Cascading events in linked ecological and socioeconomic systems

Debra PC Peters[1*], Osvaldo E Sala[2], Craig D Allen[3], Alan Covich[4], and Mark Brunson[5]

Cascading events that start at small spatial scales and propagate non-linearly through time to influence larger areas often have major impacts on ecosystem goods and services. Events such as wildfires and hurricanes are increasing in frequency and magnitude as systems become more connected through globalization processes. We need to improve our understanding of these events in order to predict their occurrence, minimize potential impacts, and allow for strategic recovery. Here, we synthesize information about cascading events in systems located throughout the Americas. We discuss a variety of examples of cascading events that share a common feature: they are often driven by linked ecological and human processes across scales. In this era of globalization, we recommend studies that explicitly examine connections across scales and examine the role of connectivity among non-contiguous as well as contiguous areas.

Los eventos consecutivos en cascada que empiezan a pequeñas escalas espaciales y que se propagan de forma no lineal a través del tiempo para influenciar áreas más grandes a menudo tienen impactos de gran envergadura sobre los recursos y servicios de los ecosistemas. La frecuencia y la magnitud de eventos tales como incendios y huracanes están aumentando mientras que los sistemas se interconectan por los procesos de la globalización. Necesitamos mejorar nuestra comprensión de estos acontecimientos para poder predecir su ocurrencia, reducir al minino los posibles impactos, y para permitir una recuperación estratégica. Aquí sintetizamos la información de estos eventos consecutivos en cascada en sistemas localizados a través del continente Americano. Discutimos una variedad de ejemplos de eventos consecutivos en casada que tienen una característica en común: son inducidos por procesos ecológicos y humanos ligados a través de las escalas. En esta era de globalización, recomendamos estudios que examinen explícitamente las conexiones a través de las escalas, y que se examine el rol de la conectividad entre áreas contiguas y no contiguas.

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Cascading events, such as wildfires and hurricanes, which start in small areas and propagate non-linearly through time to influence large areas, are becoming increasingly important in both ecological and human-dominated systems. Global change is increasing the frequency and magnitude of cascading events. At the same time, globalization is increasing the connectivity of systems in multiple ways and at multiple scales, thereby initiating new types of cascading events. In particular, globalization is allowing activities in one country to initiate and drive cascading events in other countries, and even among continents. Predicting the initiation and rate of spread of these events is particularly difficult for connections among non-contiguous areas.

Workshop: Cascading events in linked ecological and social systems – predicting change in an uncertain world

Organized by: DPC Peters and OE Sala

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Authors' contact details are on p224

The aim of the workshop reported here was to compare and contrast cascading events occurring throughout North, Central, and South America. Our goals were to: (1) identify how, when, and where these cascading events are likely to occur, so that predictions can be improved and the effects of such events averted or minimized, and (2) draw upon expertise among scientists from different disciplines, countries, and systems of interest in order to develop a conceptual and predictive framework for cascading events (Peters *et al*. 2004).

Cascading events in linked ecological–human systems

Four examples are provided here that illustrate key features of cascading events: (1) interactions of processes and patterns across scales; (2) linkages between land-use decisions and ecosystem dynamics; (3) non-linear aggregation of fine-scale processes with unanticipated effects at broader scales; and (4) extent and severity of impacts increasing non-linearly through time and across space.

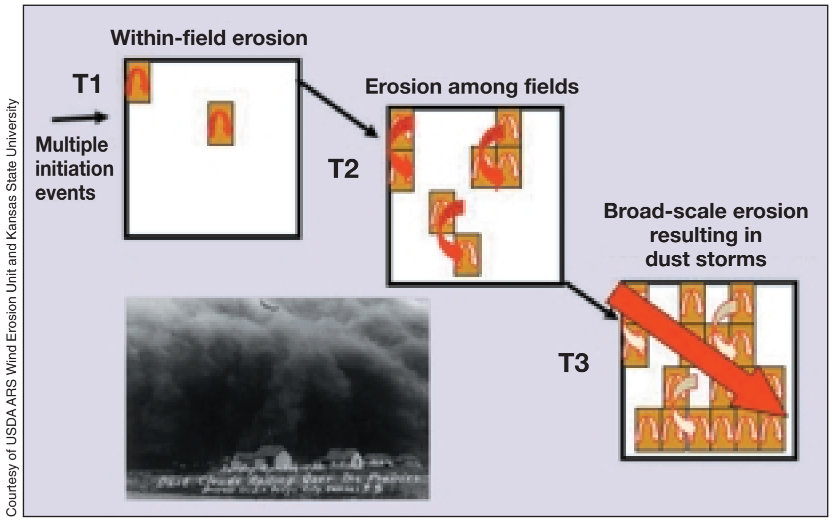

Figure 1. *Schematic of the Dust Bowl in the US, 1930s. The event was initiated by many farmers plowing and abandoning their fields during an extreme drought (T1). Initially, wind erosion was limited to movement of soil from individual fields. As more fields were abandoned, a second threshold was crossed (T2), after which the dominant process was erosion among fields. As more fields were abandoned within the Great Plains region, broad-scale erosion that likely included land–atmosphere interactions was the dominant driver, resulting in massive dust storms and the movement of soil particles as far as the East Coast of the US.*

The Dust Bowl provides a historical example of a cascading event associated with land degradation that started at localized scales (individual fields) and expanded non-linearly to impact the entire US (Peters *et al.* 2004). In the 1930s, a period of extreme drought persisted in many parts of the US, particularly in the central Great Plains. This was preceded, in the 1920s, by US government policies that promoted the cultivation of increasingly marginal cropland. The Dust Bowl was therefore initiated as a result of decisions by many individual farmers to plow marginal land for crops throughout the Great Plains (T1 in Figure 1). With the onset of the drought, many croplands were abandoned, in reaction to high plant mortality. Initially, erosion occurred within individual fields. However, as the drought continued and more fields were affected, a threshold was crossed (T2 in Figure 1) where fields affected by erosion dominated landscape dynamics. As the impact of the drought expanded and abandonment of land became widespread regionally, the fields became highly connected by broad-scale weather patterns, resulting in the creation of massive dust storms (T3 in Figure 1). These ecological impacts resulted in cascading events in human systems as well; migration out of this region to other parts of the country was common. Similar non-linear dynamics associated with land degradation are currently occurring in arid regions of the world, such as Saharan Africa, often characterized by woody plant invasion and land use. Finally, planet-wide dust storms on Mars illustrate the danger of over-connected systems cascading to broad scales (Figure 2).

Fire histories throughout the Americas also reflect linkages between human land-use practices at local scales and changes in fire regimes at regional scales, resulting in cascading events. Prior to 1900, forests with highly connected herbaceous understories were common in the southwestern US. These vegetation characteristics, combined with abundant lightning-associated fires and recurrent dry periods, resulted in high-frequency surface fires at many sites (Figure 3 a,b). Beginning in the 1880s, extensive railroad construction linked this previously economically-isolated region to national markets and triggered a boom in livestock grazing. The decision by many individual ranchers to increase their sheep and cattle herds resulted in large numbers of year-round grazers on "open-range", public lands throughout the region. Overgrazing reduced the connectivity of surface fuels below the threshold value required for fire propagation (Allen 2002), and effectively moved the system back across threshold from T2 and T1 (Figure 3c; Peters *et al.* 2004).

After 1910, land managers also actively suppressed all wildfires, based on a change in US federal policy. Thus, the former fire regime collapsed at landscape to regional scales, resulting in very few fires (Figure 3b; Swetnam *et al.* 1999). This period of fire suppression initiated a cascading series of ecosystem changes that have modified southwestern forest fire regimes up to the present. For example, greatly increased forest densities and ladder fuel loads at the patch scale have coalesced into landscape-scale powder kegs (T2 in Figure 3c), so that extreme fire behavior has become increasingly common. A further threshold (T3 in Figure 3c) is now crossed more frequently, when fires "blow up" as a result of positive feedbacks created by convective heat from high-severity fires, leading to high winds from pyrocumulus clouds (Figure 3d). Thus, human interactions with ecosystems over the past century have transformed the fire regimes of many forests in this region, from low-severity surface fires to high-severity, stand-replacing fires. These high-intensity, broad-scale fires have negative effects on forests and their watersheds, as well as on associated human communities. Elsewhere in the hemisphere (eg tropical moist forests), a different set of fire–human interactions is causing other kinds of cascading changes in fire regimes (Nepsted *et al.* 2001).

Hurricanes are complex storm events that cascade to have both immediate and long-lasting impacts on linked natural and human-dominated systems. Multiple levels of interactions among people, where and how they live, and the impacts of hurricanes, result in these cascading dynamics (Peters *et al.* 2004). A general pattern in North America is for people to move to coastal regions and increase local population densities in or near hurricane-impacted areas. Human populations exert intense pressure on natural landscapes by draining wetlands, removing coastal vegetation, and expanding impervious surfaces that increase storm runoff and flooding, as well as increasing heat island effects. These local conditions can accentuate the impacts of hurricanes and other large storms which, in turn, increase the devastation of human-dominated systems (Emmanuel 2005; Nates and Moyer 2005). For example, the local effects on soil erosion of land clearing for agriculture and pastures can be augmented by hurricane winds, reinforcing persistent patterns across regional landscapes.

The headwaters of drainages can be intensively altered, resulting in reduced water quality and food production, with cascading effects throughout human- and wildlife-dominated food webs. Disruption of ecosystem services in natural drainages is often coupled with the breakdown of engineered infrastructure (eg sewage- and water-treatment plants), so that diseases spread rapidly following natural storm events. In addition, migration following intense hurricanes often results in economic stress and public health concerns in contiguous or non-contiguous areas. For example, following Hurricane Hugo in Puerto Rico in 1989, large numbers of people migrated into the nearby Caribbean National Forest, seeking clean drinking water and a safe place to live in the short term. Following Hurricane Katrina in 2005, many people migrated throughout the US, without a clear time frame for their return. Because the frequency and intensity of hurricanes are projected to increase in the future, as a result of both atmospheric–oceanic feedbacks and local feedbacks associated with land-use change (Pielke 2005), a more comprehensive view of these cascading events is needed for those regions of the Americas influenced by them.

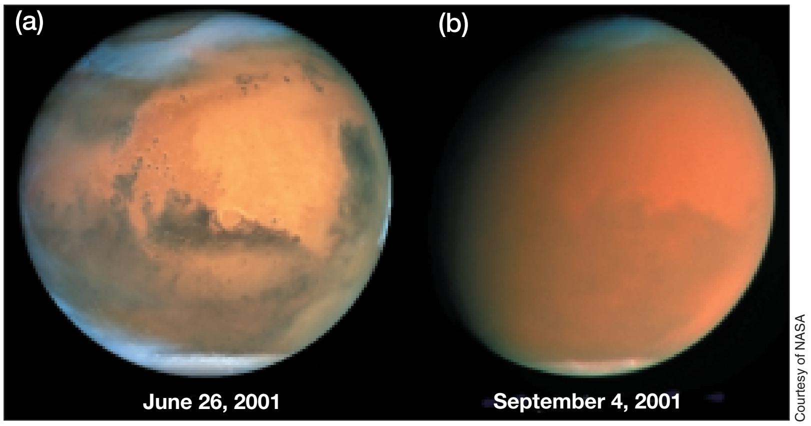

Figure 2. *A dust storm on Mars appears to follow the same processes as the Dust Bowl and other cascading land-degradation events on Earth. (a) Surface features of Mars are visible at the start of the "perfect storm" of 2001. (b) Within two weeks, the dust storm engulfed the planet, resulting in low visibility throughout the month of September.*

Recent increases in snow goose populations illustrate how widely dispersed human activities can have cascading effects on ecosystems, with feedbacks to human-dominated systems. Numbers of the greater snow goose (*Chen caerulescens atlantica*) increased dramatically in North America over the 1980s and 1990s. During migration, these birds use marshes along the St Lawrence River in numbers far exceeding carrying capacity. Mid-continent populations of lesser snow goose (*C caerulescens caerulescens*) are similarly overgrazing the Hudson Bay area, causing long-term damage to salt marshes. Population growth is attributed to factors that are important by themselves, but they also combine to cascade non-linearly through time and across space. One factor in this population growth is increased food availability in agricultural fields. As marsh habitat is degraded by overgrazing, snow geese move to adjacent farms. Diets are shifting from marsh plants to corn and grass shoots in relation to changes in food availability (Gauthier *et al.* 2005). In addition, greater snow geese now winter farther north, partly due to greater food availability, as farmers have increased corn production in southwestern Quebec, and probably also as a result of higher average temperatures (Gauthier *et al.* 2005). Thus, increasing population growth is propagating the problem over broader areas.

Another cause of increased population growth is the greater percentage of snow goose ranges not open to hunting during fall and winter (Calvert *et al.* 2005). Migration to rural areas by former urbanites who neither hunt nor allow hunting on their properties is increasing the area of protection. Wildlife managers are extending hunting seasons and bag limits to combat the problem, but these policies are insufficient if hunting access and hunter numbers continue to decline. Fragmented jurisdiction and spatial discontinuities make the problem more difficult to address. Although state and federal wildlife agencies within the US are cooperating to create a common mitigation strategy, hunter access is determined by thousands of landowners with little or no knowledge of how to access information about the effects of their decisions on ecosystems that may be over 2400 km away and in another country.

Conclusions and recommendations

Understanding cascading events can improve our ability to forecast future events in the presence of similar conditions or behavior. For example, understanding that individual decisions and localized soil erosion can cascade spatially and temporally to result in regional to global impacts on water, air, and soil quality is critical to predicting the consequences of future decisions for system dynamics. Feedbacks to human systems, such as economic hardship, increased migration from high-impact areas, and changes in management and policy decisions, can either increase or decrease connectivity in ecological systems and can result in complex system interactions and dynamics. Because global change is increasing the frequency and magnitude of

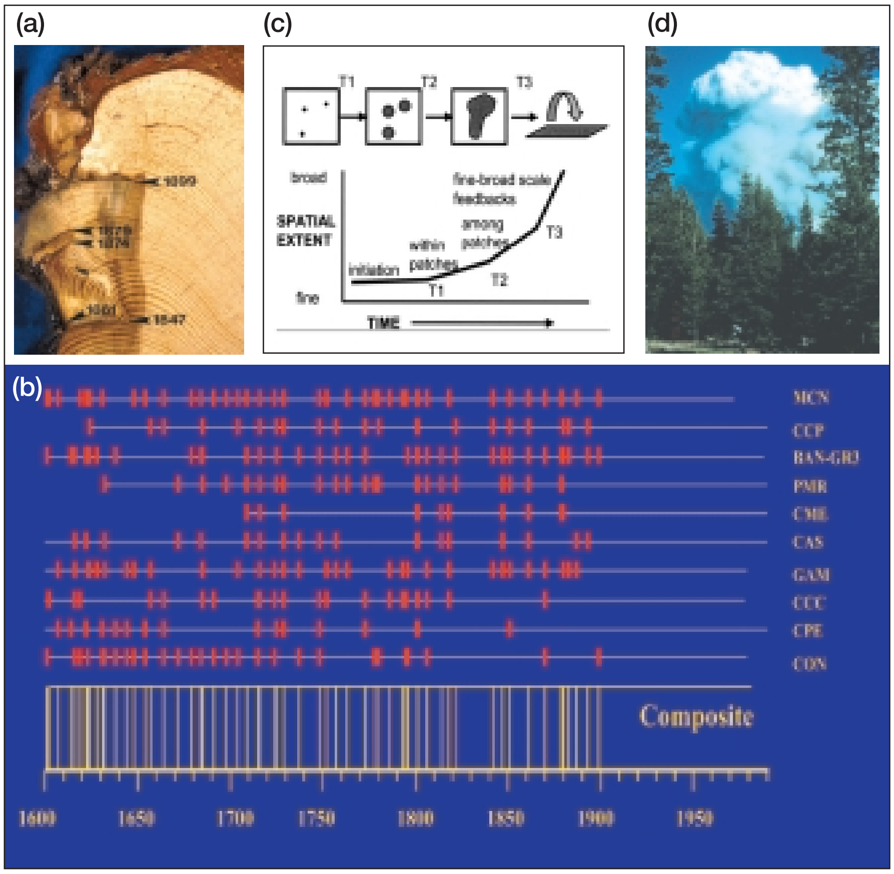

Figure 3. *(a) Cross-section of ponderosa pine from the Jemez Mountains, New Mexico, showing annual growth rings and dated fire scars. (b) Composite of fire scar chronologies for ten ponderosa pine forest stand sites in the Jemez Mountains (Touchan* et al. *1996). Horizontal timelines represent calendar years, and vertical tick marks are composite fire dates recorded for 25% or more of the trees within each site. The taller vertical lines indicate years in which > 25% of the sites recorded fire. Note that this landscape-scale fire history shows the regional trend of post-1900 fire cessation. (c) Three thresholds and associated dominant process involved in the non-linear increase in spatial extent of a cascading event through time (Peters* et al. *2004). Reprinted with permission from* Proceedings of the National Academy of Sciences. *(d) Pyrocumulus cloud generated by the 1996 Dome Fire in the Jemez Mountains.*

cascading events and globalization is increasing connectivity in multiple ways and at multiple scales, it is imperative that we examine cascading events throughout the Americas and globally, in order to improve our understanding of complex system dynamics.

We recommend the following new research directions: (1) the development of a general framework for cascading events that explicitly links ecological and socioeconomic–political systems; and (2) new experiments and predictive models to identify the conditions leading to cross-scale interactions and catastrophic events. These experiments and models need to include both threshold behavior and a change in dominant process as events cascade non-linearly through time and across space. In addition, connectivity needs to be examined among non-contiguous areas as well as contiguous areas. Cascading events can be initiated by decisions and activities made in other parts of the world that propagate to non-contiguous areas through economic activities, trade, or atmospheric and water circulation patterns. These events are inherently difficult to predict, yet they have the greatest potential to impact linked ecological and human-dominated systems in large and irreversible ways. Combining a general theoretical framework with new experiments and models will be a powerful approach for minimizing the impacts of these events and predicting their occurrence.

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[1]*USDA ARS, Jornada Experimental Range, Las Cruces, NM 88003* [*]*(debpeter@nmsu.edu);* [2]*Center for Environmental Studies, Brown University, Providence, RI 02912;* [3]*USGS, Jemez Mountain Field Station, Los Alamos, NM 87544;* [4]*Institute of Ecology, University of Georgia, Athens, GA 30602;* [5]*Department of Environment and Society, Utah State University, Logan, UT 84322*

