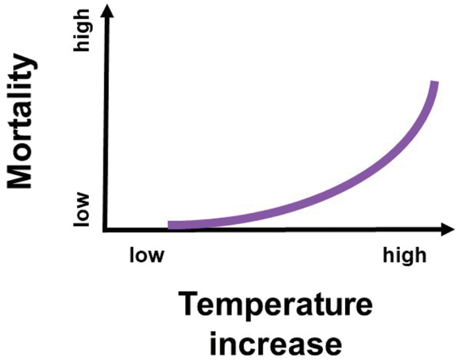

Figure 3. Extreme events are more likely to happen when response patterns of disturbance severity over intensity show a convex trend. Modified from Adams et al. 2017, who plotted the increase in mortality events over temperature increase.

limited to the spatial dimension—for example, trees that have the same threshold to drought or temperature conditions are connected in the context of climate change.

Throughout history, many benefits of forestry, especially the increased productivity and efficiency of wood production and subsequent manufacturing, resulted from management efforts to homogenize forest stands and landscapes (MacCleery 1992, Puettmann et al. 2009), for example, by creating monocultures of evenly spaced trees that are of similar size, vigor, crown conditions. In many regions, research and educational efforts have led to larger portions of the landscape being managed using a single dominant silviculture system, such as clearcut, shelterwood, or single-tree selection (Barrett 1995). An unintended side effect of such efforts was an increased similarity of forests (e.g., in terms of tree species composition and stand structures within stands and landscapes; Schulte et al. 2007). Under the assumption that increased homogeneity in various dimensions leads to higher connectivity and thus higher sensitivity to selected perturbations (Figure 4), it can be hypothesized that the choice of forest management operations influences the possibility large-scale, high severity perturbations, including extreme events.

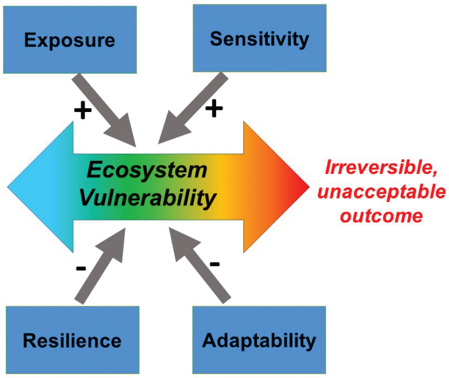

Figure 4. Higher exposure and sensitivity (defined as inverse of resistance) increase ecosystem vulnerability of ecosystems to perturbation events (+). In contrast, higher resilience and adaptability reduce ecosystem vulnerability (-). Extreme events are instances, where after exposure the sensitivity is too high and the resilience, and adaptability are insufficient to prevent unacceptable outcomes. This discussion focuses on breaking connectivity as a way to decrease sensitivity and thus prevent extreme events by reducing the ability of perturbations to spread through the system.

Recent increased attention to management practices that are not based on the "agricultural model" or aimed at homogenizing forests to ensure operational efficiency (Puettmann et al. 2009) are of special interest in this context. Examples include mixed-species management (Pretzsch et al. 2017), multiaged silviculture (O'Hara 2014), and approaches that emphasize both of these approaches simultaneously, such as ecological silviculture (Palik et al. 2020). However, often reasons

Table 1. Selected event types and factors that influence the likelihood of extreme events through connectivity at the individual tree, population/stand, or landscape/ownership levels. Managing connectivity at the appropriate scales will influence the likelihood of events becoming extreme high-impact events that lead to unacceptable outcomes.

Event Type or Factor	Influenced By	Connected Scale	Reference Examples
Fire	Crown conditions	Individual	Cruz et al. 2004
	Species	Individual	Frejaville et al. 2013
	Bark thickness	Individual	Pausas 2015
	Bark flammability	Individual	Frejaville et al. 2013
	Canopy bulk density	Stand	Ruiz-González and Álvarez-González 2011
	Juxtaposition of stands	Landscape	McKenzie et al. 2011
Insects	Species	Individual	Herms and McCullough 2014
	Bark surface	Individual	Ferrenberg and Mitton 2014
	Tree/forest age	Individual/stand	Jeffries et al. 2006
	Tree vigor	Individual/stand	Mitchell et al. 1983
	Landscape conditions	Landscape	Aukema et al. 2006
Fungi	Species	Individual	Ferguson 2010
	Tree age	Stand	Ferguson 2010
	Landscape conditions		Ellis et al. 2010
Wind	Species	Individual	Canham et al. 2001
	Deciduous versus evergreen species	Stand	Valinger and Fridman 2011
	Tree height	Individual	Valinger and Fridman 2011
	Tree trunk shape	Individual/stand	King 1986
	Stand density and layout	Stand	Cremer et al. 1982
	Stand structure	Stand	Pukkala et al. 2016
	Landscape conditions	Landscape	Dupont et al. 2015
Habitat loss	Stand structure	Stand	North et al. 1999
	Tree species composition	Stand	Gabbe et al. 2002
	Landscape conditions	Landscape	Shifley et al. 2008
Snow/Ice damage	Tree species	Individual	Whitney and Johnson 1984
	Tree trunk shape	Individual/stand	Wallentin and Nilsson 2013
	Stand density	Stand	Wallentin and Nilsson 2013
Herbivory	Species	Individual	Meiners et al. 2000
	Tree size	Individual	Saunders and Puettmann 1999
	Stand size	Stand	Meiners et al. 2000
	Stand density and layout	Stand	Walters et al. 2016
	Alternate food sources	Stand	Stokely et al. 2018
	Landscape habitat conditions	Landscape	Apollonio et al. 2010
Market shifts	Species	Individual	Grossman and Potter-Witter 1990
	Wood quality	Stand	Larson 1949
	Log size	Landscape	Kluender et al. 1997
Climate change	Drought and temperature tolerance	Individual	Park et al. 2014
	Phenology	Individual	Park et al. 2014

other than breaking connectivity to limit the spread of perturbations and thus avoid extreme events are responsible for selecting such practices, including potentially higher productivity (Pretzsch et al. 2017), lifeboating of selected species (Rosenvald and Lohmus 2008), or general conservation or biodiversity concerns (Beese et al. 2019). Thus, in many instances breaking connectivity is a byproduct and not a purposeful goal of such activities (D'Amato and Palik 2021), with notable exceptions, such as fire breaks (Ager et al. 2017).

Acknowledging that we cannot predict the future very well and that extreme events are part of that future means that breaking connectivity to avoid spread of perturbations at individual and across multiple scales may need to become a high priority in all silviculture and management decisions as a way to

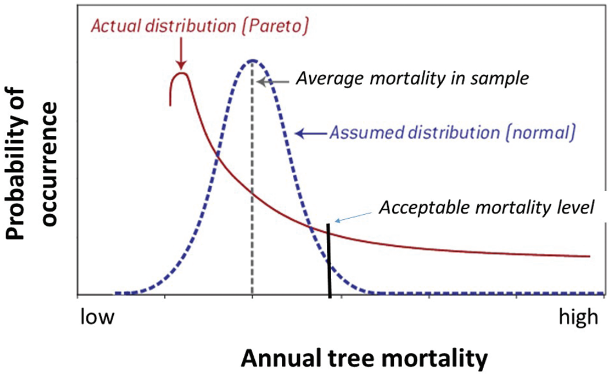

Figure 5. Example of how the assumption of an underlying distribution influences the interpretation of sampling results. Assuming a sample is from a Gaussian distribution will lead to less emphasis on extreme events. On the other hand, assuming a power law distribution indicates that most events are way below the mean, as derived from the sample, but the probability of events on the right tail, far away from the mean is higher. Thus, assuming the wrong distribution creates problems when estimating probabilities to calculate risk (e.g., as in Figure 2). Modified from Altomonte et al. (2011).

reduce ecosystem sensitivity (Figure 4). Clearly, we cannot prepare the forests for all possible surprises, but developing tables, such as Table 1, for individual operations, properties, or regions is a good starting point. Assessing how the critical events spatially map out over time in the forest would be a second step, for example, by documenting locations with higher and lower connectivity to selected critical events. Where good inventory information and modeling capacity are available, more detailed investigations could determine where specifically breaking connectivity to avoid extreme events would have the most impact on the landscape (Seidl et al. 2018).

Given our understanding of the importance of connectivity in facilitating the development of extreme events as described above and highlighted in Table 1, I propose that breaking that connectivity requires more attention when making silviculture and management decisions at patch, stand, and landscape scales. In this context, a more detailed understanding of what specifically leads to connectivity will be a valuable complement to information about inventory, marketing, and harvesting logistics typically used to develop prescriptions. For example, when managing mixed-species stands, traits of tree species other than growth potential will require more attention at the stand level: specifically, growing species together that have a different set of response-type traits (sensu Puettmann 2011)—that is, physiologial or morphological traits that determine how a species reacts to perturbations (Herben et al. 2018, Messier et al. 2019), including climate change (Neill and Puettmann 2013). Similarly, the choice of tree spacing and layout can be viewed in terms of which specific aspects of connectivity are broken or supported. For example, when managing species mixtures foresters can take the differential sensitivity of individual species to perturbation agents into account (Hennigar et al. 2008, Jactel et al. 2020).

Similarly, managing for different stand structures has been shown to have an influence on the extent of and susceptibility to perturbations. For example, when insects are specialized to penetrate trees with a specific bark characteristic that is either found in younger or older trees, the age distribution of trees in a stand or landscape can be managed to minimize the number and arrange the spatial distribution of trees that are sensitive to the insect (Ferrenberg and Mitton 2014). Another example is managing for selected stand structures to reduce the probability of surface fires climbing into the canopy (Keyes and O'Hara 2002).

At the landscape level, much can be learned from the extensive work in terms of connectivity for wildlife species (Bennett 1999). Approaches similar to the ones discussed for stands can be applied at larger spatial scales. In a landscape with fairly homogenous monocultures, ensuring different age classes can break connectivity in regard to various insects or diseases, specifically when these infestations are size (age) specific (Vogt et al. 2020). For example, lodgepole pine (*Pinus contorta*) becomes susceptible to mountain pine beetle at older ages. Thus, the potential of large-scale infestations can be reduced by avoiding a dominance of older lodgepole pine stands on an ownership or in a landscape by ensuring a more balanced age class distribution of lodgepole pine among and within stands (Gibson et al. 2009) and intermixing stands and trees with different species. Similar issues apply to landscapes where the individual stands themselves may be homogenous in terms of species and ages, but different stands have different species composition and associated sensitivity to different events, such as insect infestations (Jactel et al. 2020). Even 100 years ago, selected areas were planted with different species specifically to provide firebreaks in the landscape, such as in Wind River, WA, and much has been learned about the placement of fire breaks in landscapes with different regimes (Agee et al. 2000) that can be helpful in the broader context of extreme events. In addition, newer concepts are very insightful in this context, such as "immunizing" a landscape—so that plants and animals with traits that encourage resilience can propagate through the landscape (Messier et al. 2019). These concepts provide insights on how stands in landscapes with different layouts, such as with different ownerships or nonforested areas, can be managed to break connectivity, for example, to discourage large-scale invasions of exotic species (Theoharides and Dukes 2007).

A major challenge will be to decide how to most efficiently include practices aimed at breaking connectivity to reduce the spread of perturbations and thus avoid extreme events into day-to-day management operations. Based on experiences in other fields, just modifying a single management practice (e.g., switching from monoculture to mixed species stands) may not be sufficient. Instead, assessing the whole suite of practices in the context of their impact on connectivity may suggest the benefits or necessity to modify several practices simultaneously (e.g., switching to mixed species stands and multiple canopy layers; Palik et al. 2020). Taking a critical broad multiscale view also will be helpful to avoid or minimize unintended consequences. Of specific concern are the negative impacts of activities aimed at breaking connectivity to avoid extreme events may have for wildlife habitat and migration opportunities (Bennett 1999). Ownership patterns and associated logistical constraints will have a great influence on the ability of individual owners or foresters to influences connectivity, especially at larger scales. At the same time, the different objectives and associated management regimes of various ownerships may already provide the diversity across the landscape that reduces connectivity. Considering the possibility of different types of extreme events, as suggested in Table 1, and many logistical constraints highlights that the best choice of management practices that reduces connectivity will likely vary by region, but also by ownership, local economic, social, and ecological conditions and thus may also change over time. Finally, the impact of any application of such practice should be monitored closely over time, especially if these practices are novel, and following the adaptive management approach plans should be developed how to deal with unintended undesirable consequences.

Conclusion

Advancement in theories and concepts in various fields provide important insights for foresters and can inform forest management in general and silviculture decisions in particular. In this example, acknowledging extreme events results in a more differentiated view of forest connectivity and suggest the need for more attention how our management practices relate to increasing or decreasing connectivity for extreme events. We first need to fully acknowledge that the future is uncertain and that extreme events will happen. Next, the forestry profession can take advantage of advancements in the understanding of extreme events in other scientific fields, specifically the influence of diversity in structures and composition and connectivity within and across scales, and adapt and integrate such understanding into forestry practices. Such opportunities are not limited to the silvicultural aspects, which was the focus of my discussion. In a best-case scenario, acknowledging extreme events and managing to discourage connectivity to prevent the spread of perturbations does not have to be an additional cost, but can actually lead to higher profits. For example, being flexible and able to offer different species and qualities for sale can allow landowners to take advantage of market swings, leading to higher profitability (Knoke and Wurm 2006). Such opportunities can be viewed as an indicator of the possibility of antifragility (sensu Taleb 2012), whereby foresters can "gain from disorder."

I hope this discussion makes a convincing argument that we cannot afford to ignore extreme events just because they are so rare. Despite their rarity, avoiding the irreversible, unacceptable outcomes of such events deserves our attention. Accepting extreme events as part of forestry development forces us to critically assess assumptions and principles that were developed with little attention to extreme events, specifically the role of variability in stand structures and tree species compositions in context of breaking connectivity. Obviously, much still needs to be learned to make the application of the concept of extreme events feasible and an integral part of forestry operations. Such efforts are further complicated, as any management decisions also need to consider desirable aspects of connectivity (Correa Ayram et al. 2016). In addition, managing connectivity may also be designed to encourage ecosystem resilience (i.e., the ability of ecosystems to recover; Messier et al. 2019) and improve the ecosystem's capacity to adapt to altered conditions (Ontl et al. 2019). In addition, any multiscale approach has to overcome operational challenges, such as constraints because of mixed ownerships. However, recent progress in technologies, such as simulation models, remote sensing, GIS, and GPS will facilitate implementation of more complicated silvicultural prescriptions. Last, it is important to understand that no matter what management strategy we choose, it will not prevent all problems (no perfect top-down control, sensu Holling and Meffe 1996) and we have to prepare for an uncertain future. Despite these challenges, the recent broadening of silviculture (as evident in, e.g., Ontl et al. 2019, Puettmann and Messier 2019, Palik et al. 2020) makes me optimistic, and I hope this article stimulates further dialog.

Acknowledgments

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Erratum

Erratum to: Extreme Events: Managing Forests When Expecting the Unexpected

Klaus J. Puettmann

This article was published with an error in the caption for Figure 1. The caption should read as follows:

Figure 1. Photos of extreme events, including (a) American chestnut (*Castanea dentata*) infected with the chestnut blight (photo credit: USDA Forest Service); (b) large-scale Norway spruce (*Picea abies*) mortality in central Europe because of extended drought and bark beetle infestations (photo credit: B. Leder); (c) fire mortality 2019 in East Gippsland, Australia (photo credit: T.A. Fairman); and (d) mountain pine beetle mortality near Bonaparte Lake, BC (photo credit: L. MacLauchlan).