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comment

Please do not disturb ecosystems further

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Clearing up after natural disturbances may not always be beneficial for the environment. We argue that a radical change is needed in the way ecosystems are managed; one that acknowledges the important role of disturbance dynamics.

Recent controversy over logging of Białowieża Forest in Poland has centred largely on cutting some of the most ecologically significant pristine forests remaining in Europe, which support populations of iconic species of conservation concern[1]. However, from an ecological perspective, we suggest this controversy also underscores ongoing global policy problems with how naturally disturbed (in that case insect-affected) ecosystems are managed. Logging of Białowieża Forest was promoted as being essential to limit the impacts of pest insect outbreaks, but it is emblematic of a broader innate human inclination to clean-up and fix the damage caused by natural disturbances. Yet such management actions may have significant negative effects, such as exacerbating existing environmental problems, creating new problems, and impairing post-disturbance recovery.

Here we outline some of the impacts arising from human disturbance of ecosystems subject to recent natural disturbance (Box 1), and show that these problems extend beyond forests to alpine, aquatic, coastal, marine and other ecosystems (Fig. 1). We acknowledge that, for the purposes of this text, we have distinguished between natural and human disturbance whilst also recognizing that some apparently 'natural' disturbances can be due to human actions, either direct or indirect. Nevertheless, we argue there is a need for new policies based on a clearer understanding of both the role and importance of natural disturbances in ecosystem dynamics, and the array of detrimental impacts of human disturbances directly following a natural disturbance.

Improve post-disturbance management

Many species in disturbance-prone ecosystems recover through *in situ* population recovery from survivors, rather than recolonization from outside the disturbed area. Human disturbance impacts

Box 1 | Human disturbance after severe natural disturbance can have at least nine classes of negative ecological impacts.

Disrupted abiotic and biotic processes. For instance, post-hurricane salvage logging altered large-scale hydrological regimes in north-eastern USA (Fig. 1c) and increased the impacts of subsequent floods[15]. Such altered abiotic conditions can then disrupt ecological processes such as those that shape how species assemble into communities[16].

Increased susceptibility of ecosystems to additional and repeated severe natural disturbances. For example, forests that are burned, salvage logged and then regenerated are at risk of reburning at high severity[5] with elevated fire proneness lasting for decades after harvesting[17].

Depleted levels of native biodiversity. Ecosystems recovering after disturbance can be species-rich early successional environments but their habitat values can be impaired by post-disturbance management[18].

Increased risk of invasion by exotic plants and animals. As an example, soils of fire-damaged Australian alpine ecosystems were stabilized using hay sourced from agricultural landscapes but this introduced new pest plants (Lindenmayer *et al.* unpublished data).

Disruption of *in situ* population recovery. For instance, the way lichens and fungi colonize deadwood is resilient to insect outbreaks but inappropriate management during the early post-disturbance phase can impair this process[19].

Loss of biological legacies. Hollow-bearing trees and logs remaining after severe fires provide resources for biodiversity but these critical structures are sometimes removed in post-disturbance management[20].

Diminished restorative benefits of disturbance events. For instance, the redistribution of beach sands by the 2004 tsunami helped naturally restore suitable nesting habitat for sea turtles but the subsequent clean-up programme inadvertently destroyed much of that habitat[21] (Fig. 1e,f).

Loss of natural patterns of landscape heterogeneity. Standard post-disturbance management practices such as deliberate burning of unburned vegetation patches in otherwise burned landscapes[12] can simplify landscape heterogeneity, removing key places for population recovery. Loss of refuges may render populations more susceptible to other threats, as refuges may buffer populations against multiple environmental processes (for example, fire refuges are often also drought refuges[13]).

Elevated risks of ecosystem collapse. Broadly defined as an abrupt, long-lasting and widespread change in ecosystem state and dynamics. As an example, fire-damaged tropical rainforests in Asia that are salvage logged can re-burn and collapse into an exotic grassland state where rainforest cannot establish[22].

Figure 1 | Examples of ecosystems subject to natural disturbances and then subject to negative ecological impacts associated with subsequent human-derived disturbances. **a**, Salvage logging in streamlines after fires in the Australian Capital Territory leading to damaged riparian systems. **b**, Spatially heterogeneous stand dominated by Norway spruce (*Picea abies*) in the Bavarian Forest National Park, Germany, killed by the European spruce bark beetle 20 years ago. The tree and beetle species are the same as those associated with natural disturbance in Białowieża Forest in Poland. **c**, Logs stored in lakes following salvage logging after a major hurricane in north-eastern USA in 1938 leading to significant changes in hydrological regimes. **d**, Post-fire salvage logging in the wet forests of Victoria, Australia in which artificially regenerated stands are densely stocked and at risk of subsequent high-severity crown-scorching fire. **e**,**f**, Post-tsunami sand deposition on a Sri Lankan beach following the 2004 tsunami (**e**) and after post disturbance-management (**f**). Photo credits: D. Lindenmayer (**a**); S. Thorn (**b**); Harvard Forest Archives (**c**); David Blair (**d**); Charles Tambiah (**e**,**f**).

populations at a sensitive period, and species' adaptations for *in situ* recovery may be particularly vulnerable[2]. For instance, many plants can resprout after fire, but do not survive the physical disturbance of harvesting machinery during post-fire salvage logging[3].

Management practices in naturally disturbed areas must avoid making already damaged ecosystems prone to further problems such as subsequent high-severity disturbances and invasion by exotic species. Risk assessment underpinned by empirical studies can guide mitigation approaches that are appropriate to different ecosystems and disturbance types[4].

Forests in western North America and southern Australia are sometimes actively replanted following salvage logging of burnt forest. However, this can make them more susceptible to re-burning as a consequence of the high density of saplings[5]. Reducing the numbers of planted seedlings and increasing tree spacing may reduce the risk of recurrent high-severity fire.

Retain natural disturbance benefits

Natural disturbances can have positive ecological benefits for many ecosystems and often provide valuable habitat including for endangered species. For example, floods and tsunamis can help restore patterns of sediment depleted and/or heavily altered by human activity[6]. In the case of the Białowieża Forest, the European spruce bark beetle, *Ips typographus*, has a keystone role in shaping forest structure and dynamics[7]. Management practices must ensure that ecological benefits generated by major natural disturbances are not lost through ill-informed subsequent human action.

All natural disturbances leave behind biological legacies[8] such as living and dead trees, seeds, and eggs which play key ecological roles including: (1) facilitating species persistence, recolonization and post-disturbance succession; (2) creating important early successional habitats for a range of species; (3) maintaining processes (such as nutrient cycling); and (4) promoting the restoration of previously degraded ecosystems[9]. Management practices must be based on scientifically defensible prescriptions regulating what, and how many, biological legacies to retain. These prescriptions must ensure appropriate ecosystem recovery and the maintenance of ecosystem processes and biodiversity, as well as reduce the risks of recurrent and more severe future disturbance[4].

Maintain landscape heterogeneity

Natural disturbances are typically spatially heterogeneous regardless of their severity or intensity, leaving behind patches of undisturbed vegetation within the boundaries of the perturbed area (Box 1, Fig. 1b). For many species, population recovery comes from individuals remaining within these refugia[9]. For instance, the 2009 Black Saturday fires in Australia burnt more than 450,000 ha of forest, severely reducing the abundance of many mammal species. Some survived in refuges in the burnt landscape, such as fine-scale drainage lines, and were sources for rapid recovery as vegetation cover increased in the surrounding landscape[9]. Similar patterns of 'nucleated' recovery from refuges occurred after the 1988 fires in Yellowstone National Park[10]. Unburnt refuges are not only important for population persistence after fires, but also buffer populations against other stressors such as drought[11] and act as repositories of genetic diversity under environmental change.

An essential management action must be to preclude or limit post-disturbance 'clean-up' and related actions from refugial areas. For example, setting fire to unburned patches in a post-fire landscape during black-out burning[12]. Similarly, patches of spruce surviving extensive bark beetle outbreaks are often logged despite being refugia for many taxa[13]. These practices which homogenize landscape heterogeneity should be abandoned, particularly in areas with high ecological values (for example, nature reserves).

Landscape-level quarantine policies will be most effective if areas of exemption from human disturbance are planned and then mapped in advance of major natural disturbances. These plans should explicitly address what ecosystem values to retain, where those values are best maintained, and why. Salvage logging might be excluded from steep slopes and areas with highly erodible soils in order to preserve water catchment values and soil stability following fire, windstorm or insect outbreak, for example.

Other places to quarantine include wildlife breeding areas and biodiversity hotspots that support high levels of species richness prior to natural disturbance, and which often retain these high levels post disturbance[14].

Provide better education

It is vital to better educate resource managers, policymakers and the public about the negative impacts of human disturbance of naturally disturbed ecosystems. Many people are unaware that post-disturbance management can exacerbate existing environmental problems and create new ones. Decision-makers need to understand that many species are well adapted to severe natural disturbances[6] but they may not survive the additional human disturbances that follow soon after[20]. Public understanding can be improved by highlighting the importance of allowing early successional environments to recover after natural disturbances so that they maintain biodiversity and ecosystem processes.

While natural disturbances may be rightly considered catastrophes from a human perspective, they may not be catastrophic from an ecological one. We argue that there is a need to reconsider the implications of our human response to natural disturbances, and shift away from a psyche of having to 'clean-up' after natural disturbances. Improved policies need to limit the negative effects of post-disturbance management, capitalize on the disturbance-created ecological benefits, and reduce the risks of making naturally disturbed ecosystems more disturbance-prone. Without these improvements, there is a risk that the increasing number of naturally disturbed ecosystems worldwide will be even further damaged, potentially irreversibly. ❐

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